

MOISTURE TRANSPORT IN COMPACT FLAT ROOFS

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MOISTURE TRANSPORT IN COMPACT FLAT ROOFS

**Doctoral thesis for obtaining the Degree of “Doctor of Philosophy”,
abbreviated to “Ph.D.”**

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Summary

This thesis focuses on compact flat roofs. This type of roofs is commonly utilized in Central Europe. The main focus of this thesis is on moisture transport in these roofs due to the effect of moisture on the lifetime of the roofs. Proper moisture control reduces the future failures of the roofs and significantly extends the lifetime of the entire building. One of the moisture control elements in compact membrane roof assemblies is a vapour retarder. Vapour retarders have been implemented in these roof assemblies since the 1930s. Since then, the degree of how the perforation of vapour retarders affects water vapour transport has been the subject of much discussion.

The experimental part of the thesis focuses is on perforated vapour retarders and how much moisture content can be transported through them. A unique experimental apparatus was developed which facilitated the measure of water vapour permeability of thin products with a high diffusion resistance. A detailed description of the experimental apparatus is provided in this thesis. The results of the experimental measurements demonstrate a significant increase of water vapour transport through perforated vapour retarders. This conclusion is in accordance with known experimental results, although percentage of perforation was much lower and diffusion resistance of measured products was much higher than in the previous studies. On the basis of experimental results, an analytical model of water vapour transport through perforated products was developed. This model describes water vapour transport through thin perforated products with a high diffusion resistance. The comparison of the experimental data with the data calculated by the analytical model produced similar results. Additionally, the data from previous experimental studies compared favourably with the results calculated by the analytical model.

Since the 1960s, several discussions about the utility of the use of vapour retarders in compact membrane roofs have been presented in technical literature. Several opposing recommendations and guidelines on how and where vapour retarders should be used in compact membrane roof assemblies were published. Therefore, the other part of the thesis focuses on moisture transport in the entire roof assembly.

Numerical simulations of coupled heat and moisture transport in the roof assemblies were made with the help of the Kunzel numerical model. This model describes a much better coupled heat and moisture transport in composite building assemblies than the Glaser methods used in the Czech and European technical standards. The results of these simulations showed that the dominant factor for moisture transport in compact membrane roofs is the temperature gradient caused by short and long-wave radiation. This radiation factor is neglected by the simple Glaser methods. The comparison of three different requirements for moisture transport within roof assemblies; two standard requirements (DIN 4108-3(2001), CSN 730540-2 (2007)) and the author requirements, show that the Czech standard requirements for moisture transport within the building envelope are very strict. When the strict Czech requirements are used together with simple calculation methods that neglect short and long-wave radiation, the results indicate that vapour retarders must be utilized in compact membrane roof assemblies. However, the results of the simulation showed that compact membrane roof assemblies placed on a heavy concrete slab can be utilized without vapour retarders if short- and long-wave radiation is considered. The results proved that there are no absolute rules on which type of roof assembly to use. Instead, all types of roof assemblies must be properly calculated and

evaluated on their ability to transport moisture, and designed and implemented accordingly.

The last part of the Thesis offers new recommendations on how to efficiently design compact membrane roof assemblies from a view of moisture transport.

Resumé

Tato disertační práce je zaměřena na ploché jednoplášťové střechy, které jsou zcela běžně navrhovány ve Střední Evropě. Disertační práce se hlavně zaměřuje na transport vlhkosti v těchto střechách, neboť vlhkost má zásadní vliv na životnost střešních konstrukcí. Vhodným omezením transportu vlhkosti se snižuje riziko budoucích poruch, a tím se výrazně prodlužuje životnost jednoplášťových střech. Parotěsnicí zábrana je jedním prvkem, který omezuje transport vlhkosti do střešního pláště a který se navrhuje právě ve skladbě jednoplášťových plochých střech s klasickým pořadím vrstev. Parotěsnicí vrstvy se navrhují v obalových konstrukcích budov od 30.let 20. století. Po celou tuto dobu se vynořují diskuse, jakým způsobem proděravění parotěsnicí vrstvy ovlivňuje transport vlhkosti.

Experimentální část disertační práce se zaměřuje na porušené parotěsnicí zábrany a jak velké množství vlhkosti může být skrz ně difundováno. V rámci této práce byla vyvinuta a sestavena unikátní experimentální aparatura, která umožňuje měřit difúzní vlastnosti tenkých stavebních výrobků s velkým difúzním odporem. Experimentální aparatura je detailně popsána v disertační práci. Jedinečné výsledky experimentálního měření potvrzují výrazný nárůst transportu vlhkosti skrze proděravěné parotěsnicí zábrany. Tento závěr je v souladu s předchozími výsledky podobných experimentálních měření, přestože procento proděravění bylo o mnoho menší a difúzní odpor měřených výrobků byl vyšší než v předchozích známých studiích. Na základě výsledků experimentálního měření byl sestaven analytický model popisující transport vlhkosti skrze tenké proděravěné výrobky, které mají velký difúzní odpor. Výsledky z experimentálního měření se výrazně shodují s výsledky, které byly vypočteny pomocí navrženého analytického modelu. Taktéž, výsledky z předchozích experimentálních měření ukázaly velmi dobrou shodu s výsledky vypočtenými pomocí analytického modelu.

Od 60.let 20. století se v odborné literatuře objevují názory na užitečnost či neúčinnost použití parotěsnicích zábran v plochých jednoplášťových střechách. Bylo publikováno několik protichůdných doporučení a pravidel, jak a kdy by měly být navrženy parotěsnicí zábrany. Z tohoto důvodu je další část disertační práce zaměřena na transport vlhkosti v celém střešním plášti.

Numerické simulace současného šíření tepla a vlhkosti byly provedeny za pomoci Künzlova numerického modelu. Tento numerický model přesněji popisuje současný transport tepla a vlhkosti ve složených stavebních konstrukcích než jednoduché Glaserovy metody, které jsou popsány v českých i evropských tepelně technických normách. Výsledky numerických simulací ukázaly, že rozhodujícím potenciálem pro transport vlhkosti v jednoplášťových střechách je gradient teploty, který je způsobený krátkovlnným a dlouhovlnným zářením, avšak toto záření je zanedbáno v jednoduchých Glaserových metodách. Porovnání tří rozdílných požadavků na transport vlhkosti ve střešních pláštích – dvou norem (DIN 4108-3 (2001), CSN 730540-2 (2007)) a požadavků navržených autorem – ukázalo, že požadavky českých tepelně technických norem jsou nejpřísnější. Použití přísných normových požadavků spolu s jednoduchými výpočetními metodami, které

zanebávají krátkovlnné a dlouhovlnné záření, způsobuje, že parotěsnící zábrany musí být navrhovány v jednoplášťových plochých střeších. Výsledky simulací prokázaly, že jednoplášťové ploché střechy s těžkou nosnou konstrukcí mohou být navrženy i bez parotěsnících zábran, obzvláště pokud je ve výpočtu zahrnuto dlouhovlnné a krátkovlnné záření. Výsledky numerických simulací potvrdily, že neexistují obecná pravidla, kdy navrhnout konkrétní typ střešního pláště. Všechny typy střešních pláštů musejí být správně numericky modelovány vzhledem k vnějším a vnitřním okrajovým podmínkám a posouzeny na transport vlhkosti.

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Nomenclature

Latin letters

A	area	m^2
A	water absorption coefficient	$kg/(m^2 \cdot s^{0.5})$
C_a	volumetric heat capacity	$J/(m^3 \cdot K)$
c_a	specific heat capacity of air	$J/(kg \cdot K)$
c_e	specific heat capacity of ice	$J/(kg \cdot K)$
c_s	specific heat capacity of the dry material	$J/(kg \cdot K)$
c_w	specific heat capacity of liquid water	$J/(kg \cdot K)$
d	thickness	m
D_{va}	binary diffusion coefficient air and vapour	m^2/s
D_w	liquid transport coefficient	$m^2 \cdot s$
D_{ws}	capillary transport coefficient for the suction process	m^2/s
D_{ww}	liquid transport coefficient for redistribution	m^2/s
D_φ	liquid conduction coefficient	$kg/(m \cdot s)$
g_a	density of vapour flow in a gas mixture	$kg/(m^2 \cdot s)$
g_l	density of liquid flow	$kg/(m^2 \cdot s)$
g_v	density of vapour flow in a material	$kg/(m^2 \cdot s)$
H	total enthalpy of moist material	J/m^3
h_c	convective heat transfer coefficient	$W/(m^2 \cdot K)$
h_e	specific melting enthalpy (melting heat)	J/kg
H_s	enthalpy of a dry material	J/m^3
h_v	latent heat of phase change	J/kg
H_w	enthalpy of moisture in the material	J/m^3
K	hydraulic conductivity	$kg/(Pa \cdot m \cdot s)$
m	mass	kg
M_c	condensation deposit	kg/m^2
P_0	standard atmospheric pressure	Pa
P_c	capillary pressure	Pa
P_g	total gas pressure	Pa
p_{sat}	water vapour saturation pressure	Pa
p_v	partial water vapour pressure	Pa
q	density of heat flow	W/m^2
q_a	density of heat convective flow	W/m^2
q_c	density of heat conduct flow	W/m^2
q_r	density of heat flow caused by radiation	W/m^2
r	capillary radius	m
R	thermal resistance; (R-value)	$m^2 K/W$
RH	relative humidity	$\%$

R_v	gas constant for water vapour	J/(kg.K)
s_d	vapour diffusion thickness of a component; (sd-value)	m
S_h	heat source/sink	W/m ³
S_w	moisture source/sink	kg/m ³ .s
t	time	s
T	absolute temperature	K
v	velocity	m/s
w	water content	kg/m ³
w_e	content of frozen water	kg/m ³
w_f	free water saturation	kg/m ³
Z	diffusion resistance for a homogeneous layer	Pa.s.m ² /kg
Z_T	total moisture surface resistance	Pa.s.m ² /kg

Greek letters

α	heat transfer coefficient	W/(m ² K)
β	surface moisture transfer coefficient	kg/(Pa.s.m ²)
δ_l	water vapour permeance of a product	kg/(Pa.s.m ²)
δ_a	water vapour permeability of stagnant air	kg/(Pa.m.s)
δ_p	water vapour permeability (under vapour pressure gradient)	kg/(Pa.m.s)
ε	emissivity of grey surface	-
θ	temperature	°C
θ	contact angle	°
λ	thermal conductivity	W/(m.K)
μ	vapour resistant factor; (μ -value)	-
ρ	density	kg/m ³
ρ_a	density of air	kg/m ³
ρ_s	bulk density of the material	kg/m ³
ρ_v	concentration of water vapour	kg/m ³
ρ_w	density of water	kg/m ³
σ	Stefan Boltzmann constant	W/(m ² K ⁴)
σ	surface tension of water	N/m
τ	tortuosity factor	-
φ	relative humidity	-
ψ_0	open porosity of a material	m ³ /m ³

Chapter 1: General Introduction

1.1 Introduction

A human being has been trying to protect himself from unfavourable climate conditions since time immemorial. First of all, he used natural hiding places then he built simple and provisional shelters. Step by step, he perfected the use and treatment of new materials and objects. He began to build better houses, industrial, sportive, administrative and cultural buildings and he has been developing these buildings till now. A human being has gained knowledge in using materials and technologies in such a way that he knows how to build up a building that will last for hundreds, maybe thousands years. Nowadays, a human being is not limited by materials or technologies; he is under economic pressure that leads him to do his activities more efficiently and to exploit limited nature sources sparingly.

One of the efficient building structures is a compact flat roof that efficiently uses an interior room of buildings and the space above can be used for other activities, for example as green roof, parking lots or picnic area. The roof efficiently shields a human being and his property from unfavourable climate conditions only if it is designed properly. The proper design means mainly to control moisture transport through a roof assembly because moisture plays a significant role in durability of building materials and excessive moisture content can shorten the lifetime of the whole building structure. Thanks to the progress in a roof design and in research, the lifetime of roof structures is extended but several unanswered questions have risen in technical and scientific literature that are related the lifetime of compact flat roofs. These questions are related to proper moisture control of compact membrane roofs.

One of the questions is how much perforation of a vapour retarder that is used in compact membrane roofs affects water vapour transport. Only a few experimental measurements were done in the past and results of these measurements are ambiguous and not clear. There is no mathematical expression that describes properly this phenomenon.

The second question that has appeared in technical literature is the use of vapour retarders in compact membrane roofs. Vapour retarders have been used in building envelopes since 1930s. Their main function is to reduce moisture transport from the interior environment and to avoid excessive interstitial condensation that occurs usually beneath a waterproof membrane. Various guidelines on where to use vapour retarders for compact membrane roofing systems exist around the world. Philosophical guidance ranges from “When in doubt, leave it out” to “When in doubt, think it out”, Tobiasson (1994). Different approaches in using vapour retarders in compact membrane roofs can be also seen among roof specialists in the Czech Republic.

This Thesis is focused on moisture transport in compact membrane roofs. Ventilated roof assemblies or frame roof systems as well as roof details are not object of this Thesis. Two previous questions about moisture control in compact membrane roofs will be discussed in details in the following text and the answers should be found in the conclusion of this Thesis. My personal objective of this Thesis is to make a next step towards more efficient design of compact flat roofs.

1.2 Objective of the Thesis

Proper moisture control in compact roofs is very important because moisture is the main influence on durability of roof assemblies and buildings. The main objective of the Thesis is to secure proper moisture control of compact flat roofs. To achieve this goal, several research objectives will be solved in this Thesis. These objectives are:

- 1) To gain the newest knowledge about compact flat roof assemblies, about moisture transport in building materials and components, and about water vapour permeability measurements.
- 2) To suggest and to develop an experimental apparatus that will facilitate to measure diffusion properties of thin building products with a very high diffusion resistance (e.g. vapour retarders).
- 3) To measure diffusion properties of perforated and non-perforated vapour retarders that are used in compact membrane roofs.
- 4) To attempt to compose a mathematical model that will describe water vapour transport through perforated vapour retarders.
- 5) To specify designer rules when a vapour retarder should be used in a compact membrane roof assembly with the help of numerical simulations.
- 6) To write a list of recommendations how to design a compact membrane roof more efficiently from a view of moisture transport so that these recommendations can be used by building envelope designers.

1.3 Proposal Approaches

The research methods described in this Thesis is a combination of theoretical study, experimental work and plus numerical modelling of transport of phenomena in building materials.

- 1) Theoretical study brings and composes a lot of new knowledge from three different theoretical branches – theory of roof design, building physics (especially moisture and heat transport in building materials and components) and the theory about water vapour permeability measurement of building products. In the theoretical part of the Thesis, I would like to emphasis new connections between the design history of the building envelopes together with the development of physical knowledge of heat and moisture transport and also the unique list of experimental methods that measure water vapour permeability of building materials.
- 2) Lack of proper experimental results, that describe water vapour transport through perforated vapour retarders, leads to the experimental measurement. The objective of the experimental part of the Thesis is to develop experimental apparatus that will facilitate to measure diffusion properties of homogeneous and perforated vapour retarders. As vapour retarders have a very high diffusion resistance the experimental apparatus has to be design with a maximum effort to get accurate experimental results.
- 3) The results of the experimental measurement will show if a perforation of vapour retarder plays a significant role on moisture transport through vapour retarders.

- 4) As a mathematical model has not existed, yet, a mathematical model that describes moisture transport through perforated building materials should be designed on the basis of experimental results.
- 5) Nowadays, compact roof assemblies are designed on the basis of simple calculation methods called the Glaser methods, Glaser (1959). Simultaneously, compact roof assemblies are evaluated according to standard requirements on moisture transport within building envelopes but these requirements do not have any support in technical or scientific literature. Therefore, the objective of this part of the Thesis is to use state-of-art numerical simulation tools for coupled heat and moisture transport in building components and to evaluate compact membrane roof assembly according to different moisture requirements.
- 6) On the basis of the results from numerical simulations and also from experimental measurements, the final part of the Thesis should bring recommendations for efficient roof design and proper moisture control in compact membrane roofs.

1.4 The Thesis

The research work documented in this Thesis has the following structure. This structure was created on the basis of several theses from the entire World.

Chapter 1: General Introduction gives basic information about this Thesis. The chapter describes the scope of the Thesis, the main objectives, the research approach and the outline of this Thesis.

Chapter 2: Literature Review brings the newest information from three different scientific branches – roof design, moisture transport in building materials, and permeability measurement of building materials. The first part of this chapter gives general information about compact membrane roofs, their layers and materials. It compares individual types of compact roof assemblies and their development. The second part describes moisture transport and moisture storage in building materials in detail. Heat transport in building materials is mentioned only briefly. The last part of this chapter focuses on water vapour permeability measurements of building materials. Particular measurement methods are described in detail, their advantages and disadvantages are also mentioned. The results from the previous known studies, where diffusion properties of building products with a high diffusion resistance were measured, are given.

Chapter 3: Experimental Procedure gives information about the experimental measurement. The first part of this chapter focuses on reasons of experimental measurement. Then a development of an experimental apparatus is described in detail. The results of the experimental measurement are presented. In discussion, advantages and disadvantages of the apparatus and the accuracy of the results are discussed. Conclusion outlines the main findings of this part. The second part of the chapter focuses on the analytical description of the results. A new analytical model of moisture transport through perforated thin products with a high diffusion resistance is presented. Comparisons of measurement results with the analytical model are provided.

Chapter 4: Numerical Analysis focuses on numerical simulations of coupled heat and moisture transport in compact membrane roofs. Several roof assemblies were chosen to represent the whole range of compact membrane roof assemblies. The outdoor and indoor climate conditions were selected to represent climate conditions of the Central Europe and

residential houses. The results of the simulations show defects in standard calculation methods and also in standard requirements on moisture transport in building envelopes.

Chapter 5: Efficient Roof Assembly and Recommendations gives information, on the basis of previous chapters, how to more efficiently design the compact membrane roof assembly from a view of moisture transport.

Chapter 6: Conclusions and Recommendations for Further Work summarize the main finding of the Thesis and try to outline the future research.

All citations, paraphrases and literature reference list in the Thesis are written in the APA (American Psychological Association) publication style.

The structure of this Thesis can be also outlined by the following *Figure 1.1*.

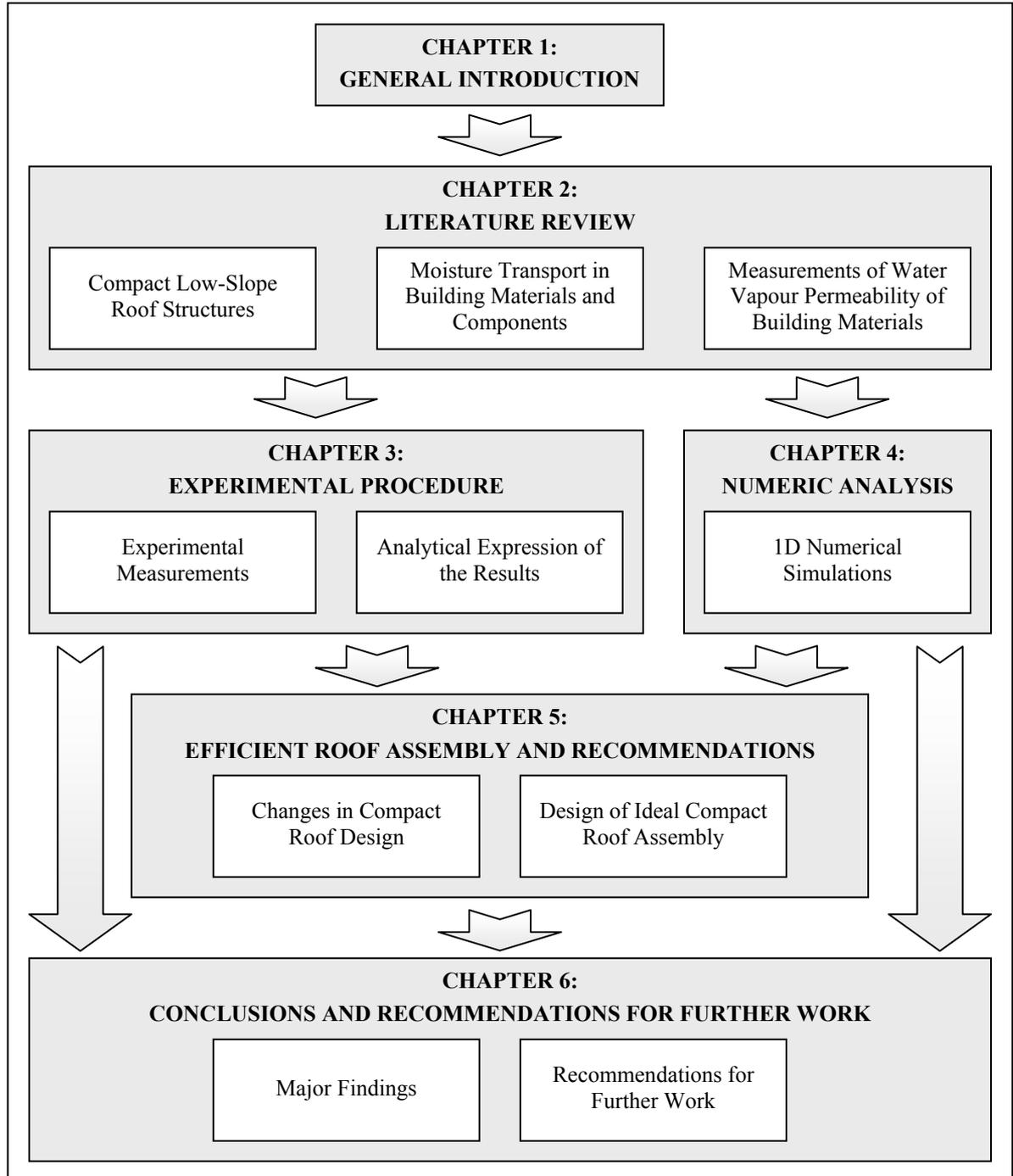


Figure 1.1. Structure of the Thesis

Chapter 2: Literature Review

2.1 Compact Flat Roof Systems

The first part of this subchapter is focused on compact flat roof systems, their classification and material possibilities of each roof layer. The second part of the subchapter presents moisture failure criteria and standard requirements for compact flat roofs. Finally the third part shows briefly the history of moisture control of flat roofs assemblies in the world and in the Czech Republic.

2.1.1 Classification of Flat Roofs

At the beginning, a definition of a flat roof is necessary. In technical literatures, a flat roof is usually defined as a roof with a slope of waterproofing membrane lower than or equal to 5° Oláh (2005a), Novotný & Misar (2003) or in ČSN 731901 (1999), but in STN 73 1901 (2005) and in Oláh (2002), the slope of flat roofs is defined as lower then or equal to 10° . In some literature, for example Griffin & Fricklas (2006), flat roof systems are also called low-slope roof systems.

On the other hand, flat roof systems must be provided with a slope to preclude ponding of water on them, Griffin & Fricklas (2006). A “dead flat” membrane is a design mistake. Fortunately, in most instances, a slope of 1:50 (about 1°) is sufficient.

Flat roof structures then can be classified according to their structures or a position of each roof layers. The main classification of flat roofs is pointed in *Figure 2.1*.

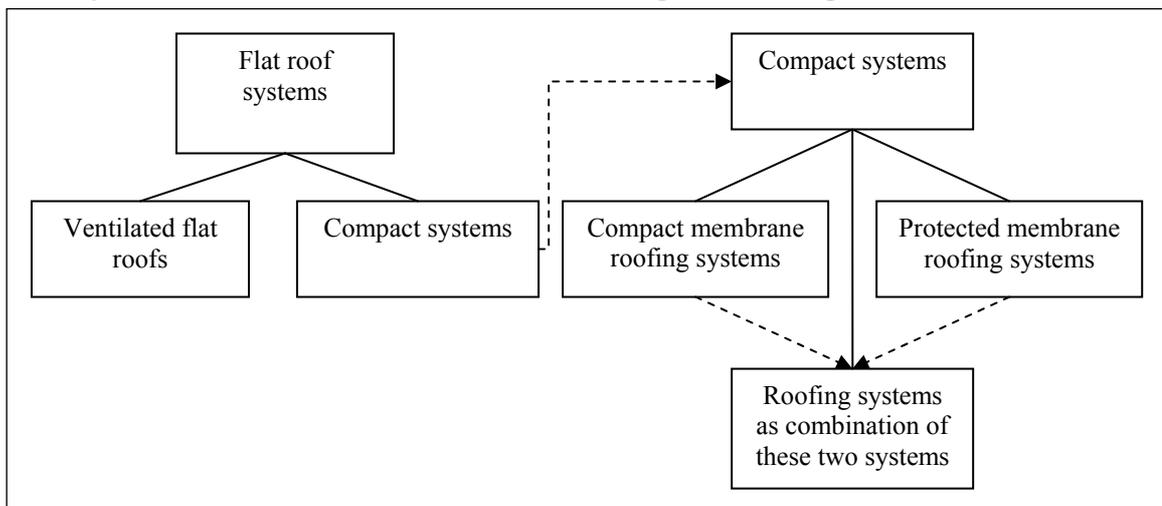


Figure 2.1. Classification of flat roof structures

2.1.1.1 Compact Systems

Nowadays, compact roof systems are the most designed system for flat roofs. The advantages of compact roof systems are lower costs compared to ventilated flat roof systems, variability of the use (green roofs or pavements etc.), short period of necessary for a construction, and simple maintenance, Šilarová (2005a).

Compact roofs can be further classified by several criteria, for example by a placement of waterproof membranes, by thermal isolations, by types of usages or by attachment systems. From view of moisture transport, a waterproof membrane is the most important layer in flat roof assemblies, so that I decided to use classification of compact flat roofs by the placement of waterproof membrane. Then, compact flat roofs can be named: Compact

Membrane Roofs, Compact Protected Membrane Roofs and combination of these two systems, see *Figure 2.1*. Similar classification of compact flat roof systems can be found for example in Tobiasson (1994), Šilarová (2005a) or Griffin & Fricklas (2006).

2.1.1.1 Compact Membrane Roofs

Compact membrane roof systems are commonly used in Europe and North America Griffin & Fricklas (2006), Šilarová (2005a). Typical assembly can be seen on *Figure 2.2*.

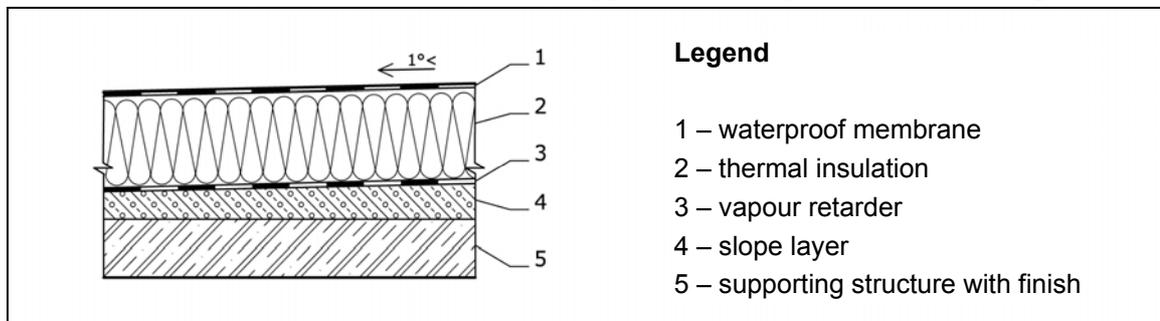


Figure 2.2. A compact membrane roof

Sometimes the compact membrane roofing system is called as “A roof with classical order of layers” or “A conventional roof system” because the system has been designed longer than compact protected membrane systems. The system of compact membrane roofs expanded after a discovery of bitumen membrane in 19th century in Germany, Oláh (2005b) and has been successfully designed till now.

Typical compact membrane roof is pointed on *Figure 2.2* and is usually composed of five basic layers (waterproof membrane, thermal insulation, vapour retarder, slope layer and supporting structure). In the following text, functions, structures and material possibilities for these layers will be discussed in details.

1) Waterproof Membranes

Main Functions

Waterproofing is the main function of a roof. That is the reason, why waterproof membrane is the most important layer in a roof assembly. Waterproof membrane is water resistant coat of the roof and it must be waterproofly sealed to all edges, roof parapets and openings, Šilarová (2005a). The slope of the membrane must be at least 1° or 1:50.

Structure and Materials

Materials for waterproof membranes can be distinguished into four types; a bituminous built-up system and membranes of plastic, rubber, or polymer-modified bitumen. A wide range of components are available from which waterproof membrane roofing systems can be assembled Tobiasson (1994). Different types and materials for a waterproof membrane are plotted on *Figure 2.3* (the most common materials are highlighted).

Similar classification and more details about each material can be found in Vykydal et. al (2005).

Foil membranes are usually used as single-ply systems with thickness of 1-3mm. On the other hand, bituminous membranes are used almost in all cases as double or multi-ply systems with total thickness of the layers 4-6mm. All membranes must be resistant to UV radiation or must be protected by additional layers. Waterproof membranes can be considered to be the airtight element in roof assemblies, Kumaran et al. (2006).

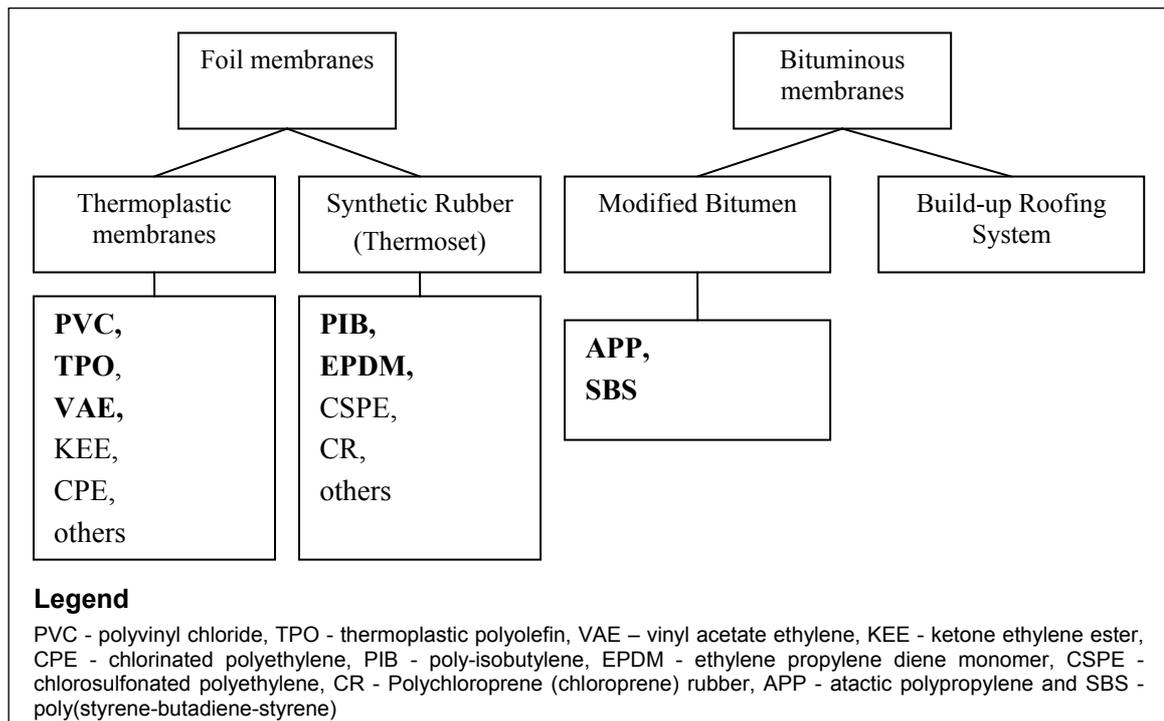


Figure 2.3. Different types and materials for a waterproof membrane (the most common materials are highlighted)

2) Thermal Insulations

Main Functions

A thermal insulation layer reduces undesirable conduction of heat from the interior of the building. Thermal insulation helps us to obtain desirable interior thermal environment and to protect building structures from harsh thermal effects, Šilarová (2005a). Also, thermal insulation prevents condensation on interior building surfaces. Griffin & Fricklas (2006).

Structure and Materials

Following groups of thermal insulation materials are commonly used in compact membrane roof systems Šilarová (2005a):

- mineral insulation boards,
- expanded polystyrene (EPS),
- extruded polystyrene (XPS),
- polyurethane boards (PU), and
- cellular glass insulation.

These materials are usually used in two or three layers to reduce multidimensional heat conduction through the seams. Thickness of the thermal insulation layer depends on thermal requirements for the U-value of flat roof systems.

3) Vapour Retarders

Vapour retarders may or may not be present in compact membrane roofs depending on outdoor and indoor climate conditions. Vapour retarders should be installed only where moisture calculations indicate they are needed. When they are not needed, vapour retarders should not be used since they are expensive and allow “cancers” of wet insulation. Tobiasson (1994).

Main functions

Vapour retarder controls water vapour transport usually from interiors into roof assemblies where interstitial condensation occurs due to low temperature. Condensation deposit can destroy or shorten durability of roof components and structures. To control water vapour transport means to eliminate water vapour diffusion and moisture convection due to air movement, Slanina (2004).

Structure and Materials

Vapour retarders can be made of various materials. A common vapour retarder, often known as a vapour seal, comprises of three bituminous moppings with two plies of saturated felt or two bituminous moppings enclosing an asphalt-coated base sheet. Vapour retarder materials also include various types of plastic sheets, aluminium foil, and laminated kraft paper sheets with bitumen sandwich filler or bitumen-coated kraft paper. Griffin & Fricklas (2006). In recent years, “smart” vapour retarders have appeared. These retarders change their diffusion properties (diffusion resistance) depending on relative humidity (RH) of the surrounding environment, for example Künzel (1999) and Korsgaard & Pedersen (1992).

Vapour retarders are placed on the warm side of compact roof assemblies, below thermal insulation. Vapour retarder must be vapour-tightly sealed to all openings, ending elements and components. Build-in moisture in concrete components should not be trapped between vapour retarder and waterproof membrane. Šilarová (2005a).

4) Slope Layer

Main functions

If a supporting structure is totally flat, a slope layer must be designed in the roof assemblies to create a slope of the waterproof membrane.

Structure and Materials

A slope layer is made from lightweight materials such as aerated concrete or slope peaces of insulation materials.

5) Supporting Structure

Main functions

A supporting structure bears roof assemblies and external loads, for example snow, traffic or vegetations.

Structure and Materials

There are two the most common types of the structure: heavyweight (concrete slab) and lightweight (steel or wooden board).

6) Other Compact Membrane Roof Layers

Expansion Layer

An expansion layer helps to equal different pressures beneath waterproof membranes. It reduces possibilities to create blisters and therefore it reduces possibilities of damage of waterproofing membranes.

The expansion layer can be designed as a component of modified bituminous membrane or as a special textile layer that is placed between plastic (rubber) foil membranes and thermal insulation. If thermal insulation is vapour permeable (i.e. mineral wool boards) the expansion layer is not necessary. Šilarová (2005a).

Separation Layers

Separation layers are designed in flat roof assemblies if there is a need to separate two layers in case of undesirable chemical reactions of the layers or reciprocal movement of nearby layers.

The following products can be used as separation layers: polyester, polypropylene or fibreglass textiles or bitumen membrane with non-absorbed fillers, Šilarová (2005a).

7) Stabilisations of Compact Membrane Roofs

Each compact roof must be stabilised against wind blow-off problems. Three possibilities and their combination exist to stabilize the roof sandwich assemblies.

Mechanically fastened systems

Mechanically fastened systems use anchors to stabilize waterproof membrane. These anchors are usually fixed to a supporting structure. The type of anchors depends on the structure (concrete, steel or wooden) and the amount of anchors depends on the wind load, Krupka (2005). The anchors usually perforate thermal insulations and vapour retarders and cause thermal and diffusion bridges, Slanina & Silarova (2006).

Ballasted systems

Ballasted layers in compact membrane roofs burden roof assemblies against wind blow-off. Following materials of the ballast are usually used: ballast gravel (fraction 8-16mm), concrete or stone pavers, road layers (concrete, tar) or sandwich of soil layers.

Ballasted layers must be separated from roof systems usually by a separation layer (filter fabric material), Šilarová (2005b).

Fully adhered systems

Stabilization of a waterproof membrane against wind blow-off problems can be achieved by adhering the membrane to thermal insulation. Thermal insulation adheres to a vapour retarder and the vapour retarder further adheres to a supporting structure with a limited amount of hot bitumen or with “cold” adhesives and polyurethane adhesives.

2.1.1.1.2 Compact Protected Membrane Roofs

The compact protected membrane roof is the second type of compact roofs. Typical assembly of this roof is plotted on *Figure 2.4*.

The compact protected membrane roof is sometimes called as “Inverted Roof” because the order of layers in the assembly is opposite than the order of layers in the compact membrane roof system, see *Figure 2.2* and *Figure 2.4*. Compact protected membrane roofs have been designed since discovery of extruded polystyrene (50s in USA). In Central Europe, these roof systems have been designed since late 70s, Kutnar (2005).

Waterproof membrane is placed on a supporting structure or on a slope layer and below thermal insulation. This order of layers optimally solves the problem with moisture control of compact membrane roofs. Fundamental principle of moisture control, that diffusion resistance of each layer decreases according to thermal gradient (usually from interior to exterior surface of the assembly), is accomplished, Šilarová (2005a).

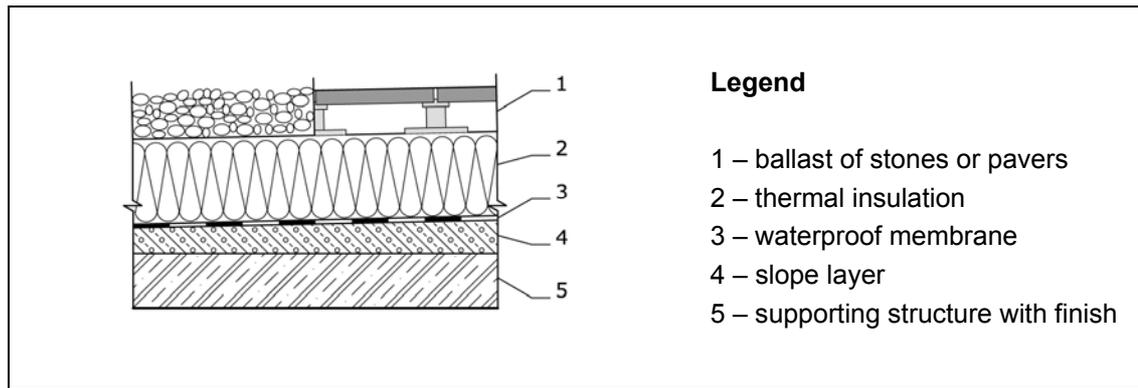


Figure 2.4. Protected membrane roof system

Protected membrane roofs usually cost more than conventional membrane roofs because of the premium paid for extruded polystyrene insulation and the need for ballast, Tobiasson (1994). That is the main reason why protected membrane roofs are not designed as often as compact membrane roofs.

Layers of Protected Membrane Roofs

Functions of roof layers in protected membrane roofs are similar to compact membrane roofs except for the order of layers, there is no vapour barrier. The differences are mentioned below.

Waterproof Membranes

The waterproof membrane is below at least some of the thermal insulation. There, it is not affected by most of the temperature variations, solar effects and mechanical abuse that exposed membranes are subject to. The membrane remains at a relatively constant temperature during day and night, summer and winter. In winter the membrane is warmer than the surface of the roof, thus, melt water is warmed as it moves down to the membrane and then to the drains, Tobiasson (1994).

Materials for the membrane are the same as for membranes in compact membrane roofs.

Thermal Insulation

The insulation above the membrane is usually loose laid and protected from the sun and from being blown off by the wind by a ballast of stones or concrete pavers. The insulation is in a relatively harsh environment. All the surfaces of the board are bathed in water during rain and moisture may remain between the ballast and the insulation, between insulation layers, and between the insulation and the membrane for some time. Because of this, the insulation above a protected membrane must be quite resistant to moisture.

In most cases, extruded polystyrene insulation should be designed above protected membrane roofs, Tobiasson (1994).

Stabilisations of Protected Membrane Roofs

Stabilization of the assembly is secured by a ballast of stones or concrete pavers. Where large arrays of pavers are used for ballast, they should be elevated on pedestals or otherwise made to discontinuously contact the insulation so that air can facilitate upward drying of the insulation. Because crushed rock or stone ballast, if reasonably clean, allows rapid drying, these less expensive ballasts are usually preferred, except for walkways and around the perimeter of the roof where wind uplift forces are the biggest, Tobiasson (1994).

The filter fabric above the insulation holds the system together and reduces the ballast needed over most of the roof. The filter fabric also keeps dirt out of the system, which facilitates drainage, Tobiasson (1994).

2.1.1.1.3 Other Compact Flat roof systems

Two other compact flat roof systems exist in addition to compact membrane roofs and protected membrane roofs. They are combination of these basic systems and they are plotted on *Figure 2.5* to *Figure 2.7*.

The compact membrane roof with thermal insulation below and above vapour retarder is outlined in *Figure 2.5*. This roof is sometimes called “Roof Plus”, Šilarová (2005a). The advantage of this roof is that vapour retarder is not violated by mechanical fasteners. This approach is known as the “nail-one, mop-one” method of constructing a compact roofing system with hot bituminous materials. This is an excellent way to achieve airtightness in a roof, to increase its wind uplift resistance, and reinforce it against stresses and strains, Tobiasson (1994).

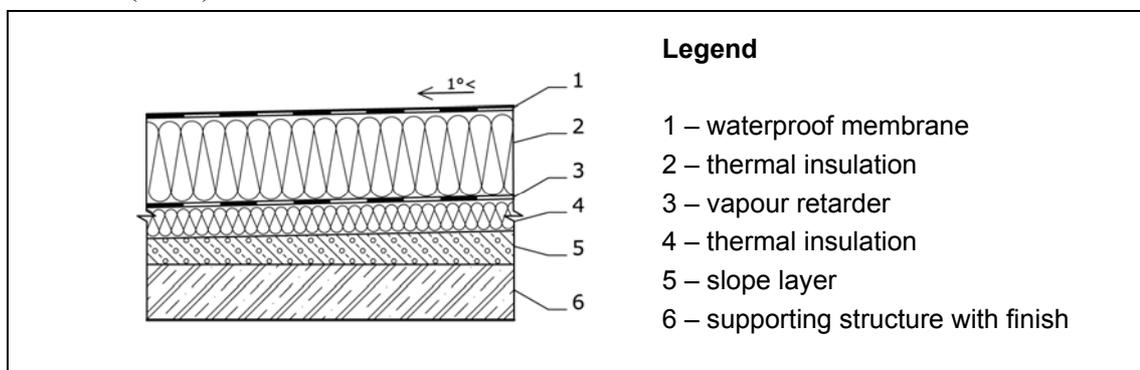


Figure 2.5. Compact membrane roof with thermal insulation below and above the vapour retarder

The protected membrane roof with vapour retarder is plotted on *Figure 2.6*. This system is usually used for renovations of compact membrane roofs where higher thermal resistance is needed. A new insulation layer is added to the original compact membrane roof. This is possible if waterproof membrane of the original roof is in a good condition, Šilarová (2005a).

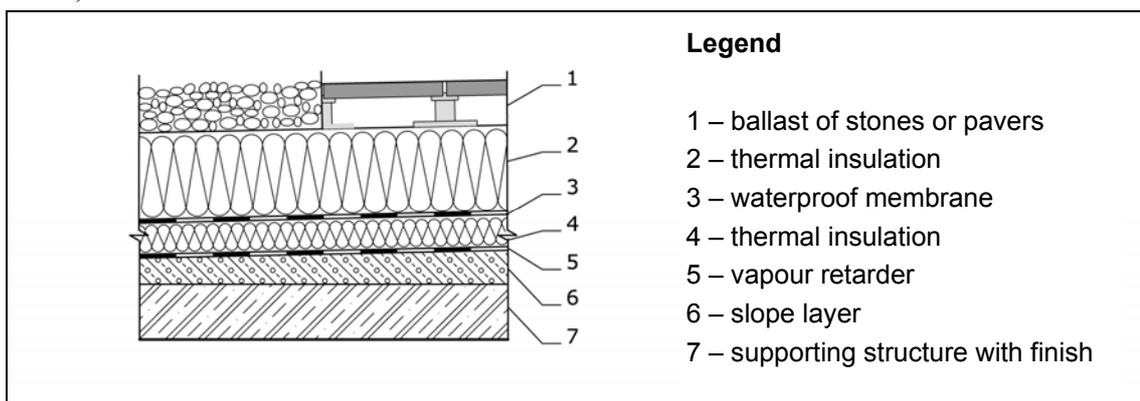


Figure 2.6. Protected membrane roof with the vapour retarder

The last compact roof system is presented on *Figure 2.7*. It is called “Duo Roof”, Künzel & Kiessl (1996) or Šilarová (2005a).

In the assemblies *Figure 2.5* and *Figure 2.7*, thermal insulation is separated in two parts. Several recommendations can be found how to provide this separation. Šilarová (2005a)

recommends using 30% of thermal insulation on the warm side of waterproof membrane (vapour retarder) and 70% above. More sophisticated method was developed by Tobiasson (1989) where thermal insulation on the warm side depends on interior and exterior climate conditions.

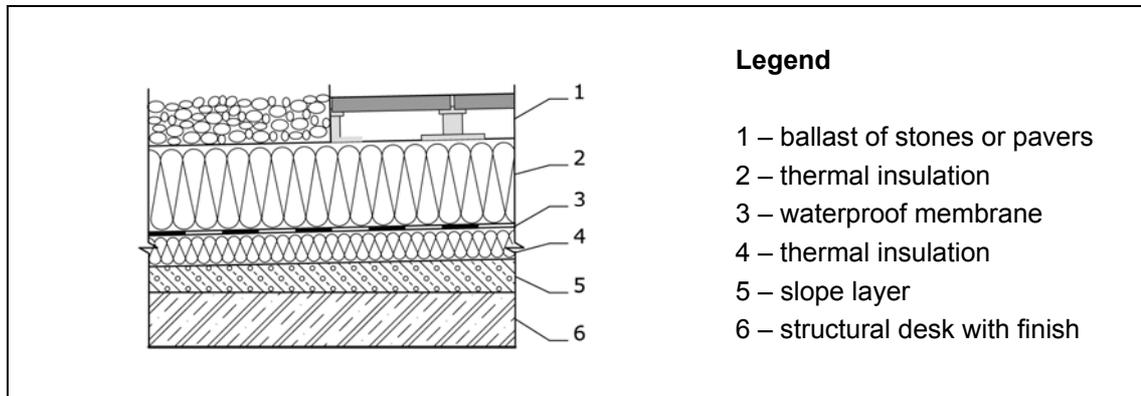


Figure 2.7. Duo roof

2.1.2 Moisture Criteria for Failures of Compact Flat Roofs

First of all the term failure has to be defined. Failure involves direct changes in the properties of materials or structures. The changes or deformations can be of various degrees: excess moisture can cause reversible or irreversible deformations or degradation in performance resulting from physical changes, chemical or biological processes. One type of failure is increased heat loss caused by high moisture contents in materials. Other types are mould growth, rot damages, freeze-thaw cycles resulting in structural failures, dimensional changes etc. Some of these failures affect only the appearance of systems under consideration, but some may have severe consequences such as risk to health of occupants or structural collapse of the whole building, Viitanen & Salonvaara (2001).

Tobiasson (1994) says:

The common manifestations of moisture problems in roofs are annoying, damaging leaks into the rooms below. However, even when leaks do not occur, the roofing system can be suffering severe deterioration from the effect of water in the wrong places.

Excess moisture in a roofing system can weaken and eventually rot wood, corrode metal, cause leaching, efflorescence and spalling of concrete and masonry and, by freeze thaw action, delaminate or disintegrate roofing components.

Each 100 mm of wet insulation can contain up to 96 kg of water per square meter. This unknown, unwanted extra load can be enough to overstress or fail the roof structure in combination with snow or wind loads.

In following text, moisture criteria for flat roofs will be summarized step by step. Each criterion if it will be possible will be compared with several building standards because building standards are often very different in various countries and they rarely present precise requirements with regard to durability and service life of building components, Viitanen & Salonvaara (2001).

2.1.2.1 Water leakage

Membrane roofing systems suffer from moisture problems, but most of these problems are caused by entry of rain and snow melt water at defect in the exterior waterproofing system of the roof, not by improper control of condensation. Flaws at flashings, penetrations, and seams are the primary cause of roof leaks for flat membrane roofs. Attention to these details is a critical design and construction issue. Moisture may also be built into the roof, Tobiasson (1994). Water leakage must not occur at any time in compact flat roofs.

2.1.2.2 Biodeterioration

In building structures and also in compact flat roofs, materials can be damaged by different microorganisms: bacteria, mould, blue stain fungi, decay fungi and insects, see *Table 2.1*. Viitanen & Salonvaara (2001).

Table 2.1. Organisms involving failures and damages of building components, Viitanen & Salonvaara (2001)

Organism Type	Failure type	Condition for grow: Relative Humidity [%] or Moisture Content [% (kg/kg)]	Temperature [°C]
Bacteria	Biocorrosion of many different materials smell and health problems	RH>97%	Around -5 to +60
Mould fungi	Surface growth on different materials, smell and health problems	RH>75%, depends on duration, temperature and mould species	Around 0 to +50
Blue-stain fungi	Blue stain of wood, permeability change of wood	Wood MC > 25-120% RH > 95%	Around -5 to +45
Decay fungi	Different type of decay in wood	RH > 95%, MC > 25-125%, depends on duration, temperature, fungus species and materials	Around 0 to +45
Lichen	Surface growth of different materials on outside or weathered materials	Wet materials needs also nitrogen and low pH	Around 0 to +45
Insect	Different type of organic materials, surface failures or strength loss of materials	RH > 65% depends on duration, temperature, insects species and environment	Around +5 to +50

Mould fungi have the most critical conditions for biodeterioration (except insect, but insect affects only organic materials), therefore in following text, the main focus will be only on mould growth as usual in literature or in building standards.

Mould growth

Mould fungi can grow on many different materials. They need nutrients from the medium, high relative humidity, or water. Ambient relative humidity above 75 to 80% is critical for the development of mould fungi in the surface of building materials, see *Table 2.2*. Viitanen & Salonvaara (2001).

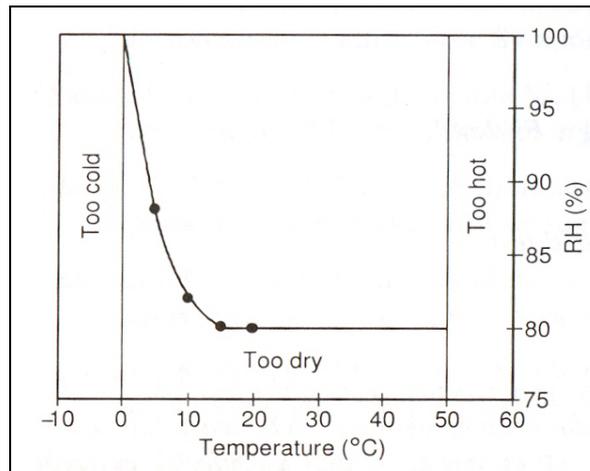


Figure 2.8. Condition favorable for initiation of mould growth on wooden material as a mathematical model Viitanen & Bjurman (1995)

The conditions (relative humidity and temperature) of mould growth, for example for wood materials, were measured by Viitanen & Bjurman (1995) and they are plotted in Figure 2.8.

Table 2.2. Critical relative humidity level for mould growth and decay failure in different materials

Material	Mould Growth	Decay
	Relative Humidity [%]	
Pine sapwood	>80-95	>95
Pine heartwood	>80-95	>95
Particle board	>80-95	>90
Gypsum board	>80-95	>95
Fibre board	>80-95	>95
Wallpapers	>75-95	>90
Mastics	>90-95	-
Different coatings	>75-95	-
Concrete	>95-98	-

Different requirements for mould growth can be found in ASHRAE 160P (2006). All of the following conditions must be met:

- 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C and 40°C, and
- 7-day running average surface RH < 98% when the 7-day running average surface temperature is between 5°C and 40°C, and,
- 24-h running average surface RH < 100% when 24-h running average surface temperature is between 5°C and 40°C.

Materials which are naturally resistant to mould growth (e.g. concrete, masonry, glass and metals) or have been chemically treated to resist mould growth may be able to resist higher surface relative humidities and/or longer terms.

Simple requirements can be found in Czech Standard ČSN 730540-2 (2007):

- Relative humidity on the surface of window glasses RH < 100% (condensation condition) and,
- For other building materials RH on the surface RH < 80% (mould growth condition).

2.1.2.3 Corrosion

Corrosion affects mainly metals, alloys, and metallic coatings (structural framing, reinforcing bars, masonry anchors, ties, flashings, fasteners, etc.) – in a broader sense other materials may also be considered susceptible to corrosion. Corrosion does not require water in liquid form – chemical attack may occur at, for example, relative humidity as low as 80%. The time of wetness of materials depends on other chemicals, too, such as NO_x, Cl₂, H₂S, etc. and it can be determined either by using calculation methods or measured directly Viitanen & Salonvaara (2001).

Requirements for prevention of corrosion must be derived from the properties and use of the particular metals used in constructions. If no such information is available, the 30-day running average of hourly values of surface RH of the metal shall remain less than 80% ASHRAE 160P (2006).

Very short note can be found in ČSN EN ISO 13788 (2002) that critical relative humidity to avoid corrosion must be equal to or lower than 60%

2.1.2.4 Moisture Content in Some Materials

Several materials have limits of moisture content which can be contained without any degradation effect. These materials are for example wood or wood based materials and insulation materials.

Wood, wood products

For wood and wood products, recurring moisture contents over fibre saturation for longer than one week shall be avoided. Fibre saturation of solid wood is usually taken to be around 30% moisture content, over dry weight basis. Fibre saturation of composite wood products, such as oriented strand board, is often lower, in the range of 20 to 25% ASHRAE 160P (2006).

For wood and wood based materials in building structures, moisture contents of these material shall be held below 18% of equilibrium moisture content, otherwise the function of structure can be threaten ČSN 730540-2 (2007).

Thermal insulation materials

Exact conditions for moisture content in thermal insulation materials do not exist. Only indirect condition of thermal resistance of the whole assembly must be fulfilled. Thermal conductivity of insulation materials strongly depends on moisture content, therefore an effort exists to set up limits of moisture content in thermal insulation materials. One approach is to use the equilibrium moisture content at 90% RH Cash (1985). Another approach is to determine the relationship between moisture content and insulation ability and establish the maximum acceptable heat loss in insulation ability. In Tobiasson (1994), second approach is preferred. Any insulation that contains enough moisture to reduce its insulating ability to 80% of its dry value is considered wet and unacceptable. *Table 2.3* presents equilibrium moisture contents for roof insulations at 45 and 90% RH and compares these values to the moisture content at which insulation ability is reduced to 80%.

2.1.2.5 Moisture Accumulation in Compact Flat Roofs

Moisture accumulates in the building envelope when the rate of moisture entering into the assembly exceeds the rate of moisture removal. When moisture accumulation exceeds the ability of the assembly materials to store the moisture without significantly degrading

performance or long-term service life, moisture problems occur. The moisture storage capacity of a material depends on time, temperature, and material properties in Lstiburek (2002). This moisture storage capacity is significant in determining performance of compact flat roofs.

Table 2.3 .Comparison of equilibrium moisture contents and moisture content of roof insulation materials, Tobiasson (1994)

Insulation	Equilibrium Moisture Content [%(kg/kg)]		Moisture Content [%(kg/kg)]
	At 45% RH	At 90% RH	Insulation ability reduced to 80%
Cellular glass	0,1	0,2	23
Expanded Polystyrene (16 kg/m ³)	1,9	2,0	383
Extruded polystyrene	0,5	0,8	185
Fibrous glass	0,6	1,1	42
Perlite	1,7	5,0	17
Urethane	2,0	6,0	262

2.1.2.6 Other Moisture Requirements for Compact Flat Roofs

Other requirements for moisture movement in compact flat roof assemblies can be found in several standards. These requirements do not appear in other technical literatures that focused on moisture control in building envelopes. These requirements are: The amount of condensate deposit inside building envelope and year balance of condensate deposit inside a building envelope.

The Amount of Condensate Deposit inside Building Envelope

For a building structure, in which condensation deposit can threaten its desired function, interstitial condensation must not occur, ČSN 730540-2 (2007).

The threat of the desired function means to shorten the lifetime of a building structure, a decrease of inner surface temperature leading to mould growth, dimension changes and an increase of structure loads out of the structure safety and an increase of moisture contents in materials causing their degradation.

For building structure, in which condensation deposit will not threaten its desired function, year condensation deposit M_c inside the structure must be reduced for compact membrane roofs, according to following condition (lower value):

$$M_c \leq 0,1 \text{ kg/m}^2 \cdot a \quad \text{or} \\ M_c \leq 3\% \text{ of square density of the material} \quad (2.1)$$

Condition (2.1) is calculated with the help of the Glaser method according to international standard ČSN EN ISO 13788 (2002) or Czech standard ČSN 730540-4 (2005), all from ČSN 730540-2 (2007).

Maximum winter interstitial condensation M_c for warm compact membrane roofs should not exceed $0,35 \text{ kg/m}^2$, according to BS 52050 (2002) and BS 6229 (2003).

$$M_c \leq 0,35 \text{ kg/m}^2 \quad (2.2)$$

According to DIN 4108-3 (2001), if winter interstitial condensation occurs in wall or roof assemblies the maximum condensation deposit M_c should not exceed $1,0 \text{ kg/m}^2$. If

interstitial condensation occurs in non capillary-active materials, the maximum condensation deposit M_c should not exceed $0,5 \text{ kg/m}^2$.

$$\begin{aligned} M_c &\leq 1,0/m^2 \text{ (capillary-active materials) or} \\ M_c &\leq 0,5\text{kg}/m^2 \text{ (not capillary-active materials)} \end{aligned} \quad (2.3)$$

Year Balance of Condensate Deposit inside Building Envelope

In building structures, where water vapour condensates (according to condition (2.1)), condensation and evaporation moisture balance at the end of the year must be without any condensation deposit that can increase moisture content in the structure continually. So, year condensation deposit must be lower than evaporation potential of the structure.

This condition is also calculated with the help of the Glaser method according to international standard ČSN EN ISO 13788 (2002) or Czech standard ČSN 730540-4 (2005), all from ČSN 730540-2 (2007).

Similar conditions are in the following technical standards DIN 4108-3 (2001), BS 52050 (2002) and BS 6229 (2003).

2.1.3 History of Moisture Control in Compact Flat Roofs

The previous subchapter shows that excessive moisture contents in compact membrane roofs may cause failures or may reduced the lifetime of roofs. This subchapter shows historical development of moisture control in building envelopes with the focus on compact membrane roofs. The subchapter focuses on the development in the World, manly in North America, and in the Czech Republic.

2.1.3.1 Moisture Control in the World

Early Insulated Assemblies, 1920 to Mid-1930

Thermal insulation was first used to prevent mould growth in industrial buildings (mills and factories with high humidity). In that time, cork was used as insulation material. It is important to note that insulation was not used primarily for comfort or energy efficiency but to prevent cold spots on the interior of humidified buildings. Moisture movement is still seen as air movement but through pores, not joints, in the insulation materials. Solution included bituminous emulsions and mopped roofing felts, Rose (1997).

This recommendation (Paul Close) was put into practice in the mid-1930 at Frank Lloyd Wright's Wingspread in Racine, where cellulosic insulation with a bitumen emulsion spray applied from below onto the mineral wool, than plaster and, of course, a wax finish at the interior were used. The entire roof assembly at Wingspread shows no evidence of any sheathing deterioration or mould growth, Rose (1997).

Development of Vapour Diffusion Theory, Mid-1930s to 1940

Fourier (France, 1820s) showed that heat flow through materials is linear with respect to the temperature difference. Pelet and Fick (1850s) showed that in still air, moisture flow could be viewed as a linear function of vapour pressure, depending on diffusion resistance of building materials. This is the diffusion theory: mass will flow from a region of high concentration to a region of low concentration. The application of the diffusion theory to buildings, and the beginnings of vapour barriers, came from the work of Dr. Frank Rowley at the University of Minnesota, Rose (1997).

The jump that Rowley took was to apply the diffusion theory to building moisture transfer in a way that overshadowed other transport mechanism such as air movement. His tests confirmed his theories. He created two storeys hut in huge refrigeration room. The accumulated moisture in the assembly was very small – 0,19grams per square meter per 24hours without a vapour barrier and 0,01grams with a vapour barrier. While this may seem a remarkable difference, it is worth noting that Rowley's test conditions were 21°C and 40% RH inside and -29°C outside. Rowley also recommended attic ventilation, Rose (1997). Rowley's work was quickly taken up by a number of people who were concerned about the problem of condensation. His findings were confirmed, and vapour barriers in the form of paint films, foils and special papers began to be recommended for insulated construction, Hutcheon (1989).

Early Requirements for Vapour Barrier, 1940-1945.

In 1942 the U.S. Federal Housing Authority updated the *Property Standards and Minimum construction Requirements for Dwellings*. This document, with no citations and no references, is the earliest known source of the two most controversial elements in moisture control: the one perm vapour barrier rule and the 1/300 attic ventilation rule, Rose (1997).

Widespread of Vapour Barrier, 1946-1952

A vapour barrier was recommended by several construction guides: By 1946 ASH&VE had introduced vapour barriers into its *Heating, Ventilation and Air Conditioning Guide*, By 1949 in *Condensation Control in Modern building* (Housing and Home Finance Agency) had introduced a vapour barrier for residential buildings. In 1952, vapour barrier was introduced for all building in *Architectural Graphic Standards* and in other building codes, Rose (1997).

In 1950, insulation and vapour barriers were used extensively on residential construction in Canada. They were also applied to other types of construction. Vapour barriers were used increasingly in conjunction with insulation in flat roof construction which was experiencing many problems. Ten years later, insulation and vapour barriers were being widely used in all types of heated buildings, Hutcheon (1989).

Vapour Barrier as the Main Moisture Control, 1952-1990s

The 1952 proceeding and guides prevailed, and vapour barriers were introduced throughout the U.S., with the questions about their usefulness and applicability put off for another forty years, Rose (1997).

Canadian practice has focused on air movement in building envelopes as the principal moisture-transport mechanism, Rose (1997). Hutcheon (1989) concluded that vapour barriers can be considered as a part of the partial solution, suitable for in certain cases, and not a fundamental requirement. The proper control of the movement of heat, water vapour, air and water through building enclosures is required.

Other Type of Moisture Control, 1990s- present

Canadian research led to different view of moisture control. Since that time, no fundamental design principle for all types of roofs has existed and exterior and interior conditions must be taken into account for each roof design.

Main moisture transport mechanism for flat compact roofs is diffusion, but ventilated roofs have a lot of condensation problems mainly due to air leakage, Tobiasson (1994).

Compact roofing systems with their membrane and upper layer of low permeability insulation fully adhering to hot bitumen are remarkably resistant to air leakage even if no deliberate vapour retarder is present, Tobiasson (1994). Waterproof membranes can be considered to be the airtight element in roof assemblies, Kumaran et al. (2006).

Tobiasson (1989) showed that a vapour retarder in compact membrane roofs is not needed for about half of regions in the U.S. with indoor temperature 20°C and RH > 50%. Similar conclusion for whole building envelope and North America can be found in Lstiburek (2002) or Lstiburek (2004). When vapour retarders are not needed, they should not be used, Tobiasson (1994), Lstiburek (2004). These recommendations are passed to Griffin & Fricklas (2006).

Another problem of compact membrane roofs was indicated – moisture trap. Vapour retarder and waterproof membrane traps moisture inside roof assemblies, Tobiasson (1994). Then it may lead to moisture accumulation in assemblies, Künzel (1998).

Moisture trap can be solved by several principals: using smart vapour retarder Künzel (1999), Korsgaard & Pedersen (1992), using groove ventilated system, Karagiozis et al. (2002) using one-way, two-way, and solar-powered breather or using other systems of compact roofs (e.g. protected membrane roof), Tobiasson (1994).

2.1.3.2 Moisture Control in the Czech Republic

Early Insulated Assemblies, 1900s to 1950s

In the first two decades of the 20th century, compact membrane roofs were designed in Czechoslovakia with silicate insulation layers and without a vapour retarder. These roofs indicated no problems with moisture for several decades. Problems of these roofs appeared after their improper reconstruction in 1950s-1960s, Kutnar (2005).

In 1930s-1950s, compact membrane roofs suffered from bad workmanship and not proper waterproofing membranes. The most frequent failure of these roofs was water leakage to roof assemblies, Kutnar (2005).

Beginning of Using Vapour retarders 1960s to 1970s

In 1960s, waterproof membranes were designed as double ply bitumen membranes with absorbed felts. Aerated silicate bricks were used as insulation materials. In second half of 60s, these aerated silicate bricks were replaced by expanded polystyrene. Roof assemblies at the beginning suffered from zero slope of the roof membrane and then from poor workmanship and water leakage. These failures were wrongly ascribed to diffusion and condensation of water vapour. This opinion led to using a vapour retarder from the beginning of 70s which was great fault, Kutnar (2005).

In 1964, technical requirement appeared that condensation should not occur in compact membrane roofs, ČSN 730540 (1964).

Bad Experience with Compact Flat Roofs 1970s to 1990s

Compact membrane roofs were designed with vapour retarders and with/without groove systems. In the case of water leakage, moisture was trapped between the membrane and the vapour barrier. Higher level of moisture content in roof assemblies did not significantly affected the lifetime of the roofs. The main problems were poor workmanship and improper application of bitumen waterproof membranes, Kutnar (2005).

From 1970s, ventilated roofs were designed due to bad experience with compact membrane roofs and also due to the standard requirements. Ventilated roofs were the most widespread ones in 1980s.

At the same time, protected membrane roofs were also designed, because these roof assemblies solved the standard requirements for condensation, Kutnar (2005).

In technical standard ČSN 730544 (1978), a new requirement for water vapour condensation appeared. Condensation inside compact membrane roofs was allowed if evaporation potential was higher than a condensation deposit and if the condensation deposit did not threaten the roof functions.

Different Approach to Use Vapour Retarder, 1990s-present

In 1990s, designers returned to compact membrane roofs without the groove system. They were led by economical reasons and also by application of new materials for waterproof membranes (mPVC) or for slope layers (sloped pieces made from expanded polystyrene). Compact membrane roofs are the most designed one with vapour barrier, Kutnar (2005).

Šilarová (2005a) demands using vapour retarders inside compact membrane roofs. Novotný & Misar (2003) recommend to use vapour retarders in compact membrane roofs and finally Fajkoš (1997) follows the criteria from ČSN 731901 (1999) and recommends using vapour retarders only where interior relative humidity is higher than 60%.

In technical standard ČSN 730540 (1994), the requirement for a maximum condensation deposit inside compact membrane roofs $M_c \leq 0,1$ [kg/m².a] was published for the first time.

2.2 Moisture Transport in Building Materials and Components

To design compact membrane roofs properly means to understand to moisture transport mechanisms in the roofs. This subchapter will focus on moisture transport and briefly on heat transport in building materials and components.

2.2.1 Moisture Storage in Building Materials

Most building materials are hygroscopic, which means that they adsorb water vapour from moist air until equilibrium conditions are achieved. This behaviour can be described by sorption curves over a humidity range between 0 and 95% RH. For some materials the equilibrium water content is not very sensitive to changes in temperature; the sorption curves are called sorption isotherms, Karagiozis (2001).

If building materials in contact with water absorb moisture by capillary suction, they are called capillary-active, if they do not, they are regarded as hydrophobic. Capillary-active materials absorb liquid water until they reach a certain state of saturation. This stage is called free water saturation or capillary saturation. Higher water contents of up to pore saturation or maximum water saturation can only be reached by applying pressure or by water vapour diffusion caused by temperature gradient. This also applied to hydrophobic building materials. In the case of capillary-active building materials, we often speak of critical moisture content, Künzel (1995).

It is possible to distinguish the following three moisture regions which may occur in building materials due to increasingly intensive moisture conditions. The regions are: sorption moisture region, capillarity water region and supersaturated region. These three regions characterize the moisture storage behaviour of hygroscopic, capillary-active building materials such as building stones, mortar and wood products. Only supersaturated region occurs in non-hygroscopic, non capillary-active materials such as most insulation materials. This means that moisture in liquid state can be found in these materials only under dew point conditions, e.g. at relative humidity of 100%. In polymeric coatings or films only sorption moisture region occurs, as they are initially without pore spaces able to absorb water. The absorbed water molecules must first find room in the polymer structure, which is usually connected with the micellar swelling of such substances, Künzel (1995).

2.2.1.1 Sorption Moisture Region

This region, which ranges from the dry state all the way to an equilibrium moisture of about 95% RH, includes all water contents resulting from water vapour sorption up to a state of equilibrium, Künzel (1995).

Typical characterization of equilibrium moisture content in hydrophobic material is sorption isotherm, see *Figure 2.9*. The lower area up to about 15% RH is mark by monomolecular coating of the solid surface, followed by transition into an area of multimolecular coating which rises in linear fashion, ending at about 50% RH. From this curve it is possible to determine the inner surface using the BET theory, Branauer et al. (1938). The rising area of the curve is attributed to capillary condensation. This involves

the appearance of condensation phenomena in the micropore area with radii between roughly 2×10^{-9} and 10^{-7} m according to Kelvin's law (2.4), Krus (1996).

$$\varphi = e^{\left(-\frac{2\sigma \cos \theta}{r \rho_w R_v T} \right)} \quad (2.4)$$

Where

- φ is relative humidity [-],
- σ is surface tension of water [N/m],
- θ is contact angle [°],
- r is capillary radius [m],
- R_v is gas constant for water vapour [J/(kg.K)],
- T is absolute temperature [K], and
- ρ_w is density of water [kg/m³].

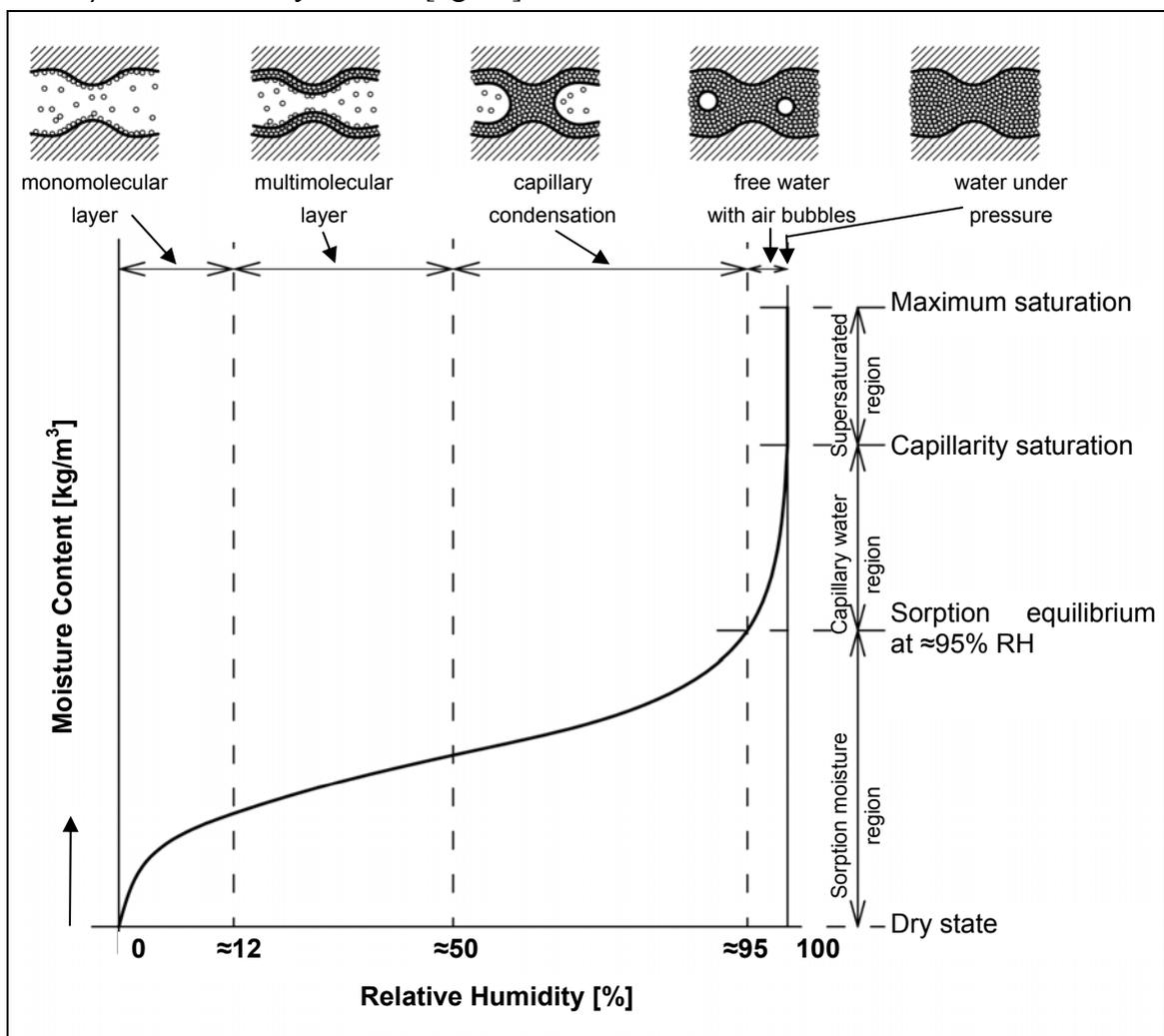


Figure 2.9. Adsorption isotherm in hygroscopic and capillary-active building materials

For hygroscopic porous building materials sorption isotherms have two different curves adsorption and desorption. The difference is called hysteresis effect and it is widely viewed as the result of differing wetting characteristics for adsorption and desorption or other phenomena created by pore space geometry, Krus (1996). One explanation of hysteresis can be found for example in Derome et al. (2008). Adsorption and desorption curves for several building materials can be found in Tveit (1966).

However, measurement by Künzel (1995) showed that for most building materials the hysteresis effect was so slight that the adsorption isotherm was adequate to characterize the sorption moisture region.

2.2.1.2 Capillary Water Region

When a capillary-active building material comes in contact with liquid water, it absorbs water until it reaches free water saturation (capillarity saturation). Capillarity saturation is defined as the material moisture content which can be attained through natural absorption under normal pressure without the influence of exterior forces. For capillary-active materials, capillarity saturation is always below the water content available from open pore space. The presence of entrapped air bubbles causes that not all pore space is filled with water. The absorption capability results from the surface tension of liquids, the wettability of solid bodies in contact with the liquid and the radius of pores. The curved surface of the liquid creates a pressure directed toward the centre of the curve which for a cylindrical capillary can be described by the following formula, Künzel (1995), Krus (1996):

$$P_c = \frac{2\sigma \cos\theta}{r} \quad (2.5)$$

Where

- P_c is capillary pressure [Pa],
- σ is surface tension of water [N/m],
- θ is contact angle [°], and
- r is capillary radius [m].

Pressure plate measurement must be used to determine moisture content in a building material for this region. The curve of water content depending on capillarity suction pressure is called retention curve and it can be transformed to sorption curve with the help of equation (2.4).

2.2.1.3 Supersaturated region

In this region, the relative humidity is always 100% or higher and the region is marked by transient processes, and steady-state moisture equilibrium cannot occur under natural conditions. This region is best defined in hydrophobic insulation materials. As soon as vapour diffusion causes condensation to occur in the temperature gradient, the supersaturated region is reached. Regardless of the water content, the relative humidity is always 100% in this case. But a supersaturated region can even be defined for capillary-active building materials. In this case, at water contents above free water saturation, pores are also filled which would not be filled through suction forces under natural conditions and which do not contribute to the capillary transport. Water contents in the supersaturated region can occur in most building material due to vapour diffusion, Künzel (1995).

2.2.2 Moisture Transport Mechanisms

Moisture transport mechanisms according to different transport forms, phases and driving potentials are presented in *Table 2.4*. The table was composed from several sources Künzel (1995), Krus (1996), Karagiozis (2001) and Peuhkuri (2003). The solid phase of moisture, ice, is not regarded as movable, Pedersen (1990). Convective moisture transfer is not mentioned here, because all the experiments and analysis in this study are performed with no air pressure differences. According to Tobiasson (1994) and other authors, compact

roofing systems with their membranes and upper layer of low-permeability waterproof insulation are resistant to air leakage even if no deliberate vapour retarder is present. Osmosis, elektrokinesis and hydraulic flow are also ignored in this Thesis. According to Krus (1996), gravitation only begins to affect liquid transport at pore radii higher than 10^{-6} m; so it will be neglected in this work.

Table 2.4. Moisture Transport mechanisms, transport mechanisms in italic letters are not discussed

Phase	transport form	Driving force (potential)
Vapour	water vapour diffusion	concentration of water vapour ρ_v , vapour partial pressure p_v
	thermal diffusion (Soret effect)	temperature T
	effusion (Knudsen diffusion)	partial pressure p_v
	<i>air convection</i>	<i>total pressure P</i>
Liquid	capillary suction	suction (capillary) pressure P_c
	surface diffusion	moisture content w, (relative humidity ϕ)
	<i>gravity-assisted flow</i>	<i>gravitation</i>
	<i>hydraulic flow</i>	<i>total pressure</i>
	<i>electrokinesis</i>	<i>electrical field</i>
	<i>osmosis</i>	<i>ion concentration</i>

Moisture transport mechanisms dependant on moisture content in one pore are plotted in Figure 2.10, composed by Künzel (1995), Krus (1996), Peuhkuri (2003) and Derome et al. (2008). It is possible to distinguish: pure water vapour diffusion, simultaneous vapour diffusion and liquid transport, and capillary transport. Each transport mechanism is discussed in the following text.

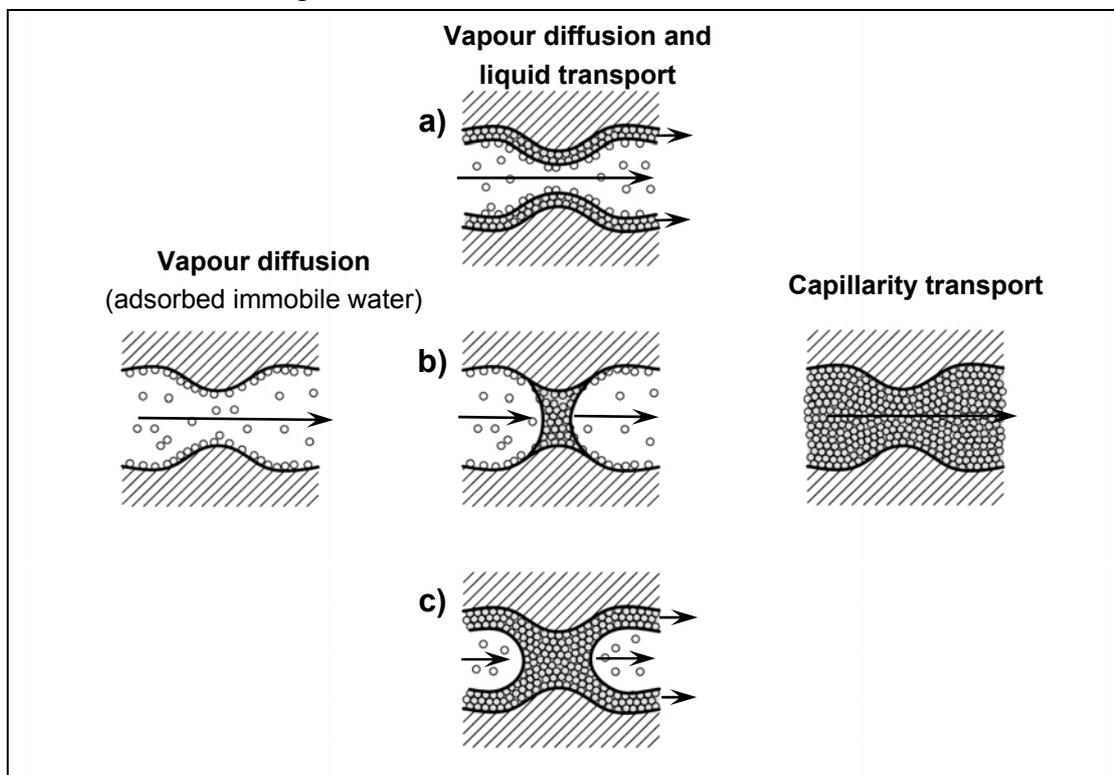


Figure 2.10. Different mechanism of vapour and liquid transport

2.2.2.1 Water Vapour Diffusion

Pure vapour diffusion occurs in the porous materials only in low relative humidity environment. Three transport mechanisms can be separated: effusion, termodiffusion and diffusion.

Effusion (Knudsen diffusion)

Effusion (Knudsen diffusion) is water vapour diffusion that takes place in very narrow capillaries, where the mean free path of the water vapour molecules is higher than the pore dimensions, $\approx 10^{-8}$ m, Krus (1996).

Thermal Diffusion

The termodiffusion base on temperature gradients – also called the Soret effect – is negligible in building components, Künzel (1995). Krus (1996) mentions that only about 0,05% of the total moisture transport can be allocated to thermal diffusion due to small temperature gradients across building materials.

Diffusion

Water vapour diffusion theory comes from Fick (1855). The first Fick's law is written for gas mixture of dry air and water vapour as,

$$g_a = -D_{va} \nabla \rho_v \quad (2.6)$$

where

- g_a is the density of vapour transport in the gas mixture [kg/(m².s)],
- D_{va} is the binary diffusion coefficient air and vapour [m²/s], and
- ρ_v is the concentration of water vapour [kg/m³].

Binary diffusion coefficient D_{va} was measured by Shirmer (1938) and can be expressed as

$$D_{va} = \frac{2,306 \cdot 10^{-5} P_0}{P_g} \left(\frac{T}{273,15} \right)^{1,81} \quad (2.7)$$

where

- T is the absolute temperature [K],
- P_g is the total gas pressure [Pa],
- P_0 is the standard atmospheric pressure, i.e. 101325 Pa.

Binary diffusion coefficient D_{va} can be also expressed according to Kumuran (1998b) as

$$D_{va} = \delta_a \cdot R_v \cdot T \quad (2.8)$$

where

- δ_a is the water vapour permeability of stagnant air [kg/(m.s.Pa)],
- R_v is ideal gas constant for water vapour, i.e. 461,5 J/(K.kg).

The concentration of water vapour can be written applying ideal gas law as

$$\rho_v = \frac{p_v}{R_v \cdot T} \quad (2.9)$$

where

- p_v is the partial water vapour pressure [Pa].

The Fick's law (2.6) with the help of equations (2.8) and (2.9) can be rewritten as

$$g_a = -\delta_a \nabla p_v \quad (2.10)$$

This equation (2.10) is still only written for pure water vapour diffusion in the gas mixture. In building porous material, the length of water molecules will be longer than in a still gas mixture due to solid matrix and only in open pores,

$$g_v = -\frac{1}{\tau} \psi_0 \delta_a \nabla p_v \quad (2.11)$$

where

- g_v is the density of vapour transport in a material [$\text{kg}/(\text{m}^2 \cdot \text{s})$],
- τ is the tortuosity factor [-],
- ψ_0 is the open porosity of a material [m^3/m^3].

Then we can define the vapour resistant factor μ [-], Kumuran (2001) as

$$\mu = \frac{\tau}{\psi_0} \quad (2.12)$$

The vapour resistance factor of a material can be also defined as the ratio between the vapour permeability of stagnant air, and that of material under identical thermodynamic conditions (same temperature and pressure) Kumuran (2001), then

$$\mu = \frac{\delta_a}{\delta_p} \quad (2.13)$$

where

δ_p is the water vapour permeability (under vapour pressure gradient)[$\text{kg}/(\text{Pa} \cdot \text{m} \cdot \text{s})$].

Finally the first Fick's law can be rewritten for water vapour diffusion in a building material as

$$g_v = -\delta_p \nabla p_v \quad (2.14)$$

The water vapour permeability increases with increasing relative humidity. In works of Künzel (1995) and Krus (1996), the water vapour permeability depends on relative humidity but according to Derome et al. (2008), it depends on moisture content. Phillip & de Vries (1957) and other authors contribute increasing vapour transport under isothermal conditions to the increased appearance of water islets with increasing relative humidity. These water islets are said to act as a short circuit for the water vapour diffusion, see *Figure 2.10b*. Künzel (1995), Krus (1996) and other authors attribute higher vapour transport with increasing relative humidity to surface diffusion, see *Figure 2.10a*. Derome et al. (2008) combine these theories and see both together as possible, see *Figure 2.10c*.

2.2.2.2 Liquid Transport

Liquid transport should be defined as surface diffusion, which takes place in sorption moisture region, and as capillary transport that happens in capillary water region. The third region – supersaturated region, moisture transports only occurs through diffusion under temperature gradient or by external pressure.

Surface Diffusion

Krus (1996) uses water content as a driving potential for surface diffusion. In contrast, Künzel (1995) uses relative humidity as the continuous potential. However, surface

diffusion can be taken together with capillary transport, Künzel (1995). Usually in numerical simulation, surface diffusion is taken into account in the vapour resistant factor and as its dependence on relative humidity.

Capillary Transport

Using Darcy's law Darcy (1856), capillary transport in one porous pore can be express as

$$g_l = -K \nabla P_c \quad (2.15)$$

where

- g_l is the density of liquid flow [$\text{kg}/(\text{m}^2 \cdot \text{s})$],
- K is the hydraulic conductivity [$\text{kg}/(\text{Pa} \cdot \text{m} \cdot \text{s})$], and
- P_c is the suction pressure [Pa].

However, the hydraulic conductivity can be hardly determined, Peuhkuri (2003). Therefore the capillary transport is often written as follows, Luikov (1973) or Krischer & Kast (1978).

$$g_l = -D_w \nabla w \quad (2.16)$$

Where

- D_w is the liquid transport coefficient [$\text{m}^2 \cdot \text{s}$], and
- w is water content [kg/m^3].

Expression (2.16) is discontinuous at materials interface, Künzel et al. (2001). Künzel (1995) suggested different equation for capillary transport that is continuous also at the boundaries of layers.

$$g_l = -D_\varphi \nabla \varphi \quad (2.17)$$

Where

- D_φ is the liquid conduction coefficient [$\text{kg}/(\text{m} \cdot \text{s})$], and
- φ is the relative humidity [-].

However, by comparing equations (2.16) and (2.17), the following connection between their transport coefficients can be established, Künzel (1995):

$$D_\varphi = D_w \cdot \frac{dw}{d\varphi} \quad (2.18)$$

It is possible to differentiate for D_φ between the capillary suction process and the redistribution. The redistribution occurs when the supply of water is cut off. The spread of liquid water continues from larger pores into smaller pores through cross-connections due to suction power, see *Figure 2.11*.

The liquid transport coefficients for the suction and redistribution are determined from the following equations, Künzel (1995):

$$D_{ws}(w) = 3,8 \cdot (A/w_f)^2 \cdot 1000^{w/(w_f-1)} \quad (2.19)$$

where

- D_{ws} is the capillary transport coefficient for the suction process [m^2/s],
- A is the water absorption coefficient [$\text{kg}/(\text{m}^2 \cdot \text{s}^{0,5})$],
- w is the water content [kg/m^3], and
- w_f is the free water saturation [kg/m^3].

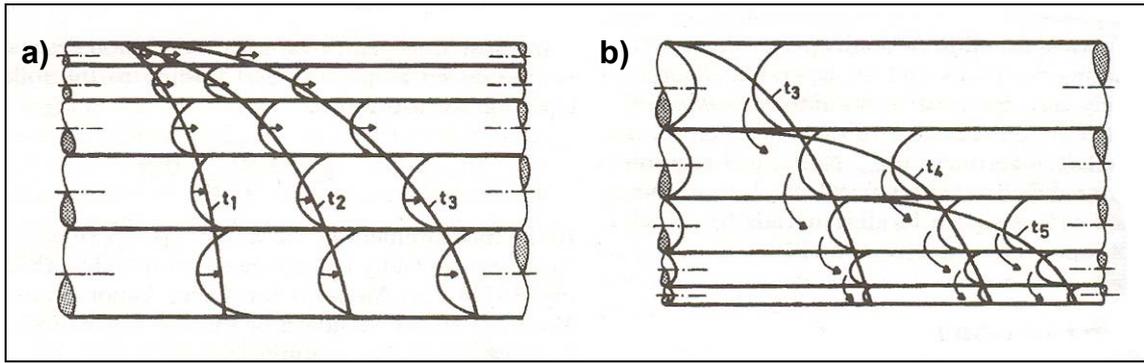


Figure 2.11. Capillary transport phenomena represented by a model of interconnected cylindrical capillaries of various diameters at time t_1, t_2 and t_3 . a) Absorption (suction) before cutting supply; b) Redistribution after cutting supply, Krus (1996)

The liquid transport coefficient of redistribution D_{ww} [m^2/s] is only roughly estimated in Künzel (1995) as follows.

$$D_{ww}(w) = 0,1 \cdot D_{ws} \quad (2.20)$$

2.2.3 Heat Storage and Transport Mechanisms

Heat storage and transport mechanisms are very well described in technical literature compare to moisture transport mechanisms, therefore heat transport mechanisms are mentioned only briefly in the Thesis.

2.2.3.1 Heat Storage in Materials

Heat content of a building material under isobaric condition is called enthalpy and can be expressed for moist material as follows, Künzel (1995)

$$H = H_s + H_w \quad (2.21)$$

where

H is the total enthalpy of moist material [J/m^3],

H_s is the enthalpy of the dry material [J/m^3],

H_w is the enthalpy of moisture in the material [J/m^3].

$$H_s = \rho_s \cdot c_s \cdot \theta \quad (2.22)$$

Where

ρ_s is the bulk density of the material [kg/m^3],

c_s is the specific heat capacity of the dry material [$\text{J}/(\text{kg} \cdot \text{K})$],

θ is the temperature [$^\circ\text{C}$].

$$H_w = \left[(w - w_e) \cdot c_w + w_e \cdot c_e - h_e \frac{dw_e}{d\theta} \right] \quad (2.23)$$

Where

c_w is the specific heat capacity of liquid water [$\text{J}/(\text{kg} \cdot \text{K})$],

c_e is the specific heat capacity of ice [$\text{J}/(\text{kg} \cdot \text{K})$],

h_e is the specific melting enthalpy (melting heat) [J/kg],

w is the total water content [kg/m^3],

w_e is the content of frozen water [kg/m³].

2.2.3.2 Heat transport mechanisms

In building envelopes, heat transport may occur by conduction, convection, and radiation. These heat transport mechanisms are shown in *Table 2.5*.

Table 2.5. Heat transport mechanisms, Karagiozis (2001)

Conduction	Convection	Radiation
$q_c = -\lambda \nabla T$ (2.24)	$q_a = \nabla \rho_a \cdot v \cdot C_a \cdot T$ (2.25)	$q_r = \varepsilon \cdot \sigma \cdot F (T_b^4 - T_\infty^4)$ (2.26)
where	where	where
q_c = density of heat conduct flow [W/m ²]	q_a = density of heat convective flow [W/m ²]	q_r = density of heat flow by radiation [W/m ²]
λ = thermal conductivity [W/(m.K)]	ρ_a = density of air [kg/m ³]	ε = emissivity of grey surface [-]
T = temperature [K]	v = velocity [m/s]	σ = Stefan Boltzmann constant [W/(m ² K ⁴)]
	C_a = volumetric heat capacity [J/(m ³ .K)]	F = view factor [-]
		T_b = surface temperature [K]
		T_∞ = surrounding temperature [K]

In the compact membrane roofs, air movement does not occur, Tobiasson (1994), therefore only heat conduction can be used as transport mechanism within the roof assemblies.

The thermal conductivity λ strongly depends on ice and moisture content in building material especially for thermal insulation materials. Results of several measurements can be found in Mrlík (1985), Mrlík (1986) or Langlais et al. (1994).

2.2.4 Coupled Moisture and Heat Transport

There are several models of coupled moisture and heat transports in porous materials, Phillip & de Vries (1957) and de Vries (1987), Luikov (1973), Krischer & Kast (1978), Pedersen (1990), Künzle (1995) and others. Some of these coupled moisture and heat models have difficulties with discontinuous potentials Luikov (1973), Krischer & Kast (1978), others Phillip & de Vries (1957) and de Vries (1987) use material coefficients that are measured with difficulties. The following description focuses only on Künzle's model Künzle (1995) that was successfully validated with measurements, e.g. Künzle et al. (2001).

In this model, the law of continuity applies to heat as well as to moisture, i.e. the change in enthalpy or moisture in volume elements is determined by the divergence of heat or moisture flows through the surface of the element and heat or moisture sources or sinks in the element. Heat balance equation can be then written as

$$\frac{\partial H}{\partial t} = -\nabla \cdot q + S_h \quad (2.27)$$

where

- H is the total enthalpy [J/m³],
- q is the density of heat flow [W/m²], and
- S_h is the heat source/sink [W/m³].

The enthalpy flows through moisture movement and phase change can be taken into account in the form of source/sink in the heat balance equation applying the following equation

$$S_h = h_v \nabla \cdot g_v \quad (2.28)$$

where

- h_v is the latent heat of phase change [J/kg],
 g_v is the density of water vapour flow [kg/(m².s)].

Moisture balance equation can be expressed as

$$\frac{\partial w}{\partial t} = -\nabla \cdot (g_l + g_v) + S_w \quad (2.29)$$

where

- w is the water content of the material layer [kg/m³],
 g_l is the density of liquid flow [kg/(m².s)],
 g_v is the density of vapour flow in the material [kg/(m².s)],
 S_w is the moisture source/sink [kg/m³.s].

Connecting the equation (2.27) with equations (2.14),(2.24),(2.28), we get the following equation for the heat transport in building materials with one potential only – temperature. And connecting the equation (2.29) with equations (2.14),(2.17),(2.18), we get the equation for the moisture transport in building materials with relative humidity as the only one potential.

$$\frac{dH}{d\theta} \cdot \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda \nabla \theta) + h_v \nabla \cdot (\delta_p \nabla (\varphi p_{sat})) \quad (2.30)$$

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_\varphi \nabla \varphi + \delta_p \nabla (\varphi p_{sat})) \quad (2.31)$$

Where

- $dH/d\theta$ is the heat storage capacity of the moist building material [J/(m³.K)],
 $dw/d\varphi$ is the moisture storage capacity of the building material [kg/m³],
 λ is the thermal conductivity of the moist building material [W/(m.K)],
 D_φ is the liquid conduction coefficient [kg/(m.s)],
 δ_p is the water vapour permeability (under vapour pressure gradient)[kg/(Pa.m.s)],
 h_v is the latent heat of phase change [J/kg],
 p_{sat} is the water vapour saturation pressure [Pa],
 θ is the temperature [°C], and
 φ is the relative humidity [-].

The coupled equation systems are only numerically soluble, and the coupling of heat and moisture transport equations must be done iteratively by solving the individual equations repeatedly and successively. The numerical discretization and the solution technique will not be described in this Thesis, and can be found in Künzle (1995).

2.2.5 Calculation Tools for Moisture and Heat Transports

This subchapter is focused on calculation tools for moisture and heat transport in building materials and components. The first part presents manual calculation tools. In the second part, numerical simulation tools will be briefly discussed.

2.2.5.1 Manual Calculation Tools

The two-best known manual design tools for evaluating the probability of condensation within exterior envelopes (exterior walls, roofs, floors) are the dew point method, ASHRAE (1997) and the Glaser diagram, Glaser (1959). Both methods compare vapour pressures within the envelope, as calculated by simple vapour diffusion equations, with saturation pressures, which are based on temperatures within the envelope. If the calculated vapour pressure is above the saturation pressure at any point within the envelope, condensation is indicated, see *Figure 2.12*.

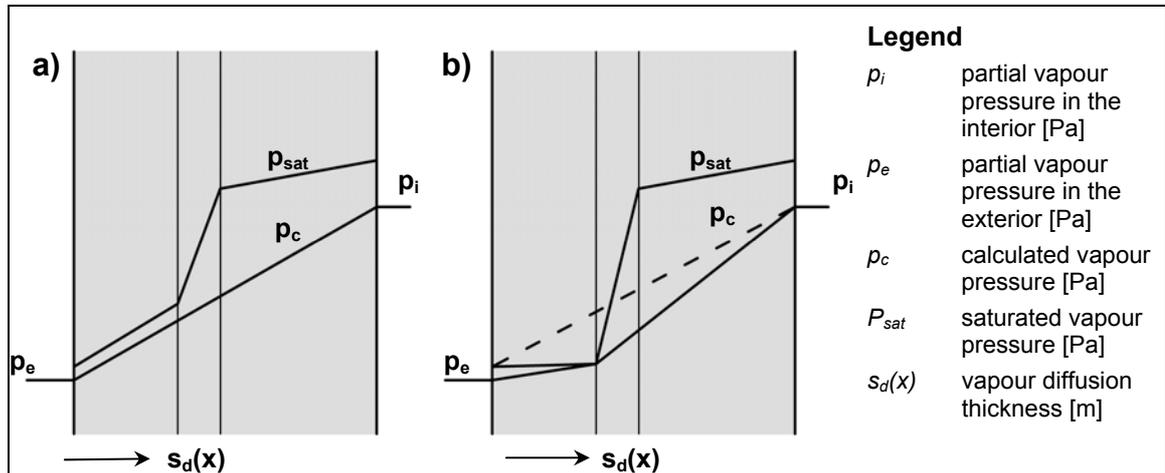


Figure 2.12. Glaser diagram: a) condensation does not occur, b) condensation occurs in the assembly

The dew point method is used in North America as well as the Glaser diagram, commonly used in Europe, are almost identical, TenWolde (2001). The Glaser diagram (Glaser method) is described in several international technical standards, i.e. ČSN EN ISO 13788 (2002) or ČSN 730540-4 (2005).

Both methods have the following limitations, ČSN EN ISO 13788 (2002) and TenWolde (2001):

- 1) Thermal conductivity not dependant on moisture and ice content in the material.
- 2) Water vapour permeability not dependant on relative humidity (moisture content).
- 3) All moisture mechanisms other than vapour diffusion are excluded.
- 4) Moisture storage in the building materials is neglected.
- 5) Movement of air through materials or in cavities is neglected.
- 6) Rain precipitation or snow is not taken into account.
- 7) Methods are steady-stated and do not take into account transient boundary conditions.
- 8) Transport of water vapour through the materials is only one-dimensional.
- 9) Short and long-way radiation is neglected.
- 10) Latent heat from evaporation/condensation is neglected.

These severe limitations will lead to more frequent use of advanced numerical tools that describe better heat, moisture and air transport mechanisms in building envelopes.

2.2.5.2 Numerical Simulation Tools

World wide, there are lot of numerical tools, that simulate coupled heat, moisture or air transport through building materials and components. The numerical tools use most finite element or finite volume methods to solve differential equations of coupled heat, moisture

and air transport in building envelopes. The list of these models can be found i.e. Karagiozis (2001) or Hill (2003).

Canada Mortgage and Housing Corporation (CMHC) did a research, Hill (2003), to assess the impact of the addition insulation and vapour/air retarder on durability of wall assemblies. Forty five numerical tools from the entire world were compared. Two models were recommended as the next step in their research. These models are MATCH and WUFI. The MATCH tool was developed by Dr. Carlsten Rode in Technical University of Denmark and WUFI tool was developed by Dr. Harwig M. Künzel in Fraunhofer Institute of Building Physics in Germany, Künzel (1995).

For future simulation in this Thesis, the Künzel numerical simulation model was chosen to simulate heat and moisture transport in compact membrane roofs. Physical background of this model has been already described in the previous subchapter.

2.3 Measurement of Water Vapour Permeability of Building Materials

Nowadays, several experimental methods how to measure water vapour permeability of building materials or water vapour permeance of products exist in the World. This chapter is focused on these methods and it is divided in subchapters according to a measurement technique or different conditions during a measurement. Standard and also non-standard methods will be discussed. In the second part of the chapter, results from previous measurements of materials with high sd-value are provided. Measurement results of non-homogeneous materials with high sd-value are summarized at the end of this chapter.

2.3.1 Measurement Methods

All measurement methods of water vapour permeability of building materials can be described by the diagram in *Figure 2.13*.

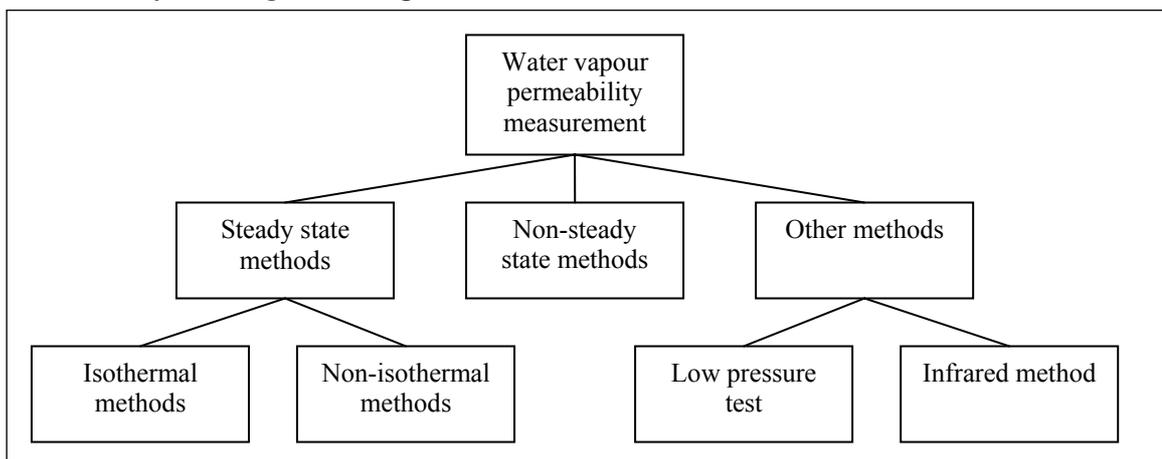


Figure 2.13. Classification of water vapour permeability measurement methods for building materials

This separation of methods occurs due to efforts to measure diffusion properties of material with higher accuracy, in shorter time period and finally to properly describe phenomenon of moisture transport through building materials.

Steady state methods are the oldest and the most widespread methods in the world. The principle of these methods is to create two environments with constant conditions on the both sides of a specimen during the whole time period of the measurement. The results are calculated after water vapour flux reaches constant value. Steady state methods can be further separated in two groups; isothermal and non-isothermal methods.

Steady state isothermal methods run under constant temperature on the both sides of the specimen. That means only a difference in relative humidity on the surfaces of the specimen is a driving force for water vapour transport. The cup methods are the most common steady state isothermal methods.

2.3.1.1 Cup methods

The simplest and the most widely used tests to measure water vapour permeability of building materials are the cup methods, Joy & Wilson (1963) and the principle of the

experimental procedure has been change just a little in past six decades, Kumuran (1998a). First time, the method was standardized in 1954 and now the cup methods are very well described in several international standards e.g. ASTM E 96/E 96M (2005), ČSN EN ISO 12572 (2002), ČSN EN 1931 (2001), ISO 7783-1 (1996), ČSN 727030 (2000) and ČSN 727031 (1975). Some cup methods have not been standardized yet and they are used for an experimental purpose only. Each cup method is named according to different relative humidity that is used on sides of a specimen and a direction of the vapour flux. In ASTM E 96/E 96M (2005), the main methods are recognized as wet-cup (water method), dry-cup (desiccant method) and inverted wet-cup (inverted water method), *Figure 2.14* and recommended test conditions of the standard are summarized in Toas (1989), *Table 2.6*.

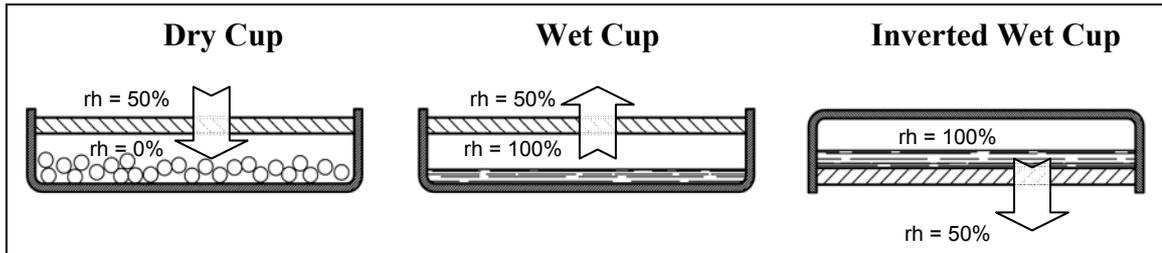


Figure 2.14. Three basic cup methods according to conditions of the methods and directions of water vapour fluxes

Different conditions for the cup method are normalized in European standard ČSN EN ISO 12572 (2002), *Table 2.7*.

Table 2.6. Conditions and names for the cup methods according to standard ASTM E 96/E 96M (2005)

Procedure	Name of method	Temperature [°C]	RH[%], on the two surfaces of specimen	
			In cup	Outside Cup
A	dry cup	23	0	50
B	wet cup	23	100	50
Bw	Inverted wet cup	23	100	50
C	dry cup	32,2	0	50
D	wet cup	32,2	100	50
E	dry cup	37,8	0	90

Table 2.7. Conditions and names for the cup methods according to standard ČSN EN ISO 12572 (2002)

Procedure	Name of method	Temperature [°C]	RH[%], on the two surfaces of specimen	
			dry condition	wet condition
A	dry cup	23	0	50
B	-	23	0	80
C	wet cup	23	50	93
D	-	38	0	93

The cup methods describe water vapour permeability of a material for specific boundary conditions only. For example, wet cup method gives characteristic values of water vapour permeability for materials that are placed in the environment with high relative humidity. The values not give any information about the same material when environmental conditions are below 50% of RH. The relation between the dry cup and the wet cup is plotted in *Figure 2.15* Chang & Hutcheon (1956) and is shown on several building materials in *Table 2.8*, Joy & Wilson (1963).

The results from the wet-cup method also give only an average value (spot value) of the property at mean relative humidity of 75% and the dry cup method at 25%. The Area *A*

from *Figure 2.15* equals to area *B* and area *C* equals to area *D*. Kumuran (1998b) says that this information is inadequate for detailed hygrothermal analysis of building components. The complete dependence of water vapour permeability on relative humidity is required by most of current computer models used for hygrothermal analysis. A technique how to evaluate water vapour permeability of a material on full range of the RH is described in Kumuran (1998b). Similar procedure was suggested by Bazant & Najjar (1972).

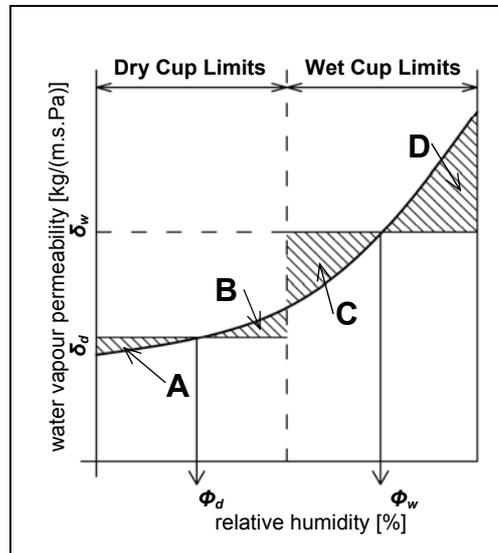


Figure 2.15. Dependence of water vapour permeability of a porous material on relative humidity and the relation between dry cup and wet cup, Chang & Hutcheon (1956)

Table 2.8. Results of measurements according to different type of cup methods

Product	Permeance ng/(Pa.s.m ²)		
	dry cup 50-0%	wet cup 100-50%	inverted wet cup 50-100%
Asphalt-saturated Sheathing paper 0,75 kg/m ²	270	480	725
Asphalt-saturated Sheathing paper 0,75 kg/m ²	190	370	-
Asphalt-saturated Sheathing paper heavy weight	47	360	500
Asphalt-saturated roofing felt 0,75 kg/m ³	110	680	910
Tar-infused sheathing paper	375	1770	4050
Asphalt- infused sheathing paper	365	1080	2400
Asphalt-coated building paper	47	63	115
Perforated asphalt/coated sheathing paper	630	800	860

2.3.1.1.1 Wet Cup

The wet cup method will be described in details because this method is used in the experimental part of the Thesis and other cup methods have a similar measurement principle. The wet cup method shall be used when a measured materials placed in the environment where the RH is for most of the time above 50%, according to *Figure 2.15*.

Principle of the Method

The principle of the wet-cup method is to create two environments with different relative humidity. The RH outside of a cup is usually 50% and the RH inside the cup is 93% (100%). Relative humidity very close to 100% is not recommended if temperature can vary because small change in temperature may cause condensation on the side of the specimen

that could cause moisture uptake and lead to errors. Others the RH on both sides of the specimen are also possible. Temperature is the same for both environments. Then vapour flux goes from the cup with higher RH through a specimen to the environment with lower RH according to equation (2.32).

$$g_v = -\frac{\delta_a}{\mu(w)} \nabla p_v \quad (2.32)$$

Where

g_v is the density of water vapour diffusion flux in a material [$\text{kg}/(\text{m}^2\text{s})$],
 ∇p_v is the gradient of water vapour partial pressure [Pa/m],
 δ_a is the water vapour permeability of stagnant air [$\text{kg}/(\text{m}\cdot\text{s}\cdot\text{Pa})$], and
 μ is the vapour resistance factor (μ -factor) of measured material [-], which depends on moisture content.

Apparatus

The apparatus of the wet cup (dry cup) method varies a little depending on measured materials or on laboratories.

Cups

The test cup shall be made of a non-corroding material, impermeable to water or water vapour. It may be of any shape, *Figure 2.16* and others examples can be found in Time & Uvsløkk (2003). Light weight cups are desirable. A large, shallow cup is preferred, but its size and weight is limited when the analytical balance is chosen to detect small weight change. The mouth of the cup shall be as large as practical and at least $0,003\text{m}^2$ ASTM E 96/E 96M (2005). If the mouth area of the cup is smaller than $0,02\text{m}^2$ five specimens are desired, if the area is larger, only three specimens are necessary ČSN EN ISO 12572 (2002). For example in thirteen European laboratories, Galbraith et al. (1992), the area of specimens varies between $0,003\text{m}^2$ to $0,07\text{m}^2$. When the specimen area is larger than the mouth area, the overlay upon the edge is a source of an error. This error is discussed later (Mask edge correction) or in Joy & Wilson (1963).

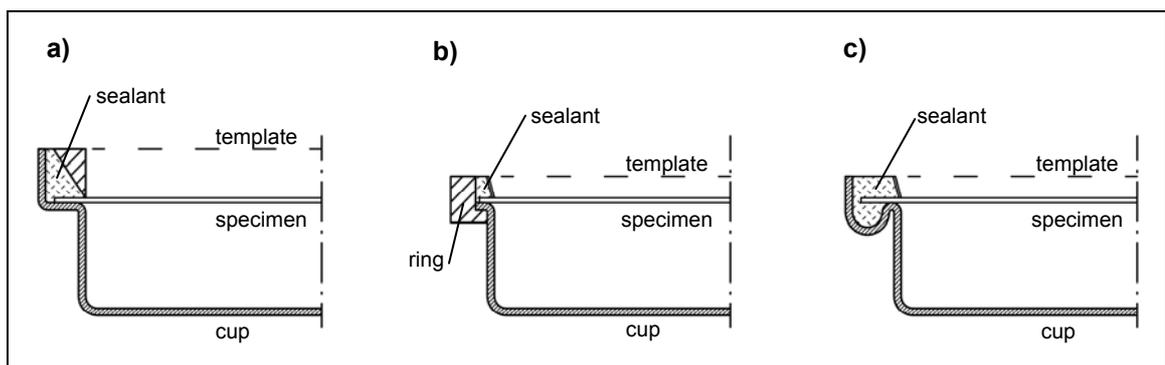


Figure 2.16. Three different types of cup shape and possibilities of sealing system, ASTM E 96/E 96M (2005)

Scales

The scales shall be sensitive as much as possible. The used scales and weights shall be accurate to 1% of the weight change during the steady state period ASTM E 96/E 96M (2005). For example, a specimen with permeance of $57 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$ with area 254mm^2 passes $0,56\text{g}$. In 18 days of steady state, the transfer is 10g . For this usage, the scales must have a sensitivity of 1% of 10g that is $0,1\text{g}$ and the weight must be accurate to $0,1\text{g}$. If,

however, the scale has a sensitivity of 0,2g or the weights are no better than 0,2g, the requirements can be met by prolonging the steady state for the next 18 days. The same procedure is in ČSN EN ISO 12572 (2002).

Conditions inside and outside the cup

Relative humidity outside the cup shall be $50\% \pm 3\%$ and RH can be controlled by temperature-humidity chamber Lackey et al. (1997) or by saturated solutions. Relative humidity inside of the cup shall be $93\% \pm 3\%$ (saturated salt solutions) or 100% (distilled water). The list of saturated salt solutions according to authors is presented in *Table 2.9*. Temperature shall be constant and varies $\pm 1^\circ\text{C}$.

Table 2.9. Relative humidity for specific temperature and saturated solid solutions according to different authors, see also Burch et al. (1992)

Saturated Solution	Temperature [°C]	Relative Humidity [%]	Source
$\text{K}_2\text{CO}_3 \cdot 2\text{H}_2\text{O}$	25	43	Mrlík (1985), Zarr et al. (1995)
$\text{LiNO}_3 \cdot 3\text{H}_2\text{O}$	-	47	Mrlík (1985)
$\text{Mg}(\text{NO}_3)_2$	23	53	ČSN EN ISO 12572 (2002)
$\text{Na}_2\text{Cr}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$	25	54	Mrlík (1985)
$\text{NaBr} \cdot 2\text{H}_2\text{O}$	23	58	Mrlík (1985), Zarr et al. (1995)
NH_4NO_3	25	62	Mrlík (1985)
NaNO_2	25	65	Mrlík (1985)
KI	23	69	Zarr et al. (1995)
NaCl	23	75	Zarr et al. (1995)
$(\text{NH}_4)\text{Cl}$	25	79	Burch & Desjarlais (1995).
$(\text{NH}_4)_2\text{SO}_4$	25	80	Mrlík (1985)
KCl	23	85	ČSN EN ISO 12572 (2002),
$\text{Sr}(\text{NO}_3)_2$	23	86	Zarr et al. (1995)
$\text{NH}_4\text{H}_2\text{PO}_4$	23	93	Galbraith et al. (1998)
KNO_3	23	94	ČSN EN ISO 12572 (2002)
$\text{Na}_2\text{SO}_3 \cdot 7\text{H}_2\text{O}$	-	95	Mrlík (1985)
K_2SO_4	25	97	Mrlík (1985), Zarr et al. (1995)

The distance between the specimen surface and the level of saturated solution or distilled water shall be $19\text{mm} \pm 6\text{mm}$ according to standard ASTM E 96/E 96M (2005) and the distance of $15\text{mm} \pm 6\text{mm}$ is required by ČSN EN ISO 12572 (2002). The air space has a small vapour resistance, but it is necessary in order to reduce the risk of water touching the specimen when the cup is handled. The correction due to air space is discussed later or in Hansen & Lund (1990).

Air shall be continuously circulated throughout the chamber or glass container with a velocity sufficient to maintain uniform conditions at all test locations. The air velocity out of the specimen shall be between $0,02$ and $0,3\text{m} \cdot \text{s}^{-1}$.

Relative humidity, temperature and atmospheric pressure shall be monitored each time when the sample is weighed, at least.

Sealant

The sealing material is the most important technical issue to obtain accurate measurement results if you want to measure products with very high sd-value. Kumuran (1998a) said

“The method of sealing the specimen to the mouth of the cup has a major influence on the result from the measurements”.

The sealant used for attaching the specimen to the cup, in order to be suitable for this purpose, must have following properties according to ASTM E 96/E 96M (2005): must be highly resistant to the passage of water vapour and water, must not lose weight to, or gain weight from, the atmosphere in the amount, over the required period of time, that would affect the test result, must not affect the vapour pressure inside the cup. Also, the sealant must not cause any chemical reaction with the cup or samples and must be easy to fit according to ČSN EN ISO 12572 (2002). The list of sealant suggestions is plotted in *Table 2.10*.

Table 2.10. Sealant suggestions from different sources

Material	Note	Source
Asphalt	softening point (82-93°C)	ASTM E 96/E 96M (2005)
Bee's wax and rosin	rate 50/50	ASTM E 96/E 96M (2005)
Microcrystalline wax and redefined crystalline paraffin wax	rate 60/40	ASTM E 96/E 96M (2005) ČSN EN ISO 12572 (2002) ISO 7783-1 (1996)
Microcrystalline wax and plasticizer (polyisobutene)	rate 90/10	ČSN EN ISO 12572 (2002)
Paraffin wax and plasticizer (polyisobutene)	rate 80/20	ISO 7783-1 (1996)
Mixture of waxes with an oil content	oil content 1,5%-3%	ISO 7783-1 (1996)
Bee's wax and paraffin	rate 50/50	Hansen & Bertelsen (1989)
Wax	not specified	Hansen & Bertelsen (1989)
Silicone	not specified	Hansen & Bertelsen (1989)
Vaseline	not specified	Hansen & Bertelsen (1989)
Rubber	not specified	Hansen & Bertelsen (1989)
Vacuum grease containing silicone	not specified	Hansen & Bertelsen (1989)

Procedure of the method

A sample is sealed to the open mouth of the test cup containing a saturated solution, and the assembly is placed in the controlled atmosphere. Periodic weighing determines the rate of density of water vapour diffusion flux (or water vapour transmission) through the area of the sample.

$$g_v = \frac{\Delta m}{\Delta t A} \quad (2.33)$$

where

- g_v is density of vapour flow in a material (water vapour transmission rate) [kg/(m²s)],
- Δm is mass change between two weighing [kg],
- Δt is time difference between two weighing [s],
- A is effective area of the specimen [m²],
- $\Delta m/\Delta t$ is slope of the straight line [kg/s].

Typical curve of the weight change per time period is plotted in *Figure 2.17*. A steady state is reached when the straight line adequately fits the plot of at least four properly spaced points ČSN EN 1931 (2001) and ČSN 727031 (1975), five points ČSN EN ISO 12572 (2002) or six properly spaced points ASTM E 96/E 96M (2005). The square regression coefficient between the straight line and measured data shall not be less than 0,998 according to Kumuran (1998b) or the mass change in the steady state shall not be higher than 5% from an average value or 10% for materials with $\mu > 750\ 000[-]$ ČSN EN ISO 12572 (2002).

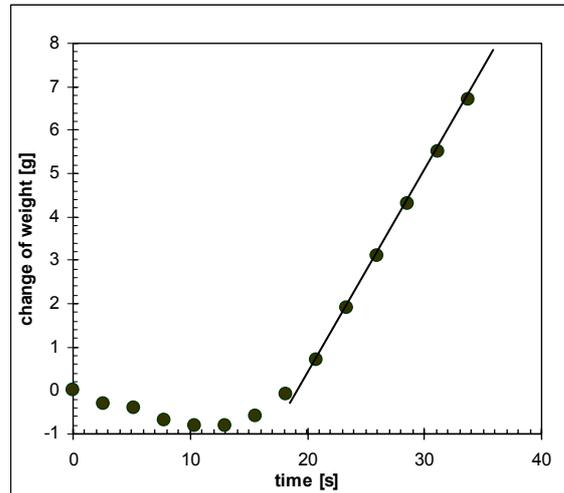


Figure 2.17. Typical dependence of mass change per time for wet cup method

The μ -factor of the material sample is determined if the equations (2.32) a (2.33) are equal, then

$$\mu = \frac{\Delta t A \Delta p_v \delta_a}{\Delta m d} \quad (2.34)$$

where

d is the thickness of the specimen [m] and

δ_a is the water vapour permeability of stagnant air [kg/(m.s.Pa)], calculated usually from Schirmer's equation, Schirmer (1938).

$$\delta_a = \frac{2,306 \cdot 10^{-5} P_0}{R_v T P_g} \left(\frac{T}{273,15} \right)^{1,81} \quad (2.35)$$

Where

T is absolute temperature [K],

P_g is the total gas pressure [Pa],

P_0 is standard atmospheric pressure (101325 Pa),

R_v is ideal gas constant for water (461,5 J/(kg . K)).

The difference in water vapour partial pressure Δp_v on each side of the sample is calculated according to ČSN EN ISO 12572 (2002) from following equation,

$$\Delta p_v = \frac{\Delta RH}{100} \cdot 610,5 \cdot e^{\frac{17,269 \cdot \theta}{237,3 + \theta}} \quad (2.36)$$

where

ΔRH is different relative humidity on each side of the sample [%] and

θ is constant temperature during the measurement [$^{\circ}\text{C}$].

Equation (2.36) is allowed to use only for temperature equal or higher than zero degree Celsius ($\theta \geq 0$ $^{\circ}\text{C}$).

The sd-value of the sample is then calculated using equation (2.37):

$$s_d = d \cdot \mu \quad (2.37)$$

where

s_d is water vapour diffusion-equivalent air layer thickness (sd-value) of the sample[m].

The sd-value as diffusion quantity of a thin product is mainly used in Europe. In North America, the water vapour permeance, δ_l [$\text{kg}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$] more often written as [$\text{ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$] is usually used for membranes and composite materials. The water vapour permeance is defined as follows,

$$\delta_l = \frac{\delta_p}{d} \quad (2.38)$$

Where

δ_l is the water vapour permeance of the sample [$\text{kg}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2)$], and

δ_p is the water vapour permeability of a material [$\text{kg}/(\text{m}\cdot\text{s}\cdot\text{Pa})$].

Sometimes, the water vapour permeance is expressed in perms (inch-pound units). One perm is defined as [$\text{grain}/(\text{h}\cdot\text{ft}^2\cdot\text{in}\cdot\text{Hg})$] and the conversion between IP units and SI units can be written as

$$1 \text{ perm} = 57,2 \text{ ng}/(\text{Pa}\cdot\text{s}\cdot\text{m}^2) \quad (2.39)$$

The conversion equation (2.39) applies only for temperature equalled to 0°C according to ASTM E 96/E 96M (2005).

2.3.1.1.2 Dry cup

The dry cup method (desiccant method) gives better results about materials that are placed in an environment with lower relative humidity, see *Figure 2.15*.

The procedure and the apparatus of the dry cup method are similar to the wet cup method. Only the environment inside the cup is different. A desiccant is used. The desiccant is usually created by calcium chloride or silica gel, both of them shall be activated at 200°C , other possibility is to use anhydrous magnesium perchlorate. Shaking to mix the desiccant is required at each time of weighing. The average moisture content at the end of a test is limited to 10% for calcium chloride and 4% for silica gel. These practices will limit the effective relative humidity inside the cup to about 3%, Joy & Wilson (1963). The other procedure is the same as in the wet cup method.

2.3.1.1.3 Inverted wet cup

The inverted wet cup method is reversed wet cup method. So, the procedure and apparatus are almost the same as for the wet cup method. The only one difference between these methods is that in the inverted wet cup method water placed in the cup is in contact with the sample. This difference usually leads to higher water vapour transport, see *Table 2.8* because moisture capillary transport occurs in the same time as water vapour diffusion. Hydraulic flow due to the small head of water was found as insignificant, Joy & Wilson (1963). Only distilled water shall be used inside the cup.

2.3.1.1.4 Modified cup

The modified cup method has not been standardized yet. Information about this method can be found in Schwartz et al. (1989), Bomberg et al. (2002) or in Mukhopadhyaya et al. (2005), for example. The method connects dry cup and wet cup methods together. The schema and the picture of the method are plotted in *Figure 2.18*.

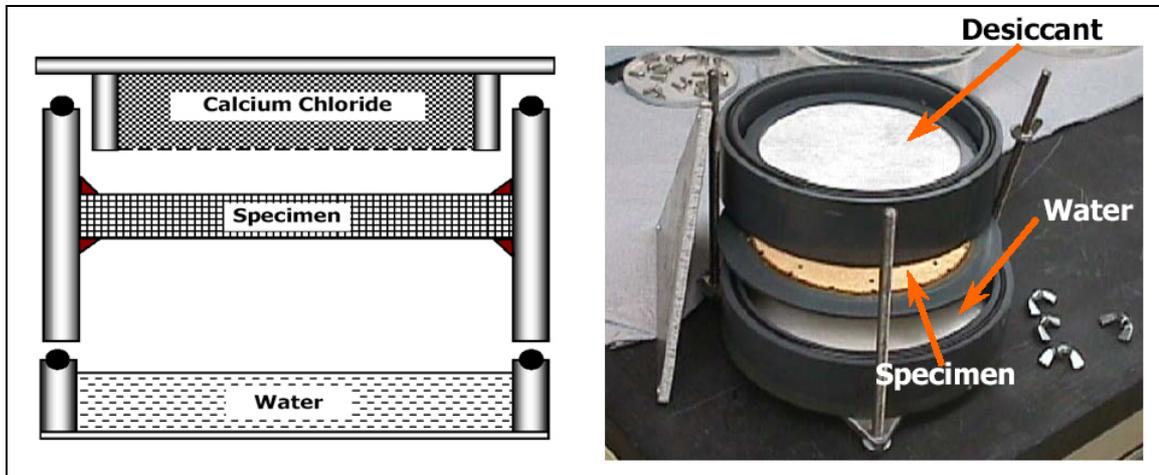


Figure 2.18. Modified cup method apparatus, cross section (left), photo (right), Mukhopadhyaya et al. (2005)

The circular specimen is sealed with silicon rubber inside a circular cylinder. This container is placed between a cylindrical wet cup with water at the bottom and a similar dry cup with calcium chloride as desiccant at the top. The desiccant in the dry cup at top is separated from the specimen by a highly permeable thin sheet of spunbonded polyolefin. The average spot of relative humidity inside the test assembly is considered to be 50%. However, the real value of the relative humidity at any stage of the test could be slightly different depending on the test material and moisture content of the desiccant. The whole test setup is held in place by two aluminium plates bolted together. The joints between the cylinder holding the specimen and the dry and wet cups are made air/vapour tight by placing a rubber ring at each joint. The whole setup is then placed in a controlled temperature chamber. The assembly is taken out of the chamber and separated at regular time intervals to measure the weights of the specimen, water and desiccant container, Mukhopadhyaya et al. (2005). Typical dependence of mass change per time for the method is presented in *Figure 2.19*.

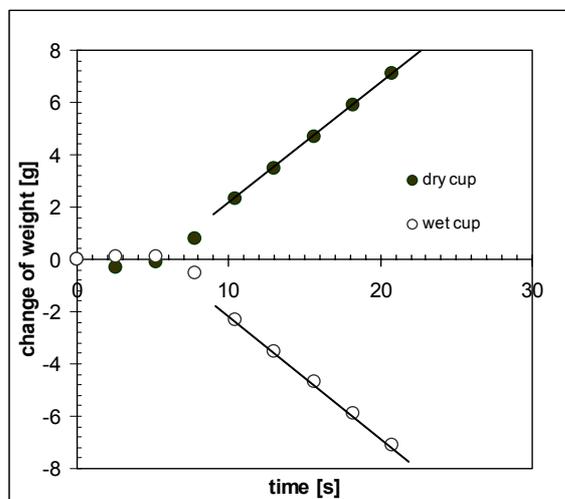


Figure 2.19. Typical dependence of mass change per time for modified cup method

The modified cup method has three following advantages:

- 1) only the temperature of the chamber is controlled, whereas both the temperature and relative humidity are controlled in the dry/wet cup method,
- 2) it provides information on moisture accumulated in the specimen during the vapour transport, whereas the dry/wet cup method gives information on the net vapour transport only, Schwartz et al. (1989) and
- 3) better assessment of steady state conditions, as well as control of moisture loss through the specimen seal can be made because the use of three experimental measures – specimen water and desiccant container, Bomberg et al. (2002).

Disadvantages of the method compare to the standard cup methods are:

- 1) The spot value of relative humidity is different from standard dry/wet cup method, but according to Mukhopadhyaya et al. (2005), properties obtained from the modified cup method with an average 50% relative humidity are as reliable as those obtained from conventional cup methods. Further experimental data are required.
- 2) Great care shall be taken during the weighing procedure when the modified cup is separated into three parts to avoid any gain/lost of weight.

The modified cup method is sometimes named as “double cup method” and also its inverted equivalent “inverted modified cup method” exists with water container at the top and desiccant at the bottom.

2.3.1.1.5 Uncertainties of the cup methods

The measurements on one particular test sample in particular test method (for example wet cup) may yield the sd-value for that sample well within a percent. But when all the measurements on all test samples used are combined to determine the sd-value of the product, the uncertainty may be as large as 30%. One source of the uncertainty is the basic nonhomogeneity of all building products. This uncertainty causes that hygrothermal properties are far greater than the uncertainties in the measurements. If the product is reasonably homogeneous, for example building membrane, the uncertainty may be less than 10%. If results from more than one tested laboratory are used to designate the property for a given product line, the uncertainty may still increase, Kumuran (2006).

The uncertainty from nonhomogeneity of building materials can be reduced by using appropriate dimensions of the samples. Uncertainties of the measurement are well described in Bomberg et al. (2002) and they are:

- Technique and materials used for sealing the specimen.
- Difference between the area of the surface exposed to vapour transport and the total area of the cross section.
- Assessment of time to establish steady state conditions.
- Period and frequency of data collection.
- Thickness measurement.
- Resistance to vapour transfer either between the source of moisture and the materials surface or between the material surface and moisture sink.
- Loss or gain of vapour from the volume of the still air during the weighing process (when containers are open).
- Change in the rate of vapour diffusion caused by a change in barometric pressure
- Changes in the capability of desiccant to absorb moisture if the moisture content of the desiccant is too high.

- Changes in the water vapour diffusion flux caused by the contribution of flow in a liquid phase.
- Changes in material structure caused by changes in temperature and moisture adsorption.

Uncertainties of the measurement can be decreased if all laboratories use the same measurement procedure and apparatus. However, the procedure and the apparatus vary among laboratories and then the corrections of the method shall be applied.

2.3.1.1.6 Corrections of cup methods

This subchapter will focus on some of the uncertainties that were mentioned above; some of them have been already discussed in the previous text.

Edge Mask Correction

When the area of the specimen is larger than the effective area because of the mask then two-dimension water vapour flux occurs and the rate of vapour transport be higher. If the specimen is a thin film, this edge mask presents no problem, but serious error may result when the specimen is thick, Joy & Wilson (1963).

Figure 2.20 shows a cup with an internal diameter of 127mm on which a 32mm thick specimen is mounted. In *Case 1*, there is no masked edge and no excess rate of water vapour diffusion flux (rate of water vapour transmission – WVT). *Case 2* shows the maximum masking when WVT should not exceed 10%. In *Case 3*, the masked edge is half the thickness of the specimen and allows a 20% error. The errors in WVT shown on Figure 2.20 are calculated by employing equation (2.40) that was analysed by Paul Greebler and published in Joy & Wilson (1963).

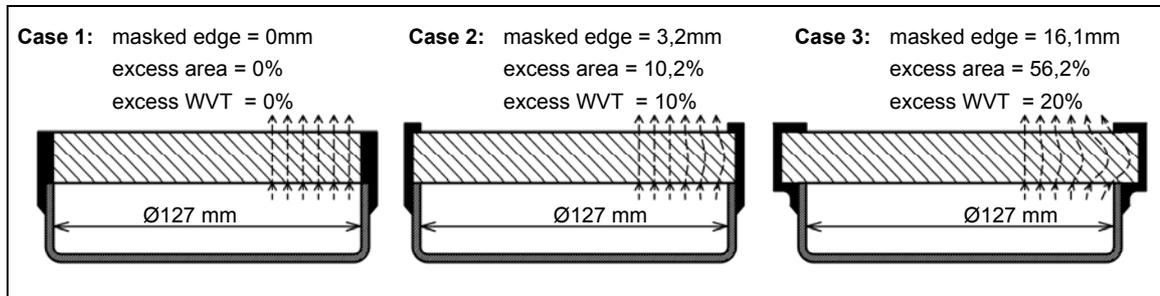


Figure 2.20. Edge Mask Effect, Joy & Wilson (1963)

$$\text{PercentExcessWVT} = \frac{400d}{\pi S} \log_e \left(\frac{2}{1 + e^{-(2\pi b/d)}} \right) \quad (2.40)$$

Where

- d is the specimen thickness [m],
- b is the width of masked edge [m], and
- S is four times the test area divided by the perimeter [m].

The comparison of measurements and the calculation for two materials is shown in Table 2.11 and was done by Joy & Wilson (1963).

If a material of the specimen is not isotropic, the edge effect may be either bigger or less than calculated. With these possibilities, it is wise to limit the masked edge to a practical minimum.

Table 2.11. The edge mask effect – measurements and calculations, Joy & Wilson (1963)

Material	Thickness [mm]	Mask width = 6,4mm Ø of Test = 142mm		Mask width = 12,8mm Ø of Test = 142mm	
		Error [%]		Error [%]	
		Measured	Calculated	Measured	Calculated
Foamed polyurethane insulation (one specimen for each thickness)	38	15	14	20	22
	25	14	12	20	17
	12,5	5,4	7,5	9,7	8,7
Extruded polystyrene insulation (average of two specimen)	38	7,4	14	13	22
	25	8,0	12	9,9	17
	12,5	2,5	7,5	2,9	8,7

Corrections for Resistance due to Still Air and Specimen Surface

The value of water vapour resistance factor (2.34) is calculated assuming only the resistance offered by the test specimen. In fact, the experiment set-up imposes four vapour resistances Hansen & Lund (1990) in series between the content of the cup (the desiccant, salt solution or distilled water) and the chamber, Lackey et al. (1997). The resistances are:

- 1) the resistance offered by the layer of still air in the cup,
- 2) the resistance offered by the surface of the specimen inside the cup,
- 3) the resistance offer by the test specimen, and
- 4) the resistance offered by the surface of the specimen outside the cup.

If the thickness of the still air layer is known, the corresponding vapour permeance and thus the resistance can be calculated using the Shirmer's equation (2.35). Two surface resistances are shown on *Figure 2.21*, Burch et al. (1992).

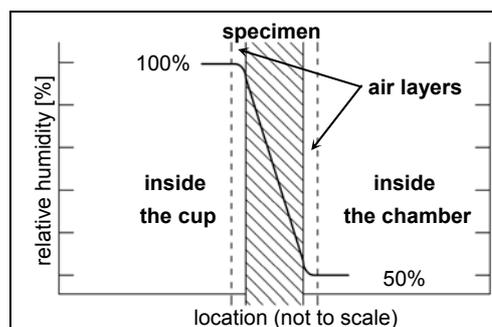


Figure 2.21. Drops in RH due to thin air layers, Burch et al. (1992)

The moisture resistances due to thin air layers on the specimen surfaces were measured by Mrlík (1980). The results from cup measurements for both moisture surface resistances depending on different materials are in *Table 2.12*. The similar values for cup methods were measured by Fanney et al. (1991).

As the air gap between the surface specimen and the saturate solution (desiccant) was calculated as surface resistance, the values are much higher than the results measured by hot/cold box apparatus *Table 2.13*. These results are closer to theoretical values.

Table 2.12. The results of water vapour surface resistances measured by cup methods, Mrlik (1980)

Materials	Water Vapour Resistances of Air Layers [10 ⁸ Pa.s.m ² /kg]
Polystyrene	5,65
Polyurethane	21,9 - 35,3
Glass balls	2,30 - 10,6
Aerated concrete	3,53 - 7,76
Cover concrete	6,0 - 11,3
Sorted crystal	2,68 - 4,44

Table 2.13. The results of water vapour surface resistances measured by hot/box apparatus, Mrlik (1980)

Materials	Water Vapour Total Surface Resistances [10 ⁸ Pa.s.m ² /kg]
OSB	0,055
Polystyrene	0,109
Polystyrene	0,170
Polystyrene	0,156
Fibreboard	0,111
Fibreboard	0,101
Fibreboard	0,092

Schwarz (1971) focused on moisture transport from surfaces to free space. He proved that moisture transport on the surface of walls depends on evaporation on the surface of free water level. Moisture transfer coefficient β depends on air convection. The dependence between β and α (heat transfer coefficient) exists in free space and it is derived from the theory of similarity in turbulent convection. According to Schwarz, between temperatures - 20°C to 40°C, it is possible to use Lewis' law:

$$\beta = \frac{h_c}{R_v \cdot T \cdot \rho_a \cdot c_a} \quad (2.41)$$

where

- β is the surface moisture transfer coefficient [kg/(Pa.s.m²)],
- h_c is the convective heat transfer coefficient [W/(m²K)],
- R_v is the ideal gas constant for water (461,5 J/(kg . K),
- T is the absolute temperature [K],
- ρ_a is the density of air [kg/m³], and
- c_a is the specific heat capacity of air [J/(kg.K).

If we fill equation (2.41) with temperature 23°C (296K), we will get the following explanation for moisture transfer coefficient,

$$\beta = 6,9 \cdot 10^{-9} \cdot h_c \quad (2.42)$$

if heat transfer coefficient is $h_c = 8 \text{ W}/(\text{m}^2\text{K})$ and two mass transfer coefficients are for both sides of the specimen, we will get for total moisture resistance

$$Z_T = 2 \cdot \frac{1}{\beta} = 2 \cdot \frac{1}{6,9 \cdot 10^{-9} \cdot 8} = 3,6 \cdot 10^7 \text{ Pa.s.m}^2/\text{kg} \quad (2.43)$$

The similar value for both moisture resistances, $Z_T = 4,0 \cdot 10^7 \text{ Pa.s.m}^2/\text{kg}$ is used in ASTM E 96/E 96M (2005).

Buoyancy Correction

When the change in mass is small, the effect of atmospheric buoyancy should be considered. The effect is discussed in Bomberg (1989) or Lackey et al. (1997). The duration of one set of measurements can be many days or weeks. The atmospheric pressure may significantly change during such periods. If the test specimen is a highly vapour resistant one, the changes in mass due to the vapour transport may be overshadowed by the apparent gravimetric changes observed. In such cases at least, all gravimetric data should be corrected to those in vacuum (the intention is to bring all the measurements to the same base line; this may also be done by making the base line to correspond to standard atmospheric conditions) Lackey et al. (1997). The following equation can be used for such corrections, McGlashan (1971):

$$\frac{m_2}{m_1} = 1 + \frac{\rho_a (\rho_1 - \rho_2)}{\rho_1 (\rho_2 - \rho_a)} \quad (2.44)$$

where

- m_1 is the weight recorded by the balance [kg],
- m_2 is the mass corrected for buoyancy effect [kg],
- ρ_a is the density of air [kg/m^3],
- ρ_1 is the density of the material of the balance weights [kg/m^3], and
- ρ_2 is the bulk density of the test assembly, [kg/m^3].

The density of air can be calculated by using the ideal gas law for the measured atmospheric pressure and ambient temperature, i.e. equation (2.9).

An alternative to the atmospheric correction is the slower procedure of weighing the cup only when the barometer is at the chosen level Joy & Wilson (1963).

Strong recommendation for using “dummy” specimen when permeance of specimens are expected to be less than $3 \text{ ng}/(\text{m}^2 \cdot \text{s} \cdot \text{Pa})$ can be found in ASTM E 96/E 96M (2005). Dummy specimen should be tested exactly like the others, except that no desiccant or water is put in the cup. The environmental effects of temperature variation and buoyancy variability due to barometric pressure fluctuation can be arithmetically found out of the weighing values. This precaution permits earlier and more reliable achievement of equilibrium conditions.

2.3.1.2 Other Methods to Determine Water Vapour Permeability

2.3.1.2.1 Non-isothermal methods

Only one gradient (gradient in relative humidity) was used in previous measurements to determine water vapour permeability of materials. Some researches have developed apparatuses, in which gradients of relative humidity and also temperature are possible to setup in the same time. Usually, non-isothermal methods are used for thick insulation material when the temperature gradient should not be neglected or when condensation occurs in specimens. More details about the methods can be found in the following references: Mrlik (1985), Schwartz et al. (1986), Krus (1996), Gailbraith et al. (1998),

Padfield et al. (2002), Peuhkuri (2003), Künzel (2005), Hens (2006) and Peuhkuri et al. (2008).

2.3.1.2.2 Low Pressure Apparatus

Total mass flux is separated into vapour and liquid in Galbraith et al. (2004). Their hypothesis is that vapour flux is inversely proportional to the prevailing barometric pressure and liquid moisture flux is independent on barometric pressure. For this hypothesis, the low pressure apparatus was developed. Results of the measurements show that this apparatus can significantly shorten time period for measurement with results comparable to standard cup methods.

2.3.1.2.3 Infrared Method

Infrared method to determine water vapour transmission rate was discussed in Dutt et al. (1994). The apparatus of this method is called Permatran and it can be used to measure the mean permeability between 0% RH and any other value, depending on the adequate salt solution used. Consequently, wet-cup (50 to 100%) results cannot be obtained with it. Dutt et al. (1994) concluded that Permatran with further development would be a reliable apparatus to determine water vapour permeability of materials.

2.3.2 Comparative Laboratory Measurements of Materials with High Diffusion Resistance

Kumaran (2006) showed that water vapour transmission property for one test specimen can be determined well within a percent, but when all measurements on all test specimens used are combined to designate the water vapour permeability or permeance of the product, the uncertainty may be as large as 30%.

The worst situation is if we look at on measurement results of water vapour tight materials especially if the measurements were done for the same product by different laboratories.

Several comparative measurements on vapour tight membrane products were done to evaluate the standard measurement procedure of the cup methods. Very interesting results of these comparative measurements (round-robin tests) will be discussed to determine the main problems to measure products with high sd-value.

Water vapour permeability of water vapour tight membranes can be found in several literatures, i.e. Seiffert (1971), Mrlik (1985), Kumuran et al. (2006).

2.3.2.1 Round Robin Test 1985

Twelve laboratories participated in the round robin and each laboratory tested three products in triplicate using ASTM procedure A and B (dry cup and wet cup methods). The products were: 0,025mm thick Mylar film; 0,14mm thick Teflon FEP (fluorinated ethylene propylene); and 0,14mm thick HDPE (high density polyethylene). The Mylar film was chosen as high permeable materials and the other as low permeable products.

The twelve laboratories obtained results with a wide disparity, especially on the low water vapour transmitting films, see *Table 2.14*.

The ASTM E 96 task force reviewed the round-robin results and concluded that the wide variety was caused by the testing laboratories that did not seal the test samples thoroughly. However, three of the twelve laboratories generally obtained precise results close to the

expected results for all three films using both test methods, and those three laboratories were judged to be skilled in sealing. All from Toas (1989).

Table 2.14. Results of the round-robin test 1985 for two water vapour tight products

Product	HDPE	HDPE	Teflon	Teflon	HDPE	HDPE	Teflon	Teflon
Method	dry cup	wet cup	dry cup	wet cup	dry cup	wet cup	dry cup	wet cup
Units	sd-value [m]				permeance [ng/(m ² .s.Pa)]			
Results obtained by all twelve laboratories								
Average value	141,8	107,0	175,2	226,5	10,08	53,87	6,56	7,30
Standard Deviation	119,9	118,9	140,9	289,6	17,45	105,56	16,05	16,39
Max. value	∞	406,0	∞	∞	77,22	396,66	93,69	89,35
Min. value	2,5	0,5	2,1	2,2	0	0,48	0	0
Results obtained by three labs judged to be skilled in sealing and testing								
Average value	244,1	243,8	335,2	264,1	0,94	0,84	0,63	0,85
Standard Deviation	77,9	49,9	77,0	83,9	0,45	0,17	0,21	0,38
Max. value	324,8	307,2	437,2	374,7	1,92	1,12	1,20	1,57
Min. value	101,5	174,0	162,4	124,0	0,60	0,63	0,45	0,52
SD within Labs	60,3	7,4	48,8	63,0	0,34	0,03	0,13	0,21

2.3.2.2 Round Robin Test 1987

Ten institutes and laboratories from the Nordic countries participated in other round-robin test. The materials used were 12mm porous board, 0,04mm PE foil and 0,8 tarred paper. The measurements were performed both as wet cup tests and as dry cup tests.

The results show a great spread among the laboratories for all three materials. The water vapour tightest product (PE foils) varied the most. The sd-value with 95% confidence interval was measured among laboratories as $s_d = 15,3 \pm 13,7m$.

The round robin test again proved the wide range of results among the laboratories. All from Hansen & Bertelsen (1989).

2.3.2.3 Round Robin Test 2003

A round robin test has been arranged in order to compare test facilities and result form measuring water vapour permeance of 3 different types of building products:

- 1mm thick foil of polyurethane laminated with polypropylene on both sides,
- 11mm hard wood fibre board, and
- 0,25mm thick PE foil with reinforcement-mash made from polypropylene.

Table 2.15. Sd-values of the same PE foil measured by six different laboratories

Product	0,25mm PE foil with PP reinforcement-mash						Average	SD
Laboratory	1	2	3	4	5	6		
sd-value [m]	-	150	101	28	122	95	99,2	40,5
permeance [ng/(m ² .s.Pa)]	-	1,30	1,93	6,96	1,60	2,05	2,77	2,11

Six laboratories from four Nordic countries participated in the round robin test. The test was performed according to European standard EN ISO 12572 and each laboratory got three samples of the same products. The test conditions were used for the wet cup method only. The results for PE foil are shown in Table 2.15.

The results for PE foil are not discussed in Time & Uvsløkk (2003) because none of the laboratories fulfilled the standard criteria for the measurements (the criteria for steady state) and the results seem to be totally independent.

2.3.3 Measurement Results of Non-homogeneous Materials with High Diffusion Resistance

In the past, water vapour permeability of perforated materials with high sd-value were measured only by a few researches. The results of these measurements are separated into two subchapter; Laboratory Measurements and Large Scale and In Situ Measurements

2.3.3.1 Laboratory Measurements

Seiffert (1960) and Seiffert (1971) measured sd-value of 1,5mm thick aluminium sheet with percentage of perforation from 0,01% to 0,22% *Table 2.16*. His measurement showed significant decrease in the sd-value.

Table 2.16. Water vapour permeability measurement of perforated Aluminium sheet, Seiffert (1960)

Material: Aluminium sheet	Thickness: d = 1,5 mm
Percentage of perforation [%]	sd-value [m]
0,014	9,30
0,0275	2,02
0,055	0,915
0,11	0,515
0,22	0,246

Bauer (1965) did similar measurements. He measured sd-values of three different materials (aluminium sheet d = 1mm, PVC foil, Fibreglas board). The percentage of perforation for these materials was between 0,03% to 10%. His measurements show that the decrease in sd-values is greater in the case of materials with higher water vapour resistance factor (i.e. aluminium sheet). Above 1% of perforation, the sd-value does not depend on material because all measured products have the same sd-value with similar perforation, *Table 2.17*.

Table 2.17. Water vapour permeability measurement of three perforated materials (Aluminium sheet, PVC foil, Fibreglas board), Bauer (1965)

Material: Thickness:	Aluminium sheet d = 1mm	PVC foil d = 0,16 mm	Fibreglas board d = 4,1 mm
Percentage of perforation [%]	sd-value [m]	sd-value [m]	sd-value [m]
0	54,00	14,24	0,45
0,03	5,00	3,00	0,44
0,3	0,60	0,40	0,34
0,5	0,47	0,33	0,31
1	0,27	0,27	0,27
1,5	0,24	0,24	0,24
2	0,22	0,22	0,22
3	0,19	0,19	0,19
5	0,15	0,15	0,15
10	0,08	0,08	0,08

The strange result of Bauer's measurement is the s_d -value of aluminium sheet without any perforation because he had measured $s_d = 54$ m and according to standards (i.e. ČSN EN 12524 (2001)) it should be infinity or at least 1500 m. Also Bauer's and Seifert's measurements vary in s_d -values of aluminium sheet for percentage 0,03% and 0,0275%. The s_d -value should be higher for Seifert (greater thickness of aluminium sheet and smaller percentage of perforation) but the result is twice higher for Bauer's aluminium sheet $s_d = 5$ m than Seifert's aluminium sheet $s_d = 2,02$ m. These two discrepancies make all the results uncertain.

Other similar measurements were done by Mrlik (1985). He measured the s_d -value of PE foil that was perforated by staples. First he measured s_d -value of PE foil with staples then he pulled out staples and measured the s_d -value of PE foil again only with pinholes. A factor of 2 to 3 was found between these two measurements, see *Table 2.18*.

Table 2.18. Water vapour permeability measurement of perforated PE foil with and without staples, Mrlik (1985)

Material: Thickness:	PE foil with staples d = 0,085 mm	PE foil only with holes d = 0,085 mm
Number of staples [items/m ²]	s_d -value [m]	s_d -value [m]
0	28,74	28,74
100	14,35	5,00
200	3,60	1,92
300	2,20	1,40
400	2,07	1,25
500	2,00	1,20
1000	1,60	0,74
1500	1,12	0,50
2000	0,70	0,30

In the other case, foils were perforated by nails with and without heads and the area of the perforation was calculated from diameter of nails, Mrlik (1986). The results of this measurement are in *Table 2.19* and show significant fall in the s_d -value. PE foil with headless nails show higher decrease in the s_d -value.

Table 2.19. Diffusion properties of PE foils with headless nails and with nails with heads, Mrlik (1986)

Material: Thickness:	PE foil with headless nails d = 0,085 mm	PE foil with nails with heads d = 0,085 mm
Percentage of perforation [%]	s_d -value [m]	s_d -value [m]
0	28,72	28,72
0,1	8,64	19,62
0,2	2,30	5,23
0,3	1,77	12,79
0,4	0,77	8,88
0,6	0,58	5,42
0,8	0,47	4,05
1,0	0,30	3,07
1,2	0,23	2,62
1,4	0,18	2,20
1,6	0,12	1,92
1,8	0,05	1,71
2,0	0,03	1,15

In the USA, measurements of perforated PE foil were done by Suprenant & Malisch (1998). They measured perforated PE foils with different thickness and different percentage of perforation. The calcium chloride cup tests were used. The results of these measurements showed significantly water vapour emission through the retarders with large holes ($\text{Ø}3,2\text{mm}$ and $\text{Ø}15,9\text{mm}$) but authors were not able to distinguish water vapour flow through different thickness of non-perforated PE foils therefore the results are unclear.

2.3.3.2 Large Scale and In Situ Measurements

A large-scale investigation of moisture and heat transport in a wood frame wall assembly with a perforated vapour barrier was performed by Zarr et al. (1995). The same wall specimen was investigated with and without a vapour barrier and with the vapour barrier with a hole of 11,5mm diameter. At interior surface of the polyisocyanurate sheathing, relative humidity falls for the case with the hole between the cases with and without a vapour retarder, see *Figure 2.22*.

Further investigations of moisture transport in roof assemblies were performed by Hens et al. (2003). Four year measurements of compact flat roof assemblies on heavyweight decks were compared. One case had a perfect vapour barrier while the other had open seams to simulate poor workmanship. The results showed that there was no condensation deposit after the first winter for the roof with a high-quality vapour barrier. The roof with leaky vapour barrier had the condensation deposit after the first winter $0,5 \text{ kg/m}^2$. H. Hens concluded that moisture tolerance in roof assemblies depends on condition that a perfect vapour and airflow retarder is mounted just below the thermal insulation.

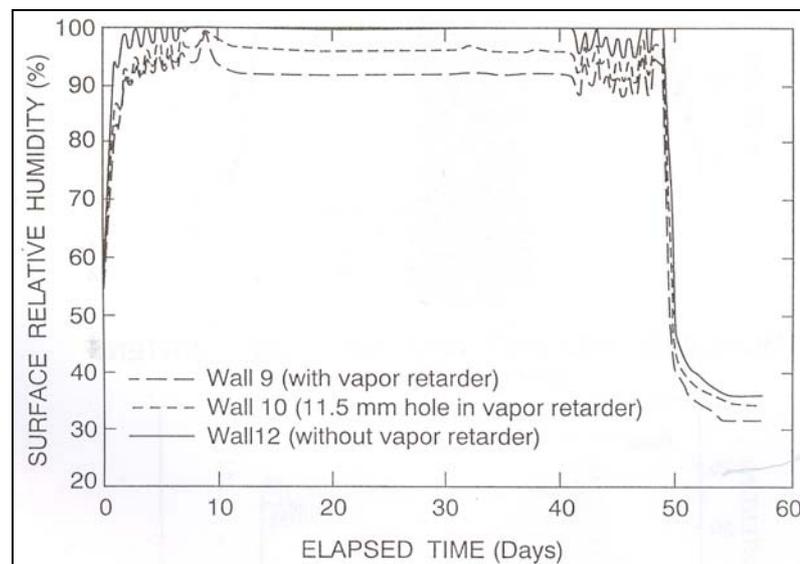


Figure 2.22. Relative humidity on inner surface of the sheathing inside test wall assembly, Zarr et al. (1995)

Chapter 3: Experimental Procedure

3.1 Experimental Measurements

This and the following subchapters are focused on the experimental measurement, results of the measurement and the analytical model that describes the results. The development of experimental apparatus, its advantages and the experimental procedure are presented in details.

3.1.1 Reasons for Experimental Measurements

Since 1930s, vapour retarders have been commonly used in membrane roof assemblies to control water vapour transport from the interior environment. The main reason is to prevent roof assemblies from excess moisture content that reduces the durability of materials, components and the whole roof structures. Vapour retarders are usually designed according to the simple calculation method, the Glaser method (Europe) or the Dew point method (North America). These methods assume water vapour diffusion in one dimension only. This is applicable when each roof layer is homogeneous, without any perforation, and when the roof assembly is truly planar. In fact, under certain circumstances three-dimensional transport of moisture may occur in the roof assembly and then the calculations – according to these simple methods – are not realistic.

The three-dimensional moisture transport may occur in roof assemblies due to several reasons:

- imperfect seams of material strips;
- bad connection of vapour retarder to openings;
- mechanical fastenings puncturing roof layers;
- bad workmanship during construction;
- structure and assembly details;
- aging of sealing materials.

The problem with multidimensional moisture transport mostly appears with imperfect layers which have a high diffusion resistance (high s_d -value) for example vapour retarders. We call the place of imperfection or perforation of an envelope layer a “diffusion bridge” because moisture transport noticeably increases in this place and because of similarity with the term “thermal bridge”. A diffusion bridge in case of the perforation of the vapour retarder in the compact membrane roof assembly is shown in *Figure 3.1*.

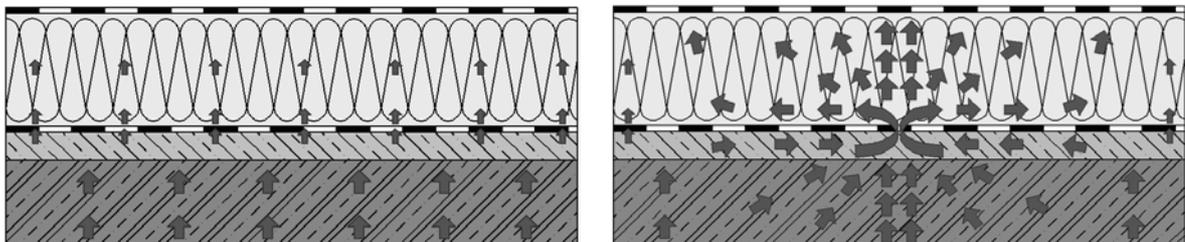


Figure 3.1. 1D and 2D(3D) moisture transport in a roof assembly. A diffusion bridge is demonstrated on the right, where vapour retarder is perforated

It is difficult to determine how much water vapour passes through perforation of the vapour retarder. In technical literature, several different suggestions can be found.

For example, technical standard ČSN EN ISO 13788 (2002) says:

The most important issue for materials with a high s_d -value is their mutual connection between boards, foils etc. and further influence of frequent imperfections as a consequence of structure details. The s_d -value can be reduced for several decimal orders.

In technical standard ČSN EN 12524, the s_d -value of PE foil, that is perforated by staples, is reduced from 50m to 8m. The following text is written as national note in the standard, “The reduced value should not be used as the design value, especially in case when PE-foil is used in the assembly on place, where the reduced value is not on the safety side”, for example as the vapour retarder.

Authors Chaloupka & Šála (2002) recommend:

The manufacture’s μ -value or s_d -value of vapour retarders should not be used for hygrothermal evaluation of roofs, but non-sealed seems, perforations caused during a construction and caused by fasteners must be taken into account. The real diffusion (air) resistance of this layer (and also the μ -value or s_d -value) is often ten or hundred times lower than the manufacture’s value of the product.

Chaloupka (2003) writes that perforated vapour retarder layer, “means to reduce the μ -values on 10% of the manufactured value”.

ASHREA (2005) says about perforated vapour barriers:

Several studies have reported a significant increase in apparent permeance as a result of small holes in the vapour retarder. For example Seiffert (1970) reports a 100-times increase in the vapour permeance of aluminium foil when it is 0.014% perforated, and a 4000-times increase when 0.22% of the surface is perforated. In general, penetrations particularly degrade a vapour retarder’s effectiveness if it has a very low permeance (e.g., polyethylene or aluminium foil).

The previous recommendations do not help to determine the real s_d -value of perforated vapour retarders.

The results from the laboratory measurements show significant decrease in the s_d -value of products with a low permeance. Only four sets of laboratories measurements of perforated vapour retarders including Seiffert’s measurement that was cited in ASHREA (2005) can be found in technical literature. These measurements are Seiffert (1960) or Seiffert (1971), Bauer (1965), Mrlik (1986) and Suprenant & Malisch (1998) and their results are presented in *Chapter 2.3.3.* in this Thesis.

The results of Bauver’s and Sieffert’s measurements vary in factor two or three for the same products. Bauer’s measured s_d -values for non-perforated aluminium sheets are significantly lower than the values founded in technical standards. These two discrepancies make all the results uncertain. The results of Suprenant and Malish’s measurements proved significant increase of moisture transport through perforated PE-foil but the authors admit that their results were inaccurate. The Mrlik’s results can not be used as percentage of perforation in one square meter because Mrlik calculated the s_d -value from the number of staples or nails.

Furthermore, all these measurement were done for percentage of perforation higher than 0,01%, but in real roof assemblies percentage of perforation can be much lower. Only four materials were measured (Aluminium sheets, PVC-foil, PE-foil, fibreglass board). The

measured sd-values of the products made from these materials were less than 54m. In real assemblies of compact membrane roofs, vapour retarders with higher sd-value than 54m are commonly designed.

All these inaccuracies and imperfections of the previous measurement, helpless recommendations and a lack of the results led to my decision to do own laboratory measurements of water vapour permeability of vapour retarder products, especially if the percentage of their penetration is lower than 0,01% and the sd-value of vapour retarders is higher than 50m.

3.1.2 Selection and the Principle of Experimental Method

To measure water vapour permeance of products with a very high water vapour resistance correctly is difficult. This was proved by several comparative laboratory measurements. The uncertainty of these measurements was much higher than 50%. The results of these comparative measurements can be found in the *Chapter 2.3.2*. To measure materials with a very high water vapour resistance correctly means to select an experimental method of the measurement properly and to upgrade this method to facilitate water vapour permeability measurement of products with a very high water vapour resistance.

3.1.2.1 Selection of Experimental Method

The wet cup method was selected as the experimental method from the list of all measurement methods which can be found in the *Chapter 2.3.1*. The reasons for this selection are simplicity and accuracy of the method, low costs and a good description of this method in technical literature. The wet cup method has only two disadvantages – long time period needed to get results and to distinguish the steady-state properly. The advantages and disadvantages are discussed in details in the following text.

Simplicity

The wet cup method measures directly the physical property (water vapour permeance) of products that means the method does not need any other substitution parameters as the infrared method or the low pressure apparatus. This straightness facilitates more exact measurement.

Isothermal conditions during the measurement process are used; therefore relative humidity is only the one potential that creates water vapour movement. This assumption can be used only in case of thin products with small thermal resistance as vapour retarders are.

Accuracy

The simplicity of the method lead to its accuracy as written above. The method uses constant condition during the measurement procedure therefore the steady-state can be easily recognized in the contrast to non-steady-state methods.

The wet cup method gives better results about materials that are placed in the environment with higher relative humidity (50% to 100%). These conditions can be found inside compact membrane roofs where vapour retarders are placed. The relative humidity in these assemblies is always higher than 40%. The dry cup method is not suitable in this case because it gives better results about materials in environmental conditions with relative humidity between 0% and 50%.

Also, the direction of the vapour flow during the measurement fits to the direction of the flow inside membrane roof assemblies in contrast to inverted wet cup method where the vapour flow is in the opposite direction.

Low Costs

Low costs are the other advantage of the wet cup method. The apparatus for the measurements can be built without expensive equipments. The laboratory scales are the most expensive item to build up the apparatus.

General Knowledge

The advantage of the wet cup method in contrast to for example the modified cup method is that the wet cup method is very well-known and described in scientific literature and international standards e.g. ASTM E 96/E 96M (2005), ČSN EN ISO 12572 (2002), ČSN EN 1931 (2001), ISO 7783-1 (1996), ČSN 727030 (2000) and ČSN 727031 (1975).

Time Period Needed

One disadvantage of the wet cup method is the time period needed to get results especially if the measured products have a high water vapour diffusion resistance. Needed time period to get results can be from 30 up to 60 days, ASTM E 96/E 96M (2005).

Reach the steady-state

To stabilize constant mass loss per time (to reach steady-state) for products with high diffusion resistance can be difficult as reported e.g. Time & Uvsløkk (2003) or Galbraith et al. (2004).

3.1.2.2 Principle of the Wet Cup Method

The principle of the wet cup method has been already described in details in *Chapter 2.3.1*. Brief recapitulation of method principles is required.

The principle of the wet-cup method is to create two environments with different relative humidity. Relative humidity outside the cup is 50% and relative humidity inside the cup is 95%. Temperature is the same for both environments. The water vapour flow then goes from the cup with higher relative humidity through the sample of a product to the environment with lower relative humidity according to simple equation (3.1) and *Figure 3.2*,

$$g_v = -\frac{\delta_a}{\mu(w)} \nabla p_v \quad (3.1)$$

Where

- g_v is the density of water vapour diffusion flux in a material [$\text{kg}/(\text{m}^2\text{s})$],
- p_v is the water vapour partial pressure [Pa/m],
- δ_a is the water vapour permeability of stagnant air [$\text{kg}/(\text{m}\cdot\text{s}\cdot\text{Pa})$], and
- μ is the vapour resistance factor (μ -factor) of measured material [-], which depends on moisture content w [kg/m^3].

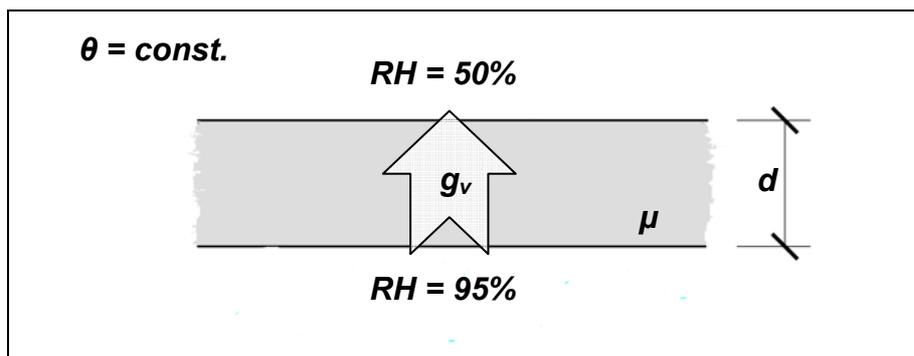


Figure 3.2. Principle of the wet cup method

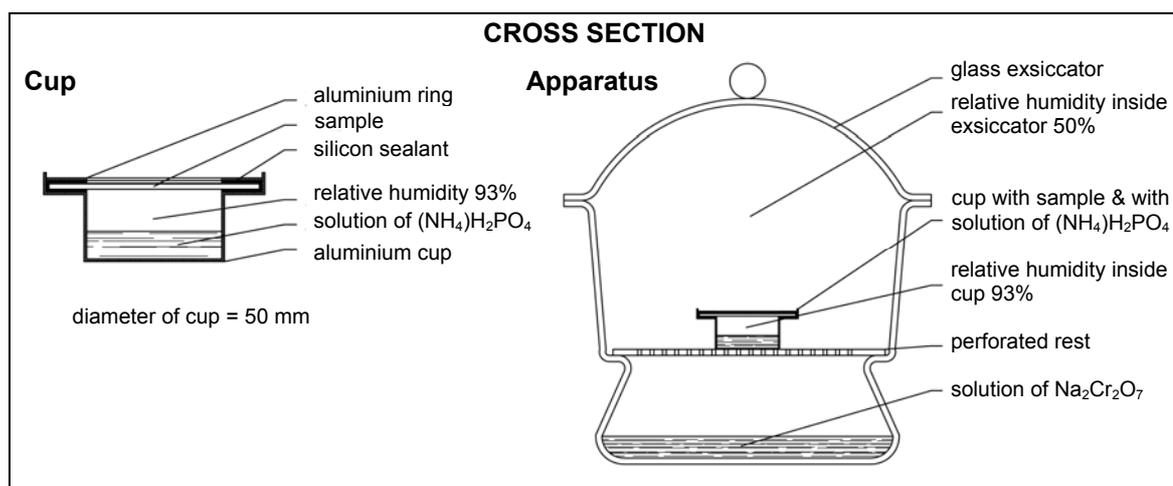


Figure 3.3. Schema of wet cup apparatus, Hajšman (2000)

3.1.3 Development of Experimental Apparatus

The development of a new experimental apparatus follows water vapour permeability measurement done by Hajšman (2000), Slanina (2004) in the laboratory of the Czech Technical University in Prague.

The Hajšman's experimental apparatus was used to measure products with a very low diffusion resistance, see *Figure 3.3*. The *sd*-value of wall finishes was only around 0,2m. This is the main reason why Hajsman's experimental apparatus appeared to be unsuitable to measure products with the *sd*-value higher than 50m. This conclusion was proven by Slanina (2004). The main reasons are:

- 1) The diameter of used cups was only 50mm. This diameter of the cup (the effective area of samples 0,002m²) is suitable only to measure products with a low diffusion resistance when great change of the mass per time occurs. If products with a high diffusion resistance are measured larger effective area of samples is necessary.
- 2) The measurement done by Slanina (2004) showed that aluminium cups chemically react with saturate solution (NH₄)H₂PO₄. The chemical reaction may cause pressure on a sealant and leakage devaluated results may occur.
- 3) The scale with resolution of 0,02g was used. Scale resolution of 0,02g is unsuitable for measurement of products with a high diffusion resistance where very small changes in the mass occur.

- 4) Silicon mastic was used as the sealant. The measurements done by Slanina (2004) indicated that silicon mastic is too permeable and unsuitable for vapour permeability measurements of products with a high diffusion resistance.
- 5) The ambient atmospheric pressure was not monitored. Change in atmospheric pressure may affect the results. This effect is discussed in Bomberg (1989) or Lackey et al. (1997).
- 6) Temperature and relative humidity were monitored occasionally and inside the exsiccator only. Continuous monitoring of temperature and relative humidity inside and outside of the cups can lead to get more accurate results.

A new experimental apparatus was developed in the laboratory of Czech Technical University in Prague to reduce the previous imperfections. The development lasted for more than one year and the following points show these improvements.

1) Cups

Completely new round cups were designed. These cups are made from aluminium sheet with 1mm thick walls only. Aluminium sheet was used because this material is lightweight and impermeable for water vapour transport. Cups were painted to avoid chemical reaction with a saturated solution. The surface of the cup that is in contact with the sample and with the sealant must not be painted, because leakage may occur in this place. Glass cups would be also good but quite heavy for exact scales.

The area of samples should be as large as possible. The diameter of a new cup is 200mm and the effective area is $0,03\text{m}^2$. Larger cups were impossible to use because the weight of the set (aluminium cup, sealant, solution, and sample) would be out of the range of the scales. Dimensions and the shape of the cup are plotted in *Figure 3.4*.

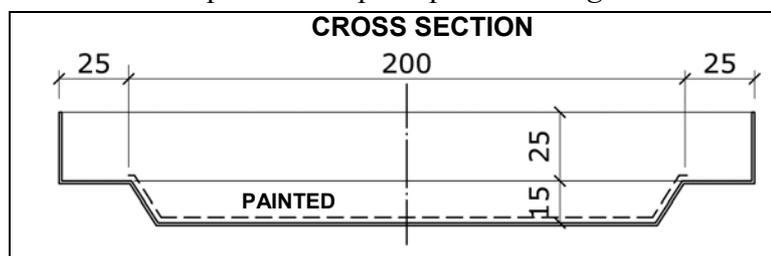


Figure 3.4. Cross section of a new aluminium cup

2) Scales

New scales with resolution of 0,001g were used. This resolution is necessary (resolution 0,0001g would be even better). The combination of the scales with higher resolution and cups with larger effective area allows to measure the water vapour permeance of products 300-times more accurately than measurements done by Hajšman (2000), Slanina (2004). Respectively, the combination allows monitoring mass change in 300-times shorter time than the previous measurements.

3) Sealant

The sealing material is the most important technical issue to obtain accurate measurement results if you want to measure products with a very high s_d -value. Kumuran (1998a) said “The method of sealing the specimen to the mouth of the cup has a major influence on the result from the measurements”.

The sealant used for attaching the specimen to the cup, so that it is suitable for this purpose, must have the following criteria according to ASTM E 96/E 96M (2005):

- must be highly resistant to the passage of water vapour and water,
- must not lose weight to, or gain weight from, the atmosphere,
- must not affect the vapour pressure inside the cup.
- Also must not cause any chemical reaction with the cup or samples, and
- must be easy to fit according to ČSN EN ISO 12572 (2002).

In a round-robin test Toas (1989), only three laboratories out of twelve were judged to be skilled in sealing. In Hansen & Betelsen (1989), 40 μ m polyethylene foil was measured by ten laboratories. The mean sd-value of the foil was measured $s_d = 15,3\text{m}$ but the 95% confidence interval was as large as $\pm 13,7\text{m}$. In Time & Uvsløkk (2003), six laboratories measured 0,25mm polyethylene foil and the results of the measurements were similar. The average sd-value of the foil was measured $s_d = 101\text{m}$. However, the standard deviation among laboratories was $\pm 45\text{m}$ (44%). Details from these comparative measurements can be also found in *Chapter 2.3.2*.

Taking into account the difficulties reported above, I decided to test the sealing materials first. Four sealing materials (silicon, bee's wax, bitumen mastic and butyl mastic) were tested for half a year with help of a "blind tests".

The blind test is a measurement where a sample is replaced by material from which the cup is made. In this case, aluminium sheets thickness of 1mm were used. These aluminium sheets were placed into the mouth of the cup and sealed by sealing materials. The mass change was monitored and plotted into graphs. The blind test with perfect sealing material shows no mass change per time. The results from blind test measurement are presented in *Figure 3.5* (small cups $\varnothing 50$ mm) and *Figure 3.6* (large cups $\varnothing 200$ mm).

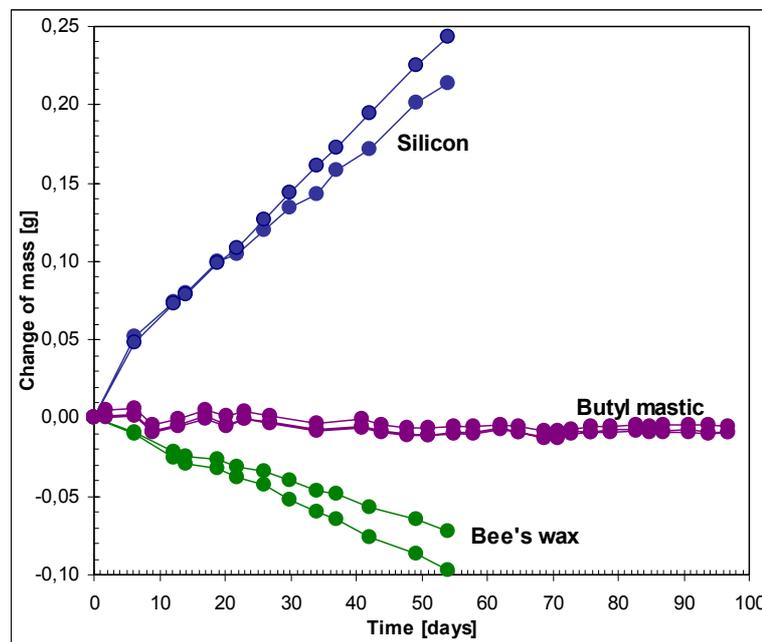


Figure 3.5. Testing sealing materials with help of blind tests (small cups) – Change of cup mass from the beginning of the measurement. (Mass decreases above zero and increases below zero)

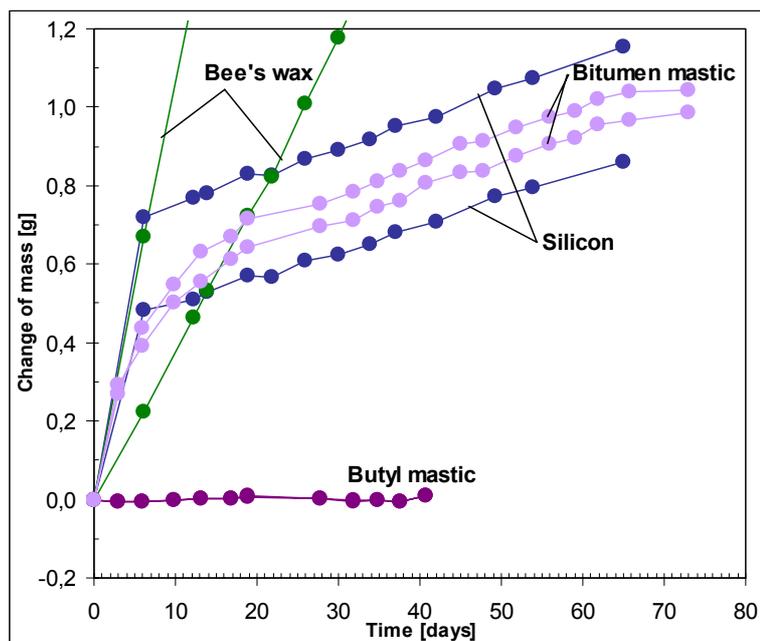


Figure 3.6. Testing sealing materials with help of blind tests (large cups) – Change of cup mass from the beginning of the measurement. (Mass decreases above zero and increases below zero)

The small blind tests showed that silicon and bee's wax are not perfect sealing materials. Two samples showed that the silicon sealant was too permeable for the water vapour flow. Bee's wax (also two samples) adsorbed too much moisture (increase in mass). Only three cups with butyl mastic sealing had almost constant weight in time.

Large cups brought similar results. In this case, bee wax sealant used in two tests shrank and water vapour leakage appeared. Silicon and bitumen mastic sealants showed almost similar permeance. And again, only butyl mastic sealant (two tests) had almost constant weight in the time period (varies $\pm 0,01$ g during period of 42 days).

Butyl mastic as sealant was finally chosen for the measurements because it perfectly fulfils the previous standard criteria. No notice exists in technical literature that butyl mastic was used as the sealant for water vapour permeability measurements.

4) Glass container

As only two large cups could be placed inside glass exsiccators, new containers made from glass were designed. One glass container facilitates to place eight large cups inside its control environment. This helps to get measurement results faster and with higher accuracy.

5) Saturated Salt Solutions

Saturated salt solutions were used in the same way as in Hajšman (2000). These solutions control constant level of relative humidity inside and outside of the cups. Saturated salt solution of $(\text{NH}_4)\text{H}_2\text{PO}_4$ was used to create constant relative humidity of 93% inside the cups. The same solution was used by Galbraith et al. (1998).

The environment outside the cups (inside of the glass containers) was created with the help of saturated salt solution of $\text{Na}_2\text{Cr}_2\text{O}_7$. Then relative humidity should be 50% as referred to Mrlík (1985).

6) Monitoring

Data-loggers placed inside the glass container record temperature and relative humidity of the interior environment. The time step of the record was every half an hour. Relative humidity inside of the cups was monitored only once, because the data-logger failed after five days of monitoring. Relative humidity appeared constant on the level of 95%.

Atmospheric pressure was monitored every time when the samples were weighed.

7) Final Set-up of the Apparatus

For each set of measurements three or four cups with samples and one cup as the blind test were used in the same time period. The blind test was used to compensate leakage and varying atmospheric pressure. The schema of the final experimental apparatus is outlined on *Figure 3.9*, the detail of the cup with the sample is plotted in *Figure 3.7*. *Figure 3.10* and *Figure 3.11* present the photos of the experimental apparatus.

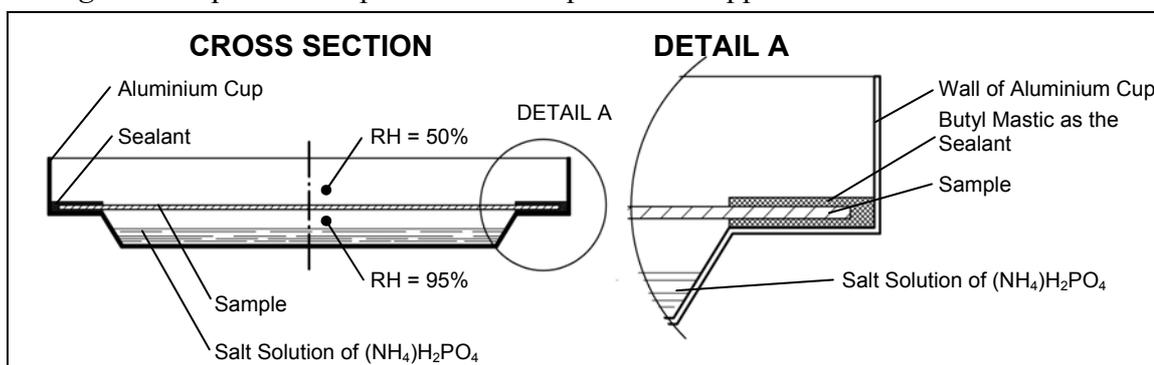


Figure 3.7. Cross section of the cup with sample and with salt solution, and the detail of the sealant

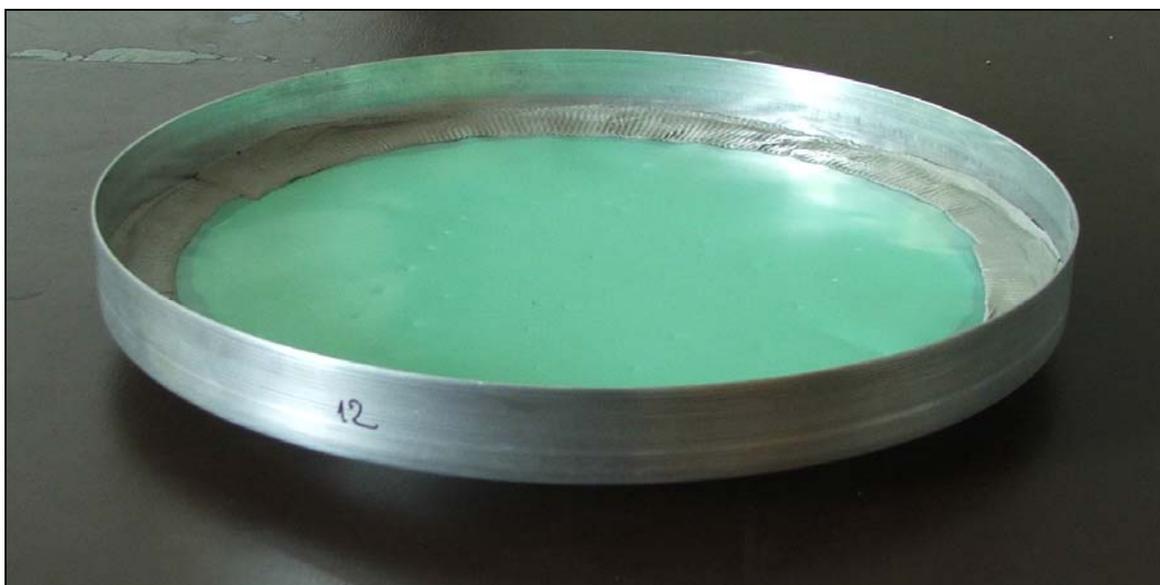


Figure 3.8. Photo of the cup with sample

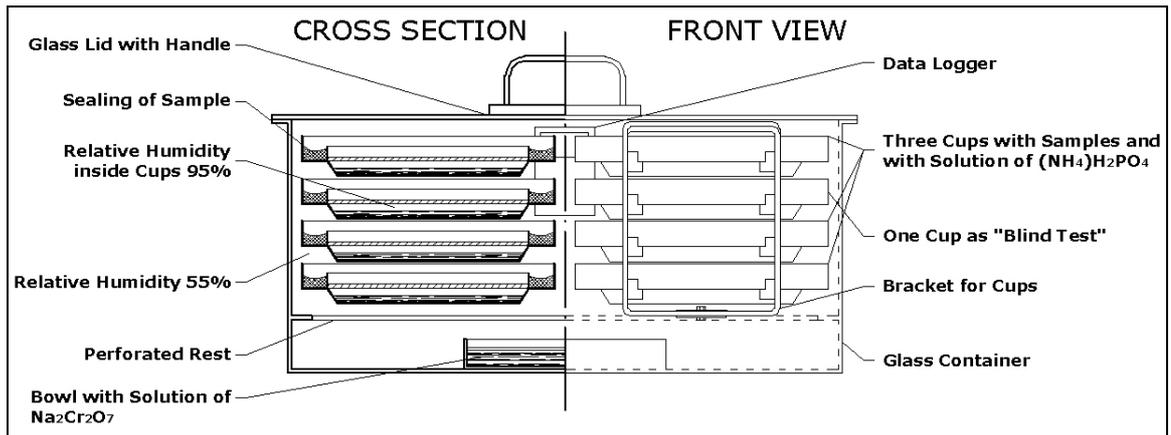


Figure 3.9. Experimental apparatus for water vapour permeability measurement of low permeable materials



Figure 3.10. Final experimental apparatus for water vapour permeability measurement with only one tray of cups



Figure 3.11. Photo of two experimental apparatuses

3.1.4 Advantages of the Apparatus

The main advantages of the developed apparatus in contrast to known and common experimental measurements ASTM E 96/E 96M (2005), ČSN EN ISO 12572 (2002) or ČSN EN 1931 (2001) are the following:

1. The blind test shows how tight the sealing system is because the change in the mass for blind tests should be zero during the whole time period of the measurement. This is extremely important if products with great diffusion resistance are measured.
2. If the blind test cups are weighed together with regular cups with samples the buoyancy effect is eliminated due to application of the following equation into equation (3.3),

$$\Delta m = \Delta m_s - \Delta m_b \quad (3.2)$$

where

- Δm is the change of the mass [kg],
- Δm_s is the change of the mass [kg] for cups with samples, and
- Δm_b is the change of the mass [kg] for blind tests.

Equation (3.2) would be also used in the first point if a sealing system is not totally vapour tight.

3. The previous two points reduce the time period needed to get results from the measurement.

3.1.5 Measurement Procedure

First of all, a selection of vapour retarder products had to be done. Then experimental measurements with selected product could begin.

3.1.5.1 Selection of Vapour Retarder Products

Five products were chosen to represent the whole range of materials and products that are used as vapour retarder. The selection has to fulfil the following basic conditions:

- 1) To select products with large variety of materials (foils and bitumen membranes).
- 2) To select products with a high water vapour resistance (sd-value > 50 m).
- 3) To select products with large range of their sd-values.

According to these conditions, five different products, three foil membranes and two bitumen membranes were finally chosen. Their properties are summarized in *Table 3.1*.

Table 3.1. Properties of selected products

Material	Thickness [mm]	Manufacturer's sd-value [m]	Note
PE	0,15	21	Polyethylene foil membrane
LD PE	0,22	198	Low density polyethylene foil membrane
LD/HD PE	0,3	360	Combination of low and high density PE foil membrane
Bitumen	2,7	130	Bitumen membrane
Bitumen + Aluminium sheet	4,0	800	Bitumen membrane including thin aluminium sheet

3.1.5.2 Procedure of measurements

The whole measurement procedure can be divided into three parts: Preparation before the measurement, measurement process and evaluation of the results. The whole procedure is pointed on the diagram, *Figure 3.12*.

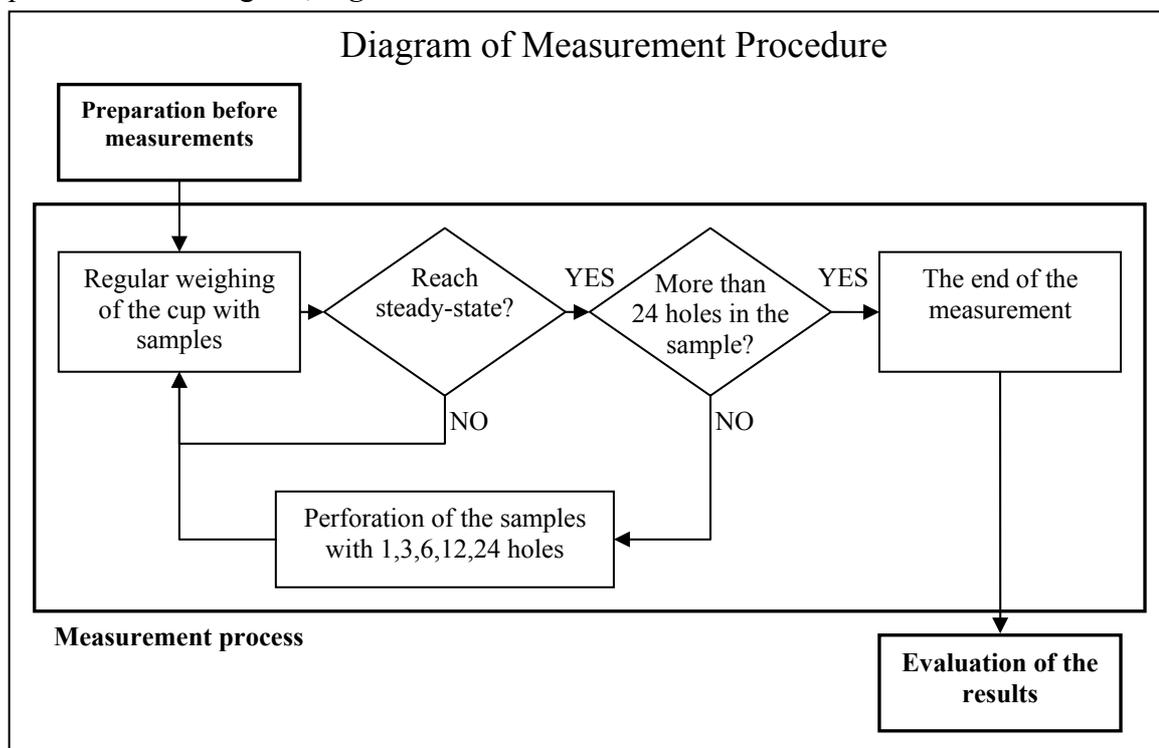


Figure 3.12. Diagram of measurement procedure

3.1.5.2.1 Preparation before the Measurement

- 1) Three or four samples from each product were cut out from a product coil in a manner to represent the whole product. Each sample was cleaned from dirt. (Samples made from bitumen membrane and from bitumen membrane with aluminium sheet were placed in the control environment approximately for 20 days before measurement process. Relative humidity of the environment was constant around 50%).
- 2) The thickness of the samples was checked if it agrees with the manufacture's value.
- 3) Saturated salt solutions were prepared. The solution $\text{Na}_2\text{Cr}_2\text{O}_7$ was placed into a bowl inside of the glass container and the solution of $(\text{NH}_4)_2\text{H}_2\text{PO}_4$ was carefully poured into the aluminium cup.
- 4) Then the samples were placed into the cup mouths and properly sealed by butyl mastic. The cup with the solution and with the sample was weighed, its weight was registered and then it was placed into the glass container.
- 5) Data-loggers were switched on and also placed into the glass container.

3.1.5.2.2 Measurement Process

Regular weighing of the cups with samples

The cups with samples were weighed in the regular time period. The time period lasted from two till five days.

During weighing, the cup was removed from the glass container (control environment), placed onto the scale, its weight was registered and then it was placed back into the glass container. The time period, when the cup with the sample was out of the control environment, should be as short as possible. This period lasted around one minute.

Steady state

The steady-state occurs when the four or five weighings show a constant decrease of the mass. Constant decrease of the mass was recognised from the graph where the change of the mass per time was plotted. (Deviation from the average value from all the same samples had to be lower than 15%).

Perforation of the samples

When the steady-state was reached each sample was punctured by a sharp pin. The sharp pin with diameter of 0.68mm was used for foil samples. Bitumen samples were punctured by the same sharp pin but no change in the mass was observed. Later, a hot pin with diameter of 1.26mm had to be used only to puncture bitumen samples so that the sealing system of the cup was not destroyed. The sample remained sealed in the mouth of the cup during puncturing. The samples were punctured step by step after the steady-state occurred with 1, 3, 6, 12 and 24 holes. The pinholes were evenly positioned over the surface of the samples.

3.1.5.2.3 Evaluation of the Results

Measurement protocols

Measurement protocol was written about each product. The following information can be found in the protocol:

- 1) Name of the product, number of the sample, thickness of the product.
- 2) Date and time of each measurement.
- 3) Weight of each sample.
- 4) Separation of periods with 0, 1, 3, 6, 12, 24 holes
- 5) Average temperature; average temperature was calculated as the average value from period between two weighings.
- 6) Average relative humidity; average relative humidity was calculated as the average value from period between two weighings.
- 7) Atmospheric pressure in time of weighing.

All measurement protocols with records of temperature and relative humidity during the measurement are placed in *Appendix A*.

Calculation of the perforated area

After water vapour permeability measurements finished, the area of holes in foil samples was measured by a microscope. The mean area for one pinhole was determined as 0,049mm² with standard deviation as 0,004mm². *Figure 3.13* shows examples of pinholes taken by the microscope. The area of pinholes in bitumen samples was calculated from diameter of the pin. In this case, the microscope could not be used because of a great thickness of samples.

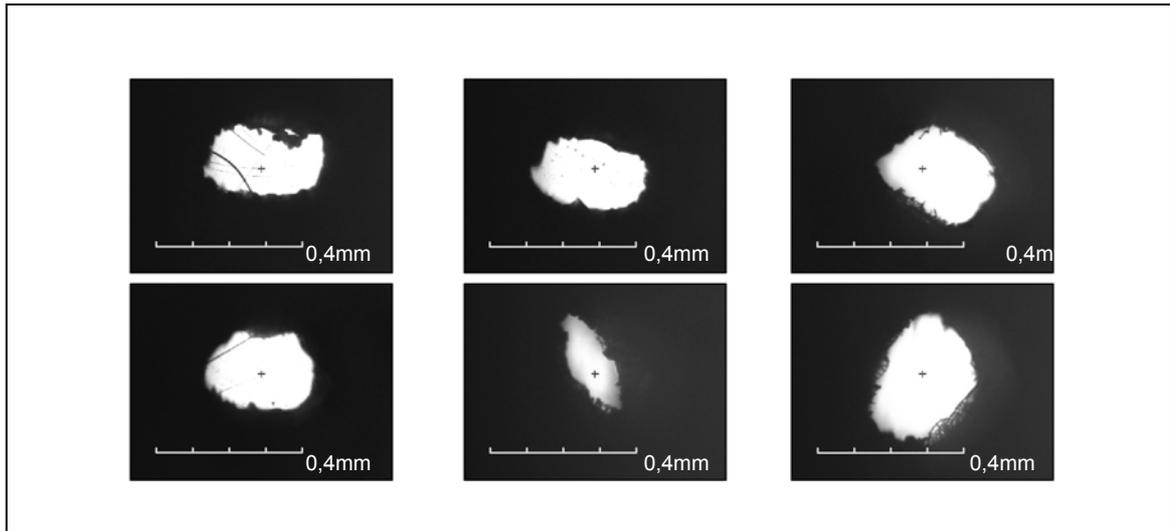


Figure 3.13. Photos of pinholes taken by a microscope

Calculation of the sd-value of samples

First, the water vapour resistance factor of the sample material was determined from equation (3.3).

$$\mu = \frac{\Delta t A \Delta p_v \delta_a}{\Delta m d} \quad (3.3)$$

where

Δt is the time difference between weighing with constant decrease of mass [s],

Δm is the mass difference between weighing with constant decrease of mass [kg],

A is the effective area of the sample [m²],

d is the thickness of the sample [m],

δ_a is the water vapour permeability of stagnant air [kg/(m.s.Pa)], calculated from the simplified Schirmer's equation taken from WTA 6-2-01 (2004),

$$\delta_a = \frac{1,97 \cdot 10^{-7} \cdot T^{0,81}}{P} \quad (3.4)$$

where

T is the absolute temperature [K],

P is the barometric pressure [Pa]; assumed constant at $P = 101325$ Pa.

The difference in water vapour partial pressure Δp_v on each side of the sample is calculated according to ČSN EN ISO 12572 (2002) from following equation,

$$\Delta p_v = \frac{\Delta RH}{100} \cdot 610,5 \cdot e^{\frac{17,269 \cdot \theta}{237,3 + \theta}} \quad (3.5)$$

where

ΔRH is the different relative humidity on each side of the sample [%] and

θ is the constant temperature during the measurement [°C].

The equation (3.5) is allowed to use only for temperature equal to or higher than zero degree Celsius ($\theta \geq 0$ °C).

The sd-value of the sample is then calculated using equation (5):

$$s_d = d \cdot \mu \quad (3.6)$$

where

s_d is the sd-value of the sample [m].

3.1.6 Results of the Measurements

In this section, results of water vapour permeability measurements of five products will be presented. Results of each product are in the separate section.

3.1.6.1 PE foil

PE foils samples were measured as the first. The blind test was not used in this case. The change of the mass per time for four samples is plotted on *Figure 3.14*. The final results as the sd-value, permeance (SI units) and permeance (IP units) with the standard deviation (SD) of perforated PE foil are presented in *Table 3.2*.

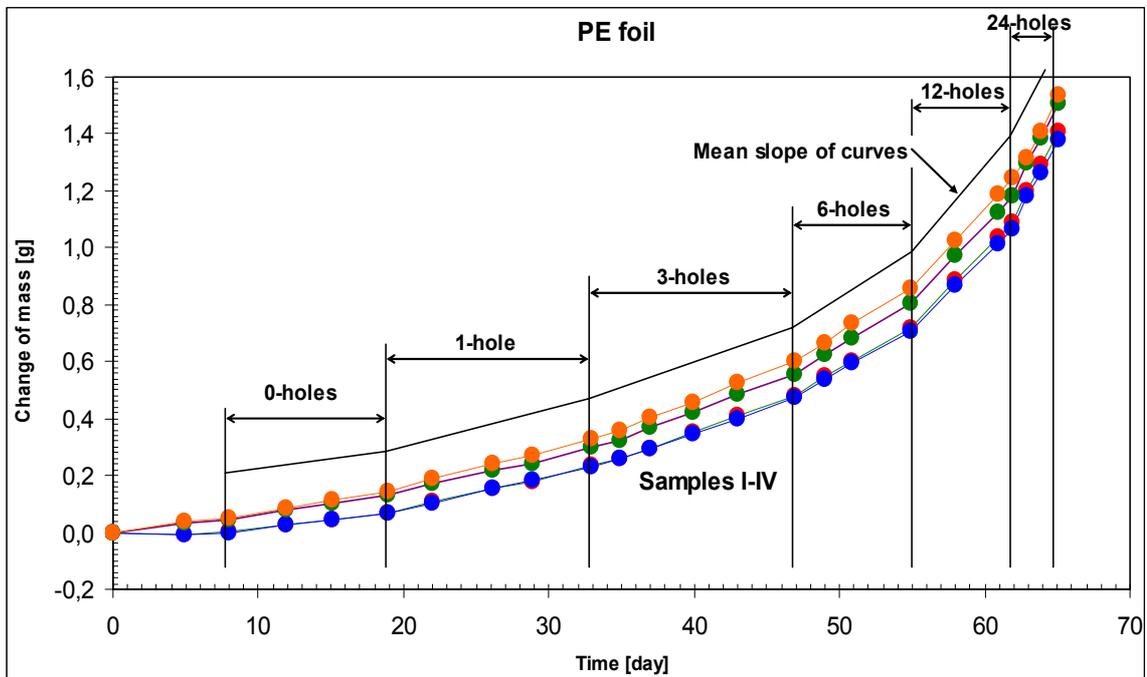


Figure 3.14. Change of mass for four PE foil samples (Mass decreases above zero and increases below zero)

3.1.6.2 LDPE foil

LDPE foils samples were measured together with one blind test. The change of the mass per time for three samples and one blind test is plotted on *Figure 3.15*. The final results as the sd-value, permeance (SI units) and permeance (IP units) with the standard deviation (SD) of perforated LD PE foil are presented in *Table 3.3*.

Table 3.2. Results of the measurements, sd-value [m], permeance [ng/(Pa·s·m²)] and permeance [perm (inch-pound)] of perforated PE foil

Product - PE foil						
percentage of perforation [%]	sd-value [m]		permeance [ng/(Pa·s·m ²)]		Permeance [perm IP] ^a	
	sample 1-4	mean (SD)	sample 1-4	mean (SD)	sample 1-4	mean (SD)
0,00000	101,8	86,0 (±14,8)	1,93	2,35 (±0,40)	0,0338	0,0410 (±0,0070)
	99,8		1,96		0,0343	
	72,9		2,68		0,0468	
	69,5		2,81		0,0492	
0,00016	47,5	47,4 (±2,0)	4,12	4,14 (±0,18)	0,0720	0,0724 (±0,0031)
	48,8		4,01		0,0700	
	49,1		4,00		0,0699	
	44,1		4,44		0,0776	
0,00047	31,5	30,5 (±1,5)	6,23	6,48 (±0,36)	0,1088	0,1132 (±0,0063)
	32,3		6,05		0,1057	
	29,8		6,67		0,1166	
	28,3		6,97		0,1218	
0,00094	21,2	20,3 (±0,8)	9,28	9,70 (±0,39)	0,1622	0,1695 (±0,0067)
	20,8		9,43		0,1648	
	20,0		9,81		0,1715	
	19,1		10,28		0,1796	
0,00187	12,7	12,5 (±0,3)	15,53	15,78 (±0,41)	0,2715	0,2759 (±0,0072)
	12,9		15,25		0,2666	
	12,2		16,10		0,2815	
	12,1		16,25		0,2841	
0,00374	6,7	6,7 (±0,1)	29,24	29,47 (±0,54)	0,5111	0,5152 (±0,0094)
	6,9		28,82		0,5038	
	6,7		29,55		0,5166	
	6,5		30,28		0,5294	

^apermeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h·ft²·in·Hg)] = 57,2 ng/(Pa·s·m²)

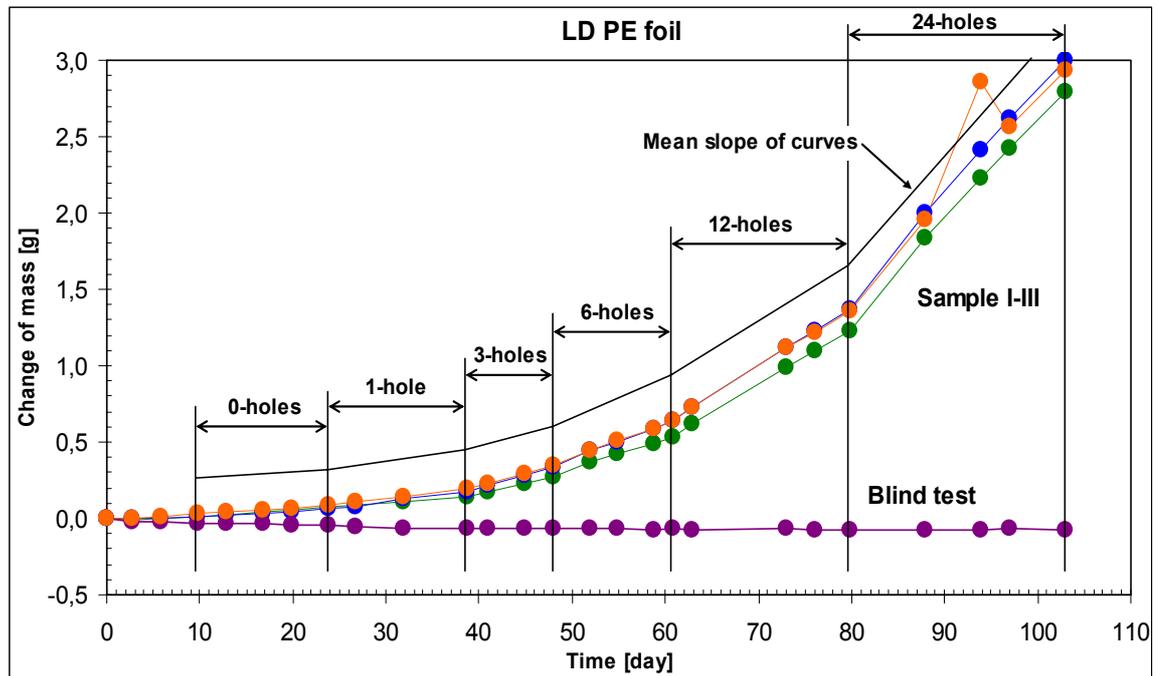


Figure 3.15. Change of mass for four LD PE foil samples (Mass decreases above zero and increases below zero)

Table 3.3. Results of the measurements, sd-value [m], permeance [ng/(Pa·s·m²)] and permeance [perm (inch-pound)] of perforated LD PE foil

Product - LD PE foil						
percentage of perforation [%]	sd-value [m]		permeance [ng/(Pa·s·m ²)]		Permeance [perm IP] ^a	
	sample 1-3	mean (SD)	sample 1-3	mean (SD)	sample 1-3	mean (SD)
0,00000	161,4	187,6 (±19,0)	1,23	1,09 (±0,10)	0,0214	0,0191 (±0,0017)
	205,8		1,04		0,0181	
	195,7		1,01		0,0177	
0,00016	-	109,2 (±0,9)	-	1,83 (±0,03)	-	0,0319 (±0,0005)
	108,3		1,85		0,0324	
	110,0		1,80		0,0315	
0,00047	54,7	49,1 (±4,1)	3,61	4,05 (±0,32)	0,0631	0,0708 (±0,0056)
	45,2		4,37		0,0764	
	47,4		4,17		0,0729	
0,00094	32,3	30,2 (±1,6)	6,07	6,51 (±0,32)	0,1061	0,1139 (±0,0056)
	28,7		6,82		0,1192	
	29,5		6,65		0,1162	
0,00187	16,8	16,1 (±0,5)	11,63	12,13 (±0,36)	0,2034	0,2121 (±0,0063)
	15,7		12,47		0,2180	
	15,9		12,29		0,2149	
0,00374	8,6	8,5 (±0,2)	22,67	23,01 (±0,45)	0,3964	0,4022 (±0,0079)
	8,2		23,64		0,4133	
	8,6		22,70		0,3969	

^apermeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h·ft²·in·Hg)] = 57,2 ng/(Pa·s·m²)

3.1.6.3 LD/HD PE foil

LD/HD PE foils samples were also measured together with one blind test. The change of the mass per time for three samples and one blind test is plotted on Figure 3.16. The final results as the sd-value, permeance (SI units) and permeance (IP units) with the standard deviation (SD) of perforated LD/HD PE foil are presented in Table 3.4.

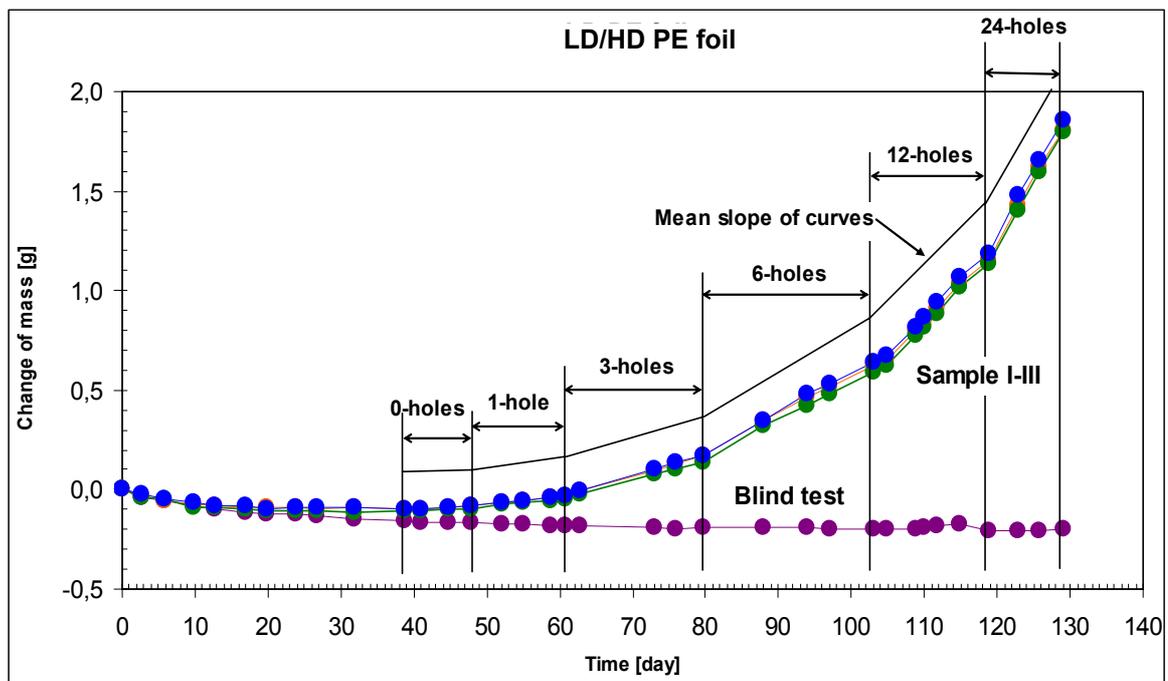


Figure 3.16. Change of the mass for four LD/HD PE foil samples (Mass decreases above zero and increases below zero)

Table 3.4. Results of the measurements, sd-value [m], permeance [ng/(Pa·s·m²)] and permeance [perm (inch-pound)] of perforated LD/HD PE foil

Product - LD/HD PE foil						
percentage of perforation [%]	sd-value [m]		permeance [ng/(Pa·s·m ²)]		Permeance [perm IP] ^a	
	sample 1-3	mean (SD)	sample 1-3	mean (SD)	sample 1-3	mean (SD)
0,00000	571,6	661,9 (±107,7)	0,35	0,31 (±0,05)	0,0060	0,0053 (±0,0008)
	813,2		0,24		0,0042	
	601,0		0,33		0,0057	
0,00016	173,4	192,4 (±13,6)	1,13	1,06 (±0,05)	0,0197	0,0186 (±0,0009)
	204,4		1,00		0,0175	
	199,3		1,05		0,0184	
0,00047	56,3	57,5 (±2,7)	3,46	3,41 (±0,15)	0,0605	0,0595 (±0,0026)
	55,0		3,55		0,0621	
	61,2		3,20		0,0560	
0,00094	30,9	30,4 (±0,5)	6,35	6,45 (±0,12)	0,1110	0,1128 (±0,0021)
	29,6		6,62		0,1157	
	30,6		6,38		0,1116	
0,00187	14,5	13,9 (±0,4)	13,45	14,05 (±0,48)	0,2352	0,2456 (±0,0083)
	13,4		14,62		0,2556	
	13,9		14,07		0,2460	
0,00374	7,9	7,8 (±0,1)	24,50	24,74 (±0,17)	0,4283	0,4324 (±0,0029)
	7,8		24,87		0,4349	
	7,8		24,83		0,4341	

^apermeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h·ft²·in·Hg)] = 57,2 ng/(Pa·s·m²)

3.1.6.4 Bitumen membrane

Bitumen samples were measured without any blind test. The change of the mass per time for four samples is plotted on *Figure 3.17*. The final results as the sd-value, permeance (SI units) and permeance (IP units) with the standard deviation (SD) of perforated bitumen samples are presented in *Table 3.5*. It must be mentioned that in this case, the area of perforation was calculated from the diameter of the pin.

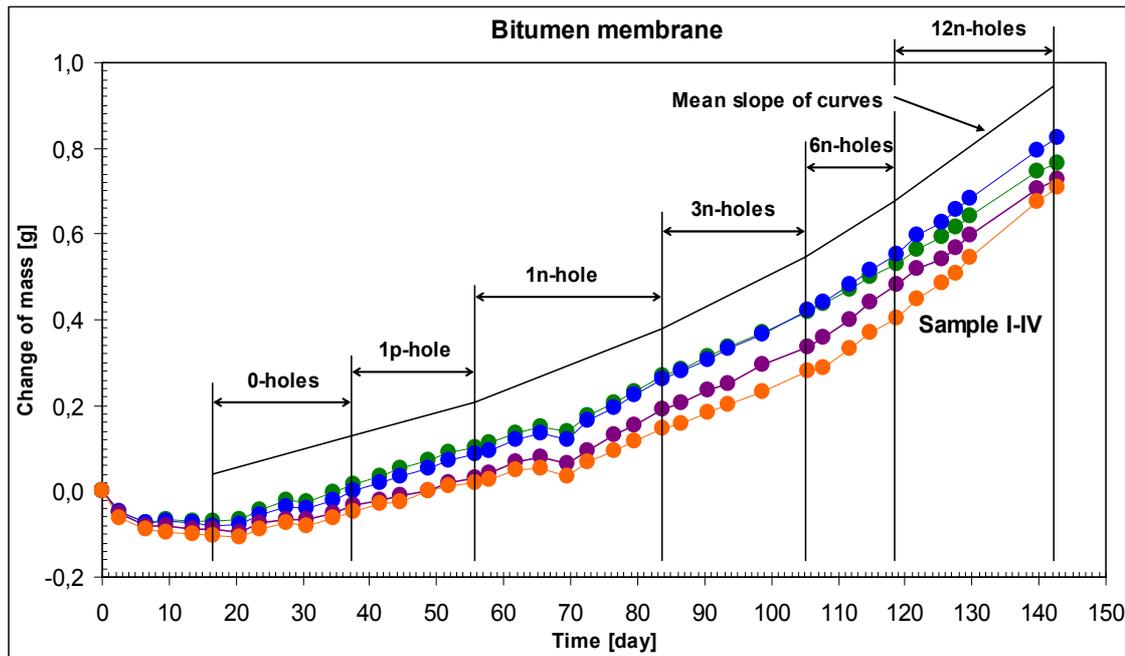


Figure 3.17. Change of the mass for four LD/HD PE foil samples; Mass decreases above zero and increases below zero. (Legend: p – pin with diameter 0,68mm; n-pin with diameter 1,26mm)

Table 3.5. Results of the measurements, sd-value [m], permeance [ng/(Pa·s·m²)] and permeance [perm (inch-pound)] of perforated bitumen membrane

Product - bitumen membrane						
percentage of perforation [%] ^a	sd-value [m]		permeance [ng/(Pa·s·m ²)]		Permeance [perm IP] ^a	
	sample 1-4	mean (SD)	sample 1-4	mean (SD)	sample 1-4	mean (SD)
0,0000	111,6	137,1 (±21,8)	1,81	1,58 (±0,18)	0,0317	0,0276 (±0,0032)
	122,2					
	167,8					
	146,7					
0,0012	172,3	181,9 (±26,9)	1,15	1,11 (±0,15)	0,0201	0,0195 (±0,0026)
	152,3					
	225,6					
	177,2					
0,0040	138,2	144,0 (±4,3)	1,51	1,46 (±0,06)	0,0264	0,0255 (±0,0010)
	142,0					
	145,8					
	149,9					
0,0079	83,8	84,4 (±6,9)	2,43	2,41 (±0,19)	0,0425	0,0421 (±0,0033)
	77,9					
	80,2					
	95,7					
0,0119	86,9	89,8 (±5,9)	2,29	2,24 (±0,14)	0,0401	0,0392 (±0,0025)
	81,5					
	94,0					
	96,6					
0,0238	71,0	64,4 (±7,7)	2,79	3,21 (±0,36)	0,0488	0,0562 (±0,0062)
	62,2					
	52,7					
	71,7					
0,0476	43,5	41,4 (±1,3)	4,50	4,78 (±0,19)	0,0787	0,0836 (±0,0032)
	40,9					
	40,0					
	41,4					

^athe area of perforation is calculated from diameter of pins

^bpermeance in [perm (inch-pound)] was calculated as 1 perm [grains/(h·ft²·in·Hg)] = 57,2 ng/(Pa·s·m²)

3.1.6.5 Bitumen membrane with aluminium sheet

Bitumen membrane with aluminium sheet was measured as the last one. Four samples were measured together with one blind test. The change of the mass per time for three samples and one blind test is plotted on *Figure 3.18*. The equilibrium water vapour flux through the samples could not be determined therefore the measurement was stopped after 100 days.

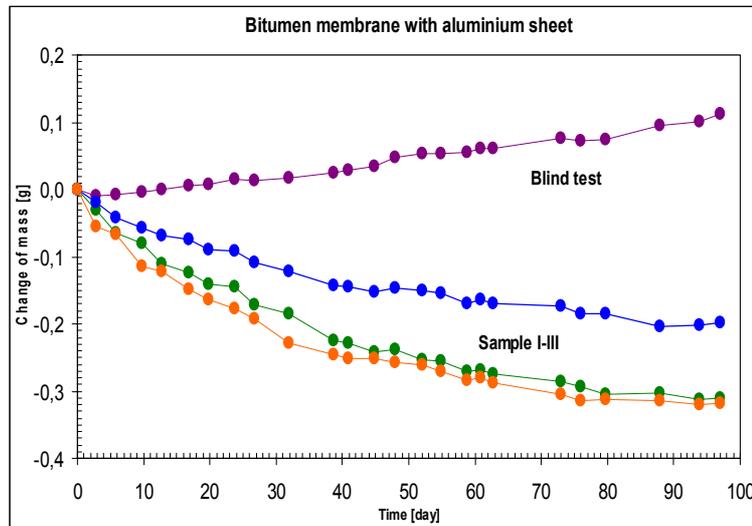


Figure 3.18. Change of the mass for three samples and one blind test (Mass decreases above zero and increases below zero)

3.1.7 Uncertainties of the Measurements and Discussion

The first part of this section focuses on possible uncertainties of the measurements. Interesting findings will be discussed in the second part of this section.

3.1.7.1 Uncertainties of the Measurements

Uncertainties of the measurements can be devaded in several points according to Bomberg et al. (2002) or see *Chapter 2.3.1.1.5* in the Thesis. These points are:

1) Technique and materials used for sealing the specimen

Blind tests, which were employed during the measurements, confirmed the good sealing qualities of butyl mastic. Three blind tests were used with samples of LD and LD/HD PE foils and with bitumen membrane with aluminium sheet. These blind tests ran at the same time period in two glass containers and showed different changes in mass. During a period of 105 days two blind tests showed increases in mass of 0,07g and 0,20g and the third blind test decreased in mass by 0,11g. This difference occurred mainly at the beginning of the measurement, *Figure 3.19*. If we look at period between 40th and 105th day, differences in the mass are 0,001g, 0,037g and minus 0,077g.

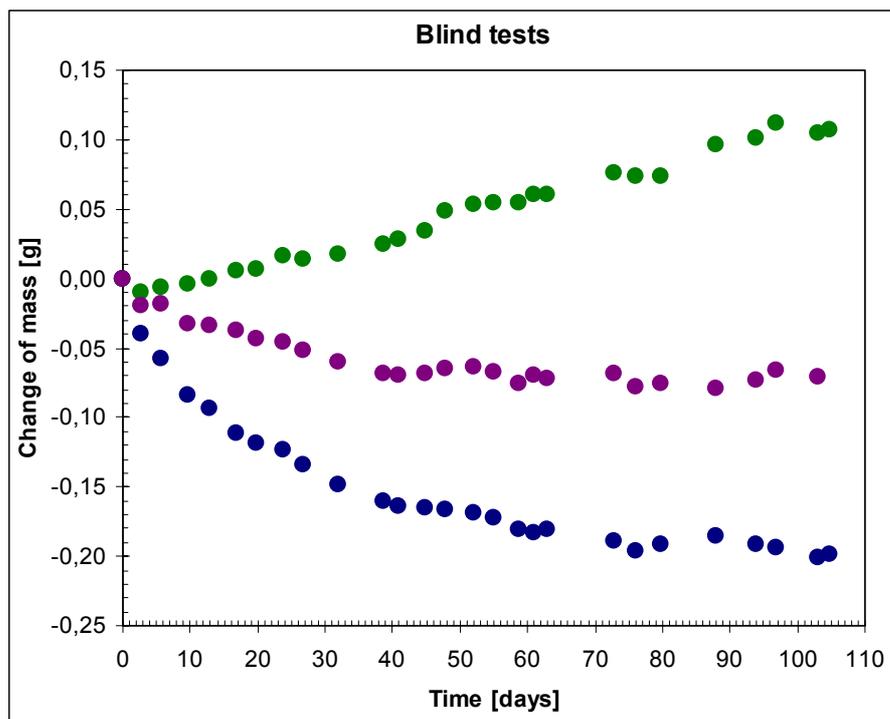


Figure 3.19. Change of mass for three blind tests ran in the same time period (Mass decreases above zero and increases below zero)

I assumed that the negative difference might be caused by leakage and two positive differences could be caused by dirt on the surface of aluminium sheets because they had been used before for testing different sealing materials and although the sheets were cleaned, some small amount of a sealing material (bee's wax) could have remained on the surface. Due to this difference and because the blind test was not used with each product measurement, equation (3.2) was not employed for final sd-values. If we apply equation (3.2), for example, for the LD PE foil, the results will vary mainly for no perforated samples or samples with a small percentage of perforation as can be seen in *Table 3.6*.

Table 3.6. Example of applying the blind test correction due to equation (3.2), sd-values of perforated LD PE foil with and without the correction and relative differences of the results

percentage of perforation [%]	sd-value [m]		sd-value [m]		relative differences [%]
	without the correction		with the correction		
	mean	standard deviation	mean	standard deviation	
0,00000	187,6	±19,0	168,0	±15,6	11,7
0,00016	109,2	±0,9	90,0	±0,7	21,3
0,00047	49,1	±4,1	49,5	±4,2	0,8
0,00094	30,2	±1,6	30,1	±1,5	0,3
0,00187	16,1	±0,5	15,8	±0,5	1,9
0,00374	8,5	±0,2	8,5	±0,1	0,0

According to my experience with water vapour permeability measurements of materials with a high diffusion resistance, I strongly recommend to use the blind tests simultaneously with regular samples and apply equation (3.2) to eliminate the uncertainties of bad sealant and the buoyancy effect.

2) The difference between the area of the surface exposed to vapour transport and the total area of the cross section - Edge mask effect

The edge mask effect correction was not employed because this effect plays an important role only for thick samples where multidimensional water vapour flux occurs as can be seen in Joy & Wilson (1963). Then the edge mask effect can be neglected in this case.

3) Assessment of time to establish steady state conditions

It can be quite difficult to assess a steady state for material with a high diffusion resistance as can be seen in Time & Uvsløkk (2003).

It was impossible to assess the steady state for bitumen membrane samples with aluminium sheet during a time period of 100 days. That was the reason why these measurements were stopped. Only four points in a straight line were used to assess the steady state for LD/HD PE foil samples due to lack of time which caused a great standard deviation for these results. The mean sd-value is 661,9m with standard deviation ±107,7m, see Table 3.4. Proper assessment of steady state can have influence on the results of products with a high diffusion resistance and without any perforation. The influence on results of products with perforation is small and it can be neglected. Blind test and suggested equation (3.2) can help to assess properly the steady state for products with a high diffusion resistance.

4) Period and frequency of data collection

The data were collected every third or fourth day. This long time period has small influence on the results.

5) Thickness of samples

Thickness of samples was checked and it was in an agreement with manufacture values.

6) Corrections for resistances due to still air and specimen surfaces

Corrections for water vapour resistances due to still air and the sample surfaces are insignificant in cases where the sd-value of materials is higher than 1,74m or permeance is lower than 114 ng/(Pa·m²·s) (2 perm inch-pound) according to ASTM E 96/E 96M (2005). Slightly different values are in Lackey et al. (1997). As the sd-values of the samples were

much higher than these values, corrections for resistances due to still air and specimen surfaces were neglected.

7) Loss or gain of vapour from the volume of the still air during the weighing process (when containers are open)

Diffusion properties of samples are calculated from water vapour flow. The water vapour flow is caused due to different conditions (relative humidity) on the sample sides. If the conditions are changed the water vapour flow will differ and diffusion properties of a product can be wrongly calculated. *Figure 3.20* presents relative humidity that was measured inside the glass container during the measurement of PE foil samples. Relative humidity is almost constant except for peaks where the container was opened. The detail of one highlighted peak is plotted on *Figure 3.21*. This figure points that relative humidity returns to constant level after 2 hours. The time period between two weightings was three or four days. The time period, when relative humidity dropped, appears to be very short and the influence on final results is insignificant.

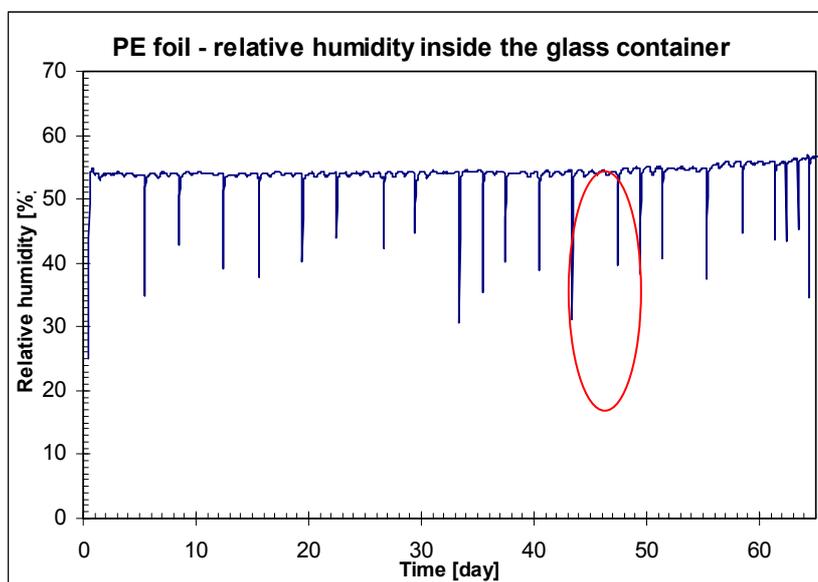


Figure 3.20. Relative humidity inside the glass container during the measurement of PE foil samples

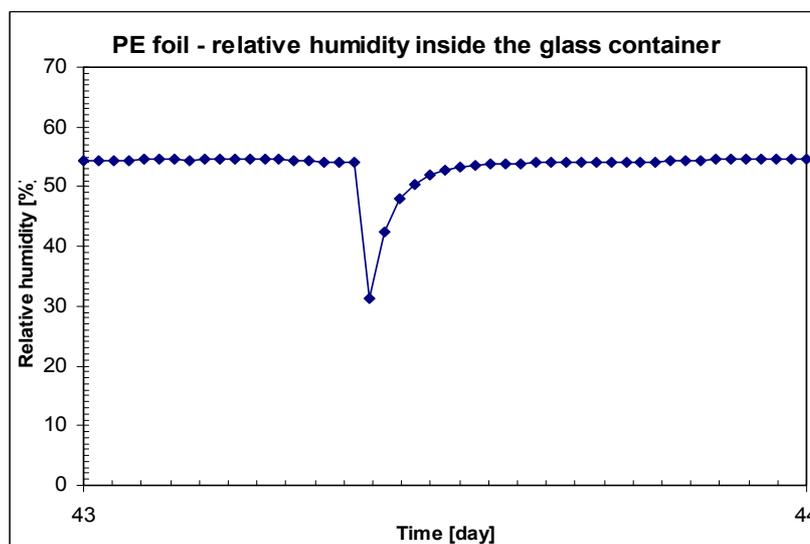


Figure 3.21. Detail of relative humidity inside the glass container during 43rd day of the measurement

8) Change in relative humidity inside cups can affect the results

Relative humidity inside cups was checked only ones. The monitoring system showed constant relative humidity of 95% but after 5 days the system collapsed due to a high relative humidity. Other measurement of relative humidity inside cups was not done. The constant level of relative humidity of 95% inside cups was assumed for all measurement according to Galbraith et al. (1998). This assumption can have some influence on the final results.

9) Change in the rate of vapour diffusion cause by a change in barometric pressure – buoyancy correction

Varying atmospheric pressure affects all gravimetric data and the buoyancy correction equation (2.44) should be applied McGlashan (1971). This correction was not taken into account because the blind test eliminates the buoyancy effect. Differences in the results due to applying the blind test can be seen in *Table 3.6*.

10) Changes in the water vapour diffusion flux caused by the contribution of flow in the liquid phase

To separate and to measure pure water vapour flow and pure water liquid flow in building materials is a big challenge for scientists. One example can be found in Derome et al. (2008). The results of the measurements probably consist of the both flows – liquid and vapour. More details can be found in *Chapter 2.2.2 Moisture transport mechanisms*.

11) Changes in material structure cause by changes in temperature and moisture adsorption

Changes in temperature and moisture adsorption affected diffusion properties of products only at the beginning of the time period of the measurements. Initial time stage of the measurement was not taken into the final results.

12) Differences in perforation area

The area of pinholes (foil samples) was calculated from the average measured value for one pinhole. The measurement of the area was made after water vapour permeability measurements finished, with the help of a microscope. The influence on the results will be almost insignificant.

The area of pinholes in bitumen samples was calculated from the diameter of the pin. In this case, the microscope could not be used because of a great thickness of samples. The influence on results will be much higher than in the previous paragraph because in the case of foil samples, the real area of one pinhole was ten times smaller than the area calculated from diameter of the pin.

3.1.7.2 Discussion

The results of the measurement on materials with a high water vapour resistance factor show a significant decrease in sd-values with increased perforation percentage. The decrease in the sd-value is greater for materials with higher value of the water vapour resistance factor. This result is in accordance with the measurements done by Bauer (1965).

I found very interesting that sd-values for the foils do not depend on the material for the percentage of perforation higher than 0,002%; all three vapour retarders (PE, LDPE, and LD/HD PE foils) have almost the same sd-value as shown in *Figure 3.22*. On the figure, a

crossing of curves (LD PE foil and LD/HD foil) can be seen. The crossing is probably due to difference in the area of pinholes. The area of pinholes (foil samples) was calculated from the average measured value for one pinhole but the area of perforation can slightly vary for each sample and each level of percentage of its perforation.

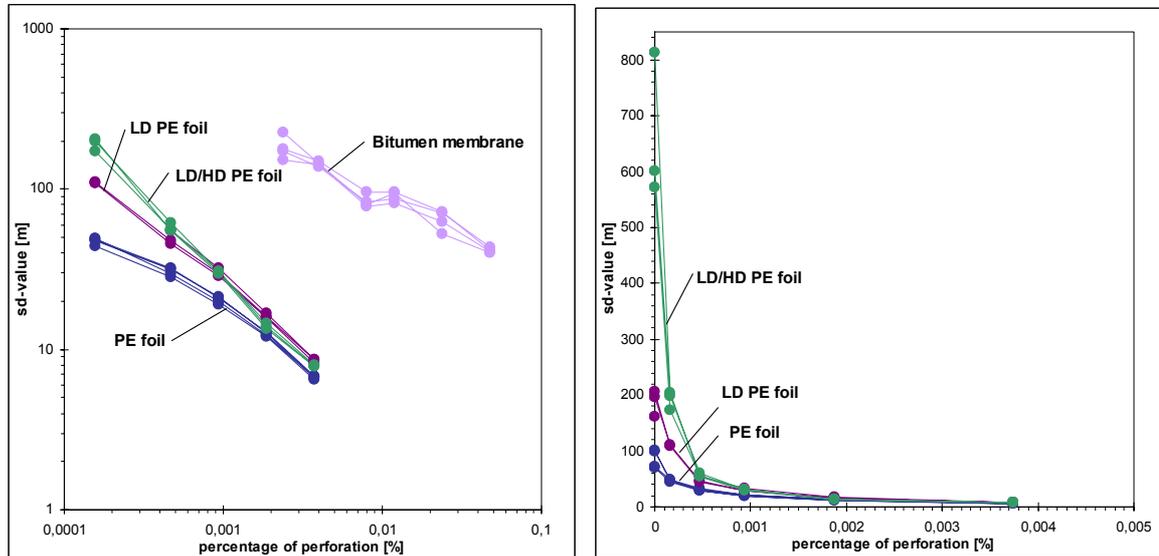


Figure 3.22. Left – Results of the measurements in logarithmic scale; Right – Results of the measurements in regular scale

The decrease in the sd-value is higher for foil membranes than for bitumen membrane. I assume that this is due to the contraction of the pinholes after perforation, because the water vapour transport does not change for bitumen samples after those samples were punctured by one pin with diameter 0,68mm. Other measurements are needed. Higher adsorption of moisture was observed in the bitumen membranes compared to foil vapour retarders. The contraction of the pinholes, the calculation of the percentage of perforation from the diameter of the pin, and the adsorption of moisture might cause that curve shape of bitumen samples varies from the curves of foil products.

The experimental results indicate that the experimental apparatus provides very accurate measurements up to the sd-value of 200m, over which the results vary more than 10% within each product. I was not able to determine the sd-value of bitumen membrane with aluminium sheet because the membrane was adsorbing more moisture than the amount of moisture being released through the samples during time period of 100 days. Then the measurements were stopped.

However, the results of the measurements were done for products where air is on both sides of samples. Usually in roof assemblies, vapour retarder is placed between two other layers. Material of these layers has higher diffusion resistance than still air and therefore the impact of perforation will be reduced according to Schule & Reichardt (1980). On the other hand, if a movement of air occurs in the roof assembly, the water vapour transport will be higher than the transport due to diffusion and the impact of perforation will play more significant role.

3.1.8 Conclusion

In the first part of this chapter, I described some problems with simulations of moisture transport in building envelopes and what diffusion bridges are. Uncertainties in similar previous measurements and different recommendations, how perforations affect diffusion properties of vapour retarders, were discussed in details. This discussion led to my decision to do own experimental measurement of diffusion properties of perforated vapour retarders.

In the second part, a detailed description of developed unique experimental apparatus for the water vapour permeability measurement was provided. The advantages of the apparatus and suggestions how to measure products with a high diffusion resistance were outlined. The main improvements of the apparatus from available studies are:

- 1) During the measurement, the blind test should be employed, as it eliminate the influence of varying atmospheric pressure on the final results and reduce possibility of leakage through a sealant.
- 2) Several sealing materials (bee's wax, silicon, bitumen and butyl mastic) were tested. Testing with the help of blind tests showed that butyl mastic is the best sealant for the experimental measurement in which products with a high diffusion resistance are measured.

Diffusion properties of five vapour retarders with a different level of perforation were measured. I was not able to measure the sd-value of the bitumen membrane with aluminium sheet. The results of four products show significant increases of vapour transport through vapour retarders due to its perforation. The percentage of perforation was much smaller, and sd-values higher than in previous known studies. The results of the measurement proved that perforation of vapour retarders or diffusion bridges must be taken into account when hygrothermal behaviour of building envelope assemblies is simulated.

Final results indicate that the experimental apparatus provides very accurate measurements up to the sd-value of 200m, over which the results vary more than 10% within each product.

3.2 Analytical Expression of the Results

The previous subchapter presents results of the experimental measurement. This subchapter will be focus on the general analytical expression of these results.

3.2.1 Reasons to Create Analytical Model

The measurements were performed only for four different membrane products with percentage of the perforation going from 0,00016% to 0,0037% (foil samples). In the cases of other products or a wider range of the perforation, a simple mathematical equation is needed. Nowadays, the diffusion properties of perforated thin products have to be determined only by an experimental measurement. The simple mathematical equation will help to determine diffusion properties of any thin layer with different percentage of perforation.

In literature, only a few attempts can be found. For example in Spoel (2003), the analytical solution expresses effective μ -value for a perforated foil between two nearby layers. The final equation describes the following example that is plotted on *Figure 3.23*.

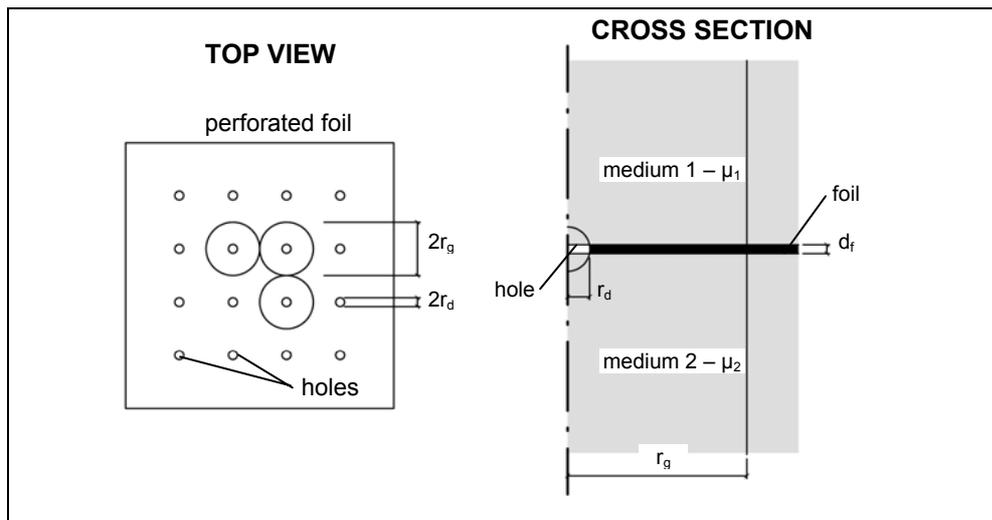


Figure 3.23. Schema of Spoel's solution; Left-Top view of regular redistribution of holes, Right –Cross section of foil between two other materials, Spoel(2003)

The final equation is created as cylindrical problem domain. The author's simplified solution can be written as

$$\mu_{per} d_f = \frac{r_d^2}{r_g} \left(\frac{5\mu_1}{6} + \frac{5\mu_2}{6} + \frac{\mu_g d_f}{r_g} \right) \quad (3.7)$$

where

- μ_{per} is the water vapour diffusion factor of the perforated foil [-],
- μ_g is the water vapour diffusion factor of the pinhole [-],
- μ_1 is the water vapour diffusion factor of a underlay material [-],
- μ_2 is the water vapour diffusion factor of an upper lay material [-],

- d_f is the thickness of the foil [m],
- r_g is the radius of the pinhole [m], and
- r_d is a half distance of nearby holes [m].

The disadvantages of this model are:

- 1) The model assumed that holes are regularly placed in a thin foil.
- 2) The material constant for pinholes is unknown (the author assumed $\mu_g = 1$)
- 3) The equation is complicated for common use.

Otherwise, the simple equation has been used for thin low permeable products (steel rib decks) with joints in Mrlik (1985) or in Mrlik(1986). *Figure 3.24* describes Mrlik's solution.

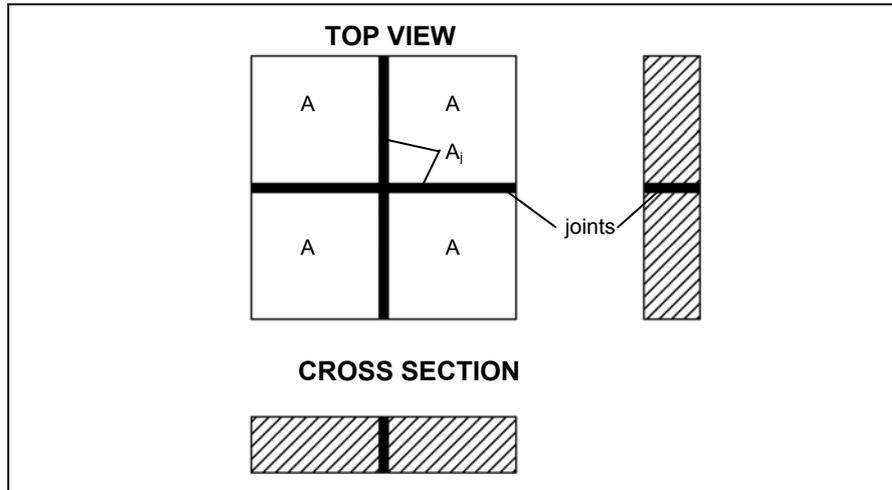


Figure 3.24. Mrlik's schema of compound composite

The analytical equation is written as parallel circuit of diffusion resistances,

$$\frac{A_{tot}}{Z_{ekv}} = \frac{A}{Z} + \frac{A_j}{Z_j} \quad (3.8)$$

where

$$A_{tot} = A + A_j \quad (3.9)$$

- A_{tot} is the total area of the layer (product) [m²],
- A is the area of the homogeneous layer [m²],
- A_j is the area of a joint [m²],
- Z_{ekv} is the equivalent diffusion resistances for the layer with the joint [m/s],
- Z is the diffusion resistance for the homogeneous layer [m/s], and
- Z_j is the diffusion resistance for the joint [m/s].

The Mrlik's model has these disadvantages:

- 1) The model is designed for joints not holes.
- 2) The diffusion resistance for joints Z_j has to be experimentally measured for each product and a type of joints (open or sealed).
- 3) The equation is applied only for single layer systems.

I decided to create an analytical model that would describe the results of experimental measurements and that could be quickly applied in the cases where vapour retarder is

perforated. The model should be applied without any experimental measurement that will assess material constant for perforated products.

3.2.2 Analytical Model of Measured Results

As I wanted to express the sd-value of perforated products with low permeance with the help of the simple equation, I plotted all experimental results with results from the previous measurements (Seiffert (1960), Bauer (1965)) into a logarithmic graph *Figure 3.25* to see if there is some relationship between the experimental curves.

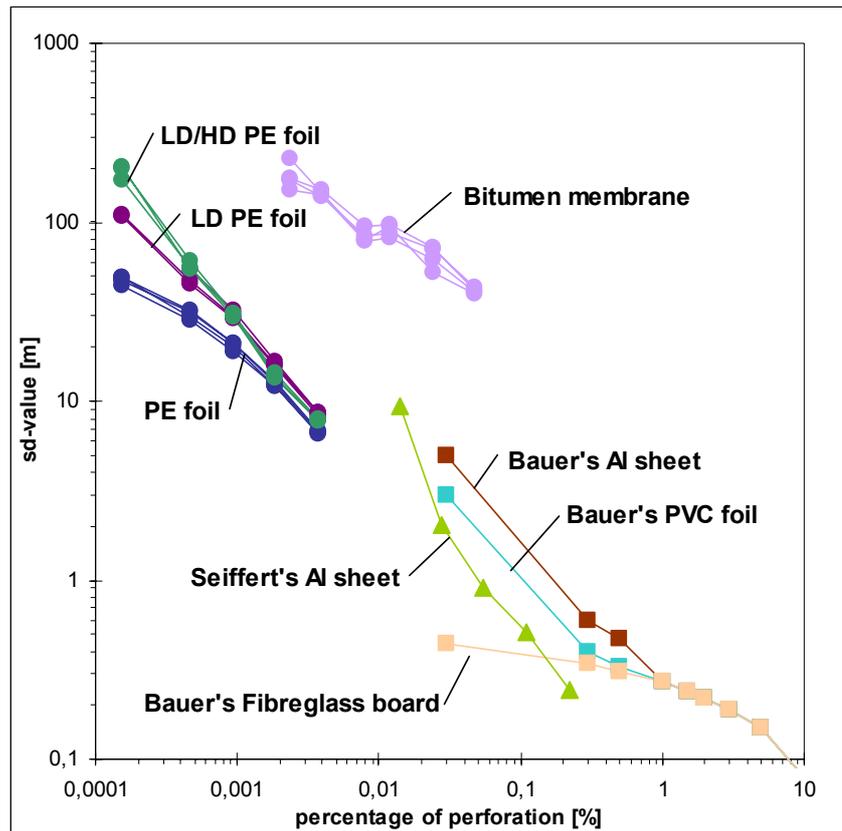


Figure 3.25. Comparison of the experimental results and Bauer's and Seiffert's results

Figure 3.25 shows that three foils (PE, LD PE and LD/HD PE foil) have the same curve pattern in contrast to the curves made by bitumen membranes. The curves of Bauer's measurements (aluminium sheet and PVC foil) have very similar pattern like the foil curves only a little moved to the right. Seiffert's aluminium sheet has also the same pattern like foils only without the first measured point.

I tried to outline the curve pattern in *Figure 3.26*. The functions f_1 to f_4 belong to four fictional products that have sd-values without any perforation s_{d1} to s_{d4} . The function f_t stands for an impermeable product, for example aluminium sheet.

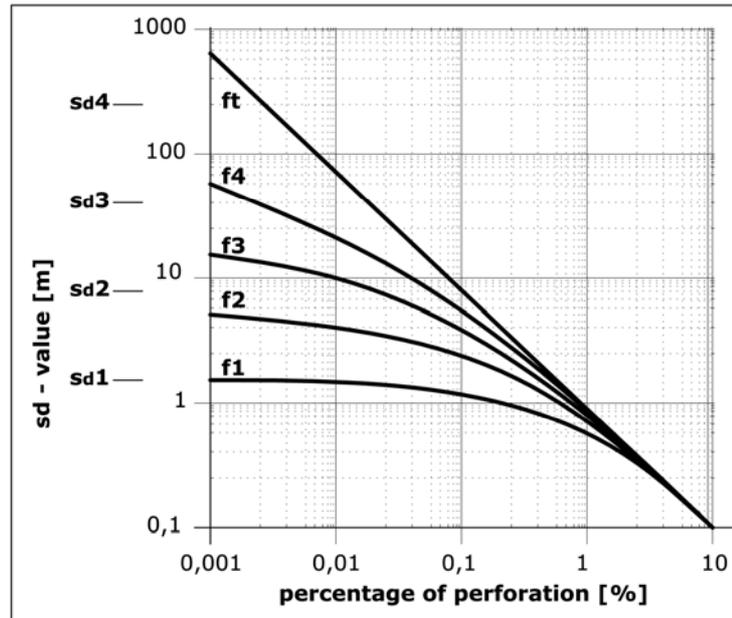


Figure 3.26. Dependence of the s_d -value on percentage of perforation. Curve patterns for five fictional products $f1$ - $f4$ with percentage of perforation 0,001-10%

The explanation of the functions that are sketched on Figure 3.26 can be written as follow:

$$\frac{1}{s_{df}} = \frac{1 - \frac{A_p}{A_{tot}}}{s_d} + \frac{\frac{A_p}{A_{tot}}}{s_{da}} \quad (3.10)$$

where

- s_{df} is the final s_d -value for perforated product in [m],
- s_d is the s_d -value of the product without any perforation in [m],
- s_{da} is the s_d -value for holes (perforation) in [m],
- A_p is the perforated area [m²], and
- A_{tot} is the total area in [m²].

The fraction of areas can be expressed as the area factor, i.e.

$$f_{Ap} = \frac{A_p}{A_{tot}} \quad (3.11)$$

where

- f_{Ap} is the area factor [-].

If we employ equation (3.11) into (3.10) and modify equation (3.10), we will get the following relationship

$$s_{df} = \frac{1}{\frac{1 - f_{Ap}}{s_d} + \frac{f_{Ap}}{s_{da}}} \quad (3.12)$$

In equation (3.12), which is an alternative expression of equation (3.8), the unknown is the s_d -value of the perforated area s_{da} [m]. I determined this coefficient by least square regression with experimental results of measurements (only foils) and I got

$$s_{da} = 0.000292 \text{ m} \quad (3.13)$$

If we substitute equation (3.13) into (3.12) and compare this with the results of the measurements, the mean square correlation coefficient will be $r^2 = 0.98$ for all ten foil samples and $r^2 = 0.99$ for eight foil samples if we exclude two samples of PE foil with higher sd-values. The comparison between measured results and calculated results are presented in *Table 3.7* to *Table 3.9*.

Table 3.7. Comparison between measured and calculated results for PE foil

Product – PE foil – measurement vs. calculation								
percentage of perforation [%]	sd-value [m]							
	Sample 1		Sample 2		Sample 3		Sample 4	
	measured	calculated	measured	calculated	measured	calculated	measured	calculated
0,00000	101,80	101,80	99,79	99,79	72,92	72,92	69,54	69,54
0,00016	47,47	65,98	48,83	65,13	49,14	52,50	44,11	50,73
0,00047	31,46	38,73	32,29	38,43	29,78	33,66	28,35	32,92
0,00094	21,20	23,91	20,80	23,80	19,99	21,88	19,09	21,56
0,00187	12,65	13,55	12,89	13,51	12,20	12,87	12,09	12,76
0,00374	6,73	7,26	6,85	7,25	6,70	7,06	6,50	7,02
r² [-]	0,934		0,947		0,990		0,974	

Table 3.8. Comparison between measured and calculated results for LD PE foil

Product – LD PE foil – measured vs. calculation						
percentage of perforation [%]	sd-value [m]					
	Sample 1		Sample 2		Sample 3	
	measured	calculated	measured	calculated	measured	calculated
0,00000	161,42	161,42	205,75	205,75	195,72	195,72
0,00016	-	86,75	108,30	98,11	110,02	95,76
0,00047	54,68	45,06	45,18	47,94	47,38	47,37
0,00094	32,34	26,18	28,68	27,13	29,48	26,95
0,00187	16,77	14,25	15,66	14,52	15,94	14,47
0,00374	8,59	7,45	8,24	7,53	8,58	7,51
r² [-]	0,991		0,996		0,992	

Table 3.9. Comparison between measured and calculated results for LD/HD PE foil

Product – LD/HD PE foil – measured vs. calculation						
percentage of perforation [%]	sd-value [m]					
	Sample 1		Sample 2		Sample 3	
	measured	calculated	measured	calculated	measured	calculated
0,00000	571,57	571,57	813,23	813,23	600,98	600,98
0,00016	173,40	141,19	204,44	152,38	199,35	142,92
0,00047	56,34	56,34	55,00	58,04	61,18	56,62
0,00094	30,87	29,63	29,63	30,10	30,58	29,71
0,00187	14,48	15,21	13,41	15,33	13,88	15,23
0,00374	7,92	7,71	7,81	7,74	7,81	7,71
r² [-]	0,996		0,995		0,988	

The comparison of measurement results with equation (12) is shown on *Figure 3.27, left* with logarithmic scales and with regular scale on *Figure 3.27, right*.

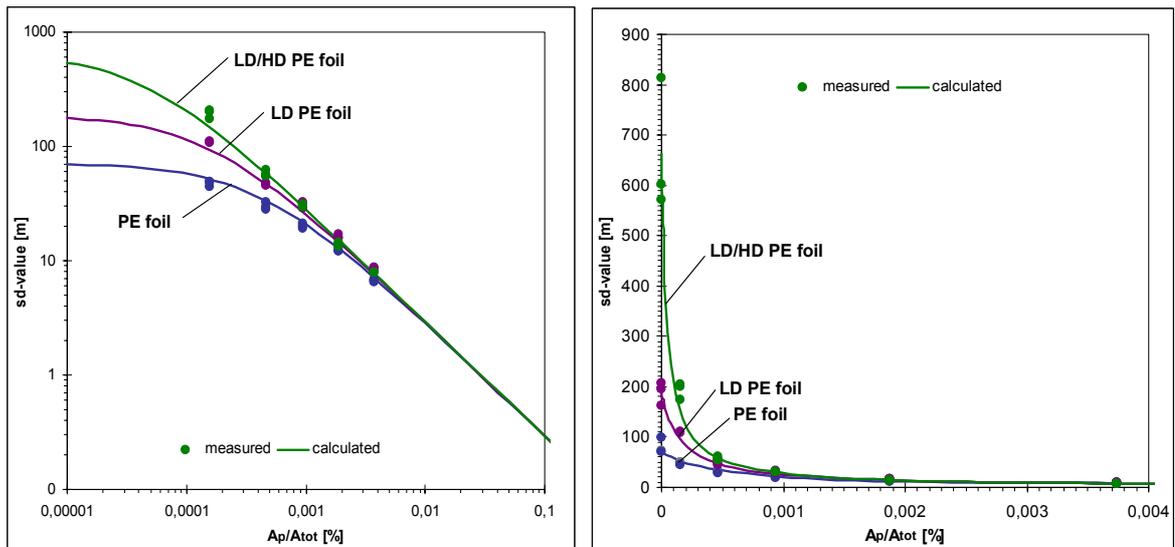


Figure 3.27. Comparison of measurement results with calculation; Left-logarithmic scale; Right-regular scale

3.2.3 Comparison of the Model with Other Measurement Results

The previous section showed that the results from experimental measurements fit very well to the analytical model. In this section, I will discuss how the model fits with other experimental measurement results of perforated products with high diffusion resistance.

The analytical model can only be compared with experimental results of Bauer (1965) because other results do not include all information, e.g. results of Seiffert (1960) do not include the sd-value of non-perforated aluminium sheet and results of Mrlik (1986) were calculated with percentage of perforation that includes diameter of nails.

The comparison of Bauer’s experimental results and results calculated with the help of the analytical model can be seen in *Table 3.10*.

Table 3.10. Comparison between Bauer’s results (Bauer 1965) and analytical model

percentage of perforation [%]	sd-value [m]			
	Aluminium sheet		PVC foil	
	measured	calculated	measured	calculated
0	54,00	54,00	14,24	14,24
0,03	5,00	0,96	3,00	0,91
0,3	0,60	0,10	0,40	0,10
0,5	0,47	0,06	0,33	0,06
1	0,27	0,03	0,27	0,03
1,5	0,24	0,02	0,24	0,02
2	0,22	0,01	0,22	0,01
3	0,19	0,01	0,19	0,01
5	0,15	0,01	0,15	0,01
10	0,08	0,00	0,08	0,00
r^2 [-]	0,993		0,973	

The comparison of Bauer's results and calculated results show also a quite good agreement, but with higher percentage of perforation the results vary in one decimal order. The differences are probably caused by diffusion resistances of air layers because the sd-value of experimental results includes these resistances but the analytical model does not. These air layers play an important role mainly for diffusion-opened products, e.g. Lackey et al. (1997).

3.2.4 Discussion and Conclusions

The analytical model showed a very good agreement with experimental results. Therefore the model can indicate how much moisture will be transported through perforated low-permeable thin layers such as aluminium sheets or membrane foils.

The analytical model showed a good agreement with results of Bauer's experimental measurement mainly for a low percentage of perforation. It is a pity that the model could not be compared with other measurement results because the other known results do not include all necessary information (e.g. percentage of perforation, the sd-value of a product with no perforation).

However, the analytical model was designed for products where air is on both sides of samples. Usually in roof assemblies, vapour retarder is placed between two other layers. Material of these layers has lower water vapour permeability than still air and therefore the impact of the penetration will be reduced according to Schule & Reichardt (1980). On the other hand, if a movement of air occurs in the roof assembly, the water vapour transport will be higher than the transport due to diffusion and the impact of the penetration will play more important role.

In cases, where only diffusion of water vapour occurs in a roof assembly, the Spoel's analytical equation (3.7) can be used with the material constant (3.13), which was determined by least square regression from experimental results, to evaluate moisture transport inside envelope assemblies with perforated low-permeable layers.

Chapter 4: Numerical Analysis

4.1 1D Numerical Simulations

The full title of this chapter should be “1D Numerical Simulations of Coupled Heat and Moisture transports in Compact Membrane Roof Assemblies”. This full title exactly expresses the subject of the chapter. 1D numerical simulations will be presented for several compact flat roof assemblies with the help of state-of-art numerical model. The results of the simulations should lead to efficient designs of compact flat roofs.

4.1.1 Reasons for the Numerical Simulations

Since 1930s, vapour retarders have been commonly used in membrane roof assemblies to control water vapour transport from the interior environment. The main reason is to prevent roof assemblies from excess moisture content that reduces the durability of materials, components and then the whole roof assembly. Vapour retarders are usually designed according to simple calculation methods, the Glaser methods or the Dew point method.

The Dew point method ASHRAE (1997), which is used in North America, and the Glaser methods, Glaser (1959), commonly used in Europe, are almost identical, TenWolde (2001). The Glaser methods (Glaser diagram) are described in several international technical standards, i.e. ČSN EN ISO 13788 (2002) or ČSN 730540-4 (2005).

Both methods have the following limitations according to ČSN EN ISO 13788 (2002) and TenWolde (2001):

- 1) Thermal conductivity does not depend on moisture and ice content in the material.
- 2) Water vapour permeability does not depend on relative humidity (moisture content).
- 3) All moisture mechanisms other than vapour diffusion are excluded.
- 4) Moisture storage in building materials is neglected.
- 5) Movement of air through materials or in cavities is neglected.
- 6) Rain precipitation or snow is not taken into account.
- 7) Methods are steady-stated and do not take into account transient boundary conditions.
- 8) Transport of water vapour through materials is only one-dimensional.
- 9) Short and long-way radiation is neglected.
- 10) Latent heat from evaporation/condensation is neglected.

These severe limitations show that calculations with the help of the Glaser or the Dew point method only indicate the heat and moisture transport in envelope assemblies and the results of the calculations are not exact scientific values. Technical standard ČSN EN ISO 13788 (2002) says:

Moisture transport is complex phenomena and knowledge of moisture transport mechanisms, material properties, initial, outside and inside conditions, is often insufficient and still under development. That is the reason why this standard uses simple calculation method, based on experiences and generally accepted knowledge.... The method should be used as a guess, not an exact tool. It is

suitable for a comparison of building structures. It does not describe an exact prediction of moisture behaviour inside structures during regular operating conditions and it is insufficient for calculations of evaporation build-in moisture contents.

The use of vapour retarders as moisture control in compact membrane roofs is not exactly determined. The development of using vapour retarder is described in details in *Chapter 2.1.3 Moisture Control in Compact Flat Roofs*. Various guidelines on where to use vapour retarders for compact membrane roofing systems exist around the world. Philosophical guidance ranges from “When in doubt, leave it out” to “When in doubt, think it out”, Tobiasson (1994). He concluded that:

When they are not needed, vapour retarders should not be used, since they are expensive and allow ‘cancer’ of wet insulation to grow within a compact roof having membrane or flashing flows.

In the Czech Republic, several different recommendations for the use of vapour retarders in compact membrane roofs exist.

Kutnar as the author of ČSN 731901 (1999) recommends to use vapour retarders in compact membrane roofs only when relative humidity of interiors is higher than 60% or in well-founded cases where the risk of condensation can reduce the lifetime of the compact roof systems. Šilarová (2005a) demands using vapour retarders inside compact membrane roofs. Novotný & Misar (2003) recommend to use vapour retarders in compact membrane roofs and finally Fajkoš (1997) follows the criteria from ČSN 731901 (1999) and recommends the use of vapour retarders only where interior relative humidity is higher than 60%.

The previous totally different recommendations about the use of vapour retarders in compact membrane roofs were made mainly on the basis of simple calculation methods (Glaser or Dew point methods). Simultaneously, the Czech recommendations were made on the basis of requirements for the moisture transport that can be found in technical standards ČSN 730540-2 (1994) or ČSN 730540-2 (2002) or recently in ČSN 730540-2 (2007).

The goal of this chapter is to specify conditions when vapour retarders are needed in compact membrane roof assemblies in the Central Europe. The conditions will be specified on the basis of numerical simulations and several requirements for moisture transport. The numerical simulations will be done by a state-of-art numerical model of coupled heat and moisture transport in building materials. The several standard requirements for moisture transport in compact flat roofs will be used together with requirements that will be suggested by the author.

4.1.2 Numerical Model

There are many numerical models that simulate coupled heat, moisture or air transport through building materials and components. The numerical tools use most finite element or finite volume methods to solve differential equations of coupled heat, moisture and air transport in building envelopes. The list of these models can be found in e.g. Karagiozis (2001) or Hill (2003).

Canada Mortgage and Housing Corporation (CMHC) made a research, Hill (2003), with the aim to assess the impact of the addition insulation and vapour/air retarder on durability of wall assemblies. Forty five numerical tools from the entire world were compared. Two models were recommended for next step of their research. The models are MATCH and WUFI. The MATCH tool was developed by Dr. Carlsten Rode in Technical University of Denmark and WUFI tool was developed by Dr. Harwig M. Künzel in Franhofer Institute of Building Physics in Germany, Künzel (1995).

The numerical model developed by Künzel (1995) was finally chosen for the following simulations in this Thesis. Physical background of the model is properly described in Chapter 2.2.4 *Coupled Moisture and Heat Transport*. The model has the following advantages compared to manual calculation tools such as the Glaser methods or the Dew point method. The advantages of Künzel's numerical model are:

- 1) Moisture transport is coupled with heat transport in building materials.
- 2) Thermal conductivity depends on moisture and ice content in materials.
- 3) Water vapour permeability depends on relative humidity in materials.
- 4) Moisture transports is assumed as vapour and also liquid transport.
- 5) Moisture storage in building materials is taken into account.
- 6) Rain precipitation and driven rain by wind is taken into account.
- 7) Model uses transient boundary conditions with initial moisture content in building materials at the beginning of the calculation.
- 8) Short and long-way radiation is taken into account.
- 9) Latent heat from evaporation/condensation is taken into account.
- 10) Moisture and heat sinks/sources can be used in the calculation.

The numerical model is only another step to express better the real transport of phenomena in building materials. The model has the following disadvantages:

- 1) Transport of heat and moisture through the materials is only one- or two-dimensional.
- 2) Movement of air through materials or in cavities is neglected.
- 3) Moisture storage in materials is described only by adsorption curve; the hysteresis effect is not taken into account
- 4) Gravitational forces are not taken into account.
- 5) Snow cover is not taken into account. The amount of melt water is calculated as rain precipitation.
- 6) Chemical reactions of materials, hydraulic flows, electrokinesis, and osmosis are neglected.

The previous disadvantages of the model are discussed in detail in the following points:

- Add1) The numerical simulations will be done for one dimensional moisture and heat transport, it is not limitation in this case.
- Add2) According to Tobiasson (1994) and other authors, compact roofing systems with low-permeability waterproof membranes are resistant to air leakage even if no deliberate vapour retarder is present.
- Add3) Measurements done by Künzel (1995) showed that for most building materials the hysteresis effect is so slight that the adsorption isotherm is adequate to characterize the sorption moisture region.

- Add4) I do not know a numerical model that solves moisture transport including gravitational forces. According to Krus (1996), gravitation only begins to affect liquid transport at pore radii higher than 10^{-6} m; so it will be neglected in this work.
- Add5) Snow can affect temperature and relative humidity within building envelopes. The effect of a snow cover is on the safety side because the snow cover behaves like an additional thermal insulation layer.
- Add6) Osmosis, elektrokinesis and hydraulic flow are also ignored in this Thesis.

4.1.3 Selected Roof Assemblies and Their Materials

The compact membrane roof with different materials for each layer has been chosen for numerical simulations. General schema of the roof and all possibilities for each layer are plotted in *Figure 4.1*. The scheme of the compact membrane roof describes typical compact roof assemblies that were discussed in *Chapter 2.1.1 Classification of Flat Roofs*.

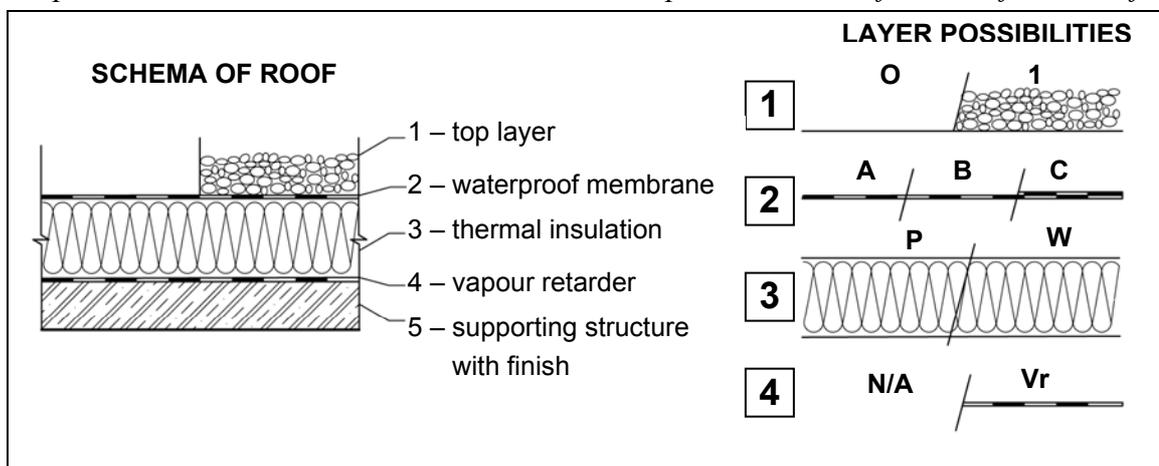


Figure 4.1. Schema of selected roof assemblies with material possibilities for several roof layers

The following material possibilities were chosen for selected roof layers.

1) Top layer

The main reason, why two different top layers were chosen, is to include or to exclude the influence of long-wave and short-wave radiation on moisture and heat transport within the assembly. Two possibilities are in *Table 4.1*.

Table 4.1. Different properties for top layer

No.	Differentiation	Short-wave radiation absorbtivity [-]	Long-wave radiation emissivity [-]	Note
0	no layer	0,86	0,90	short-wave and long-wave radiation are taken into account (grey, green, blue (not white/black) colour of waterproof membrane)
1	additional layer	-	-	e.g. ballast of stones or pavers - short-wave and long-wave radiation is not taken into account

The first variation is that the roof assembly is not covered with any layer – the short-wave and long-wave radiation is taken into account. The roof assembly can be stabilized by adhered systems or by mechanical fasteners.

The second possibility is that the roof assembly is covered with an additional layer; e.g. ballast of stones or the roof assembly is in shadow. Short-wave and long-wave radiation is not taken into account.

2) Waterproof membrane

Waterproof membrane is the most important roof layer from a view of moisture transport therefore I decided to use three different materials. These materials were chosen by diffusion properties to represent a wide range of materials waterproof membrane. Three possibilities are in *Table 4.2* with their diffusion properties. Other material properties of these membranes can be found in *Appendix B*.

Table 4.2. Three variations of materials used for waterproof membrane

No.	Differentiation	thickness [mm]	μ -value [-]	Note
A	low diffusion resistance membrane	1,2	15000	correspond to single ply foil roofing systems, e.g. 1,2mm PVC foil membrane or 1,5mm VAE foil membrane, μ -value not depends on relative humidity
B	high diffusion resistance membrane	1,5	150000	correspond to single ply foil or bitumen systems, e.g. 1,5mm FTO foil membrane, 1,2mm PIB foil membrane or 4,5mm single ply bitumen membrane, μ -value not depends on relative humidity
C	very high diffusion resistance membrane	10	50000	correspond to usually double ply bitumen system, e.g. 10mm double ply bitumen system or 2,5mm PIB foil membrane, μ -value not depends on relative humidity

3) Thermal insulation layer

Two types of materials for a thermal insulation layer are used for numerical simulations. These types (expanded polystyrene, mineral insulation board) are the most designed materials for the insulation layer. Thickness of these thermal insulation layers is 240mm. This thickness fulfils the requirements for the U-value of the whole flat roof assembly according to CSN 730540-2 (2007). Diffusion properties of the insulation materials are in *Table 4.3*, all hygrothermal properties of the materials are in *Appendix B*.

Table 4.3. Two different thermal insulation material used for thermal insulation layer

No.	Differentiation	thickness [mm]	μ -value [-]	Note
P	expanded polystyrene	240	50	density 30kg/m ³ , dry thermal conductivity 0,04 W/(mK)
W	mineral insulation board	240	1,3	density 60kg/m ³ , dry thermal conductivity 0,04 W/(m·K)

4) Vapour retarder

At the beginning of the numerical simulations, vapour retarders are not used. Vapour retarders are used only in some cases to compare moisture transport in compact roof assemblies. One type of vapour retarders is u

sed for the simulation and its diffusion properties are shown in *Table 4.4*.

Table 4.4. Diffusion properties of vapour retarder

No.	Differentiation	thickness [mm]	μ -value [-]	Note
Vr	vapour retarder	1,0	200000	correspond to foil membrane e.g. 0,22mm LDPE foil membrane, μ -value not depends on relative humidity
-	no vapour retarder	-	-	roof assembly without vapour retarder

5) Supporting structure

Only one type of supporting structure is used for all simulations – a concrete slab. The main diffusion properties are in Table 4.5, other properties are in Appendix B.

Table 4.5. Diffusion properties of concrete slab

No.	Differentiation	thickness [mm]	μ -value [-]	Note
-	structural concrete slab	150	179	μ -value not depends on relative humidity, but liquid transport coefficient depend on the RH

A note about properties of used materials

It was very difficult to find and to choose hygrothermal properties of used materials. There are three main reasons:

- 1) In literature, several values for one hydrothermal property exist for the same building material. The values vary sometimes more than one decimal order as can be seen for concrete in Table 4.6.
- 2) Differences in hygrothermal values can be caused by different understanding of moisture transport mechanisms. For example, when the both liquid and water vapour transport are assumed, the μ -value for concrete can be constant and liquid transport coefficient depends on relative humidity. On the other hand, when only water vapour transport is assumed, the μ -value depends on relative humidity and liquid transport coefficient is not taken into account.
- 3) Differences in hygrothermal values for the same building material can be caused by different measurement technique.

Table 4.6. Diffusion properties of concrete according to several authors

Name	bulk density [kg/m ³]	μ -value [-]	Note	Source
concrete	2100, 2300	15, 20	μ -value not depends on RH	Mrlik (1985)
reinforced concrete	2400	26	μ -value not depends on RH	Mrlik (1985)
concrete	2100, 2200, 2300	17,20,23	μ -value not depends on RH	CSN 730540-3 (2005)
reinforced concrete	2300, 2400, 2500	23,29,32	μ -value not depends on RH	CSN 730540-3 (2005)
concrete	2200±100	140-32	μ -value depends on RH	Kumaran (2001)
concrete w/c 0,5	2308	179-0,25	μ -value depends on RH	Hedenblad (1996)

A note about used roof assemblies

Twelve different compact membrane roof assemblies can be composed of material layers noticed above (vapour retarder is not taken into account). These assemblies consist of basic layers that play an important role on moisture and head transport. The other layers (e.g. expansion layer, separation layer or slope layer) are neglected for the numerical simulation

because in most cases, these layers are very thin layers with low thermal and diffusion resistances.

The example of one compact roof assembly called 0AP is plotted in *Figure 4.2*.

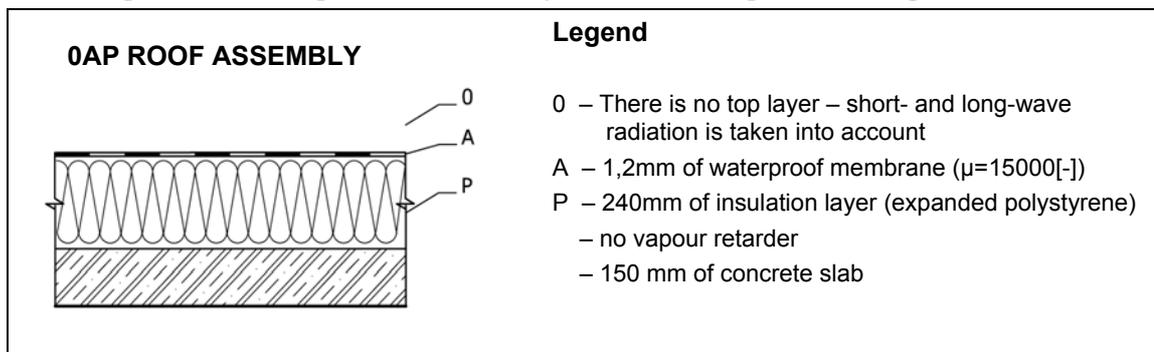


Figure 4.2. One example of composted roof assembly

4.1.4 Selected Climate Conditions

Conditions for numerical simulation can be divided into three groups: Initial conditions, indoor conditions and outdoor climate conditions. Each group will be discussed in detail separately.

4.1.4.1 Initial Conditions

Numerical simulations will be done for five year period. At the beginning of the simulations, materials should contain initial moisture contents. The initial moisture content is determined from moisture storage function for relative humidity equalled to 80%. The initial moisture content for all used materials is summarized in *Table 4.7*. Initial temperature of 20 °C was used.

Table 4.7. Initial moisture contents in used materials

No.	Name of material	Initial moisture content [kg/m ³]
A	low diffusion resistance membrane	0
B	high diffusion resistance membrane	0
C	very high diffusion resistance membrane	0
P	expanded polystyrene	1,8
W	mineral insulation board	1,8
Vr	vapour retarder	0
-	supporting concrete slab	85

4.1.4.2 Indoor Conditions

There are many indoor conditions that can be found in several technical standards. Some of them are simple constants of temperature and relative humidity for interior environments (i.e. CSN 730540-3 (2005)), others are more sophisticated and depend on outside climate conditions (i.e. ČSN EN ISO 13788 (2002)). For the numerical simulation, I finally chose indoor conditions that are recommended in WTA 6-2-01 (2004). These indoor conditions are described by sine curves as can be seen on *Figure 4.3*.

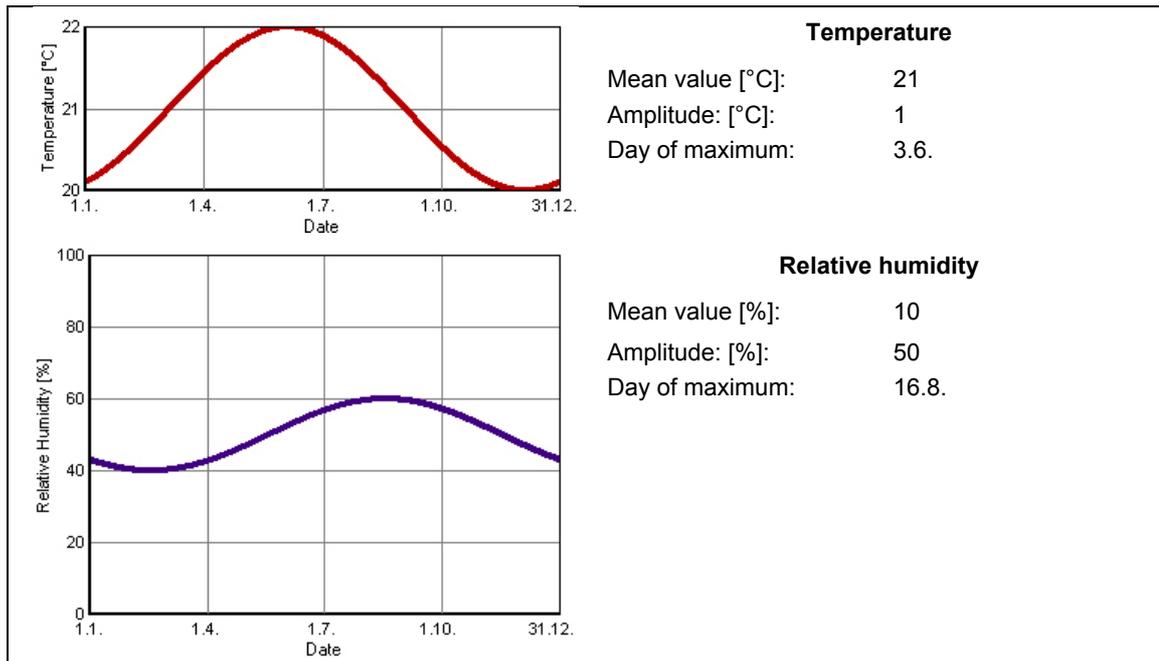


Figure 4.3. Indoor conditions – temperature and relative humidity sine curves

4.1.4.3 Outdoor Climate Conditions

Hourly measured values for several meteorological parameters were used as outdoor climate conditions for numerical simulations. The meteorological parameters are:

- 1) Temperature of the exterior air in [°C].
- 2) Relative humidity of the exterior air [%].
- 3) Solar radiation vertically incident on the exterior surface in [W/m²], horizontal surface of roof assemblies was assumed.
- 4) Long-wave atmospheric counterradiation [W/m²].
- 5) Rain load vertically incident on the exterior surface in [Ltr/m²h].

These climate parameters were measured by Fraunhofer institute for Building Physics (IBP), German National Meteorological Service (DWD) or by Technical University Lodz. The moisture reference year was used for the calculation. The moisture reference year can be defined as year with outdoor temperature that is a little lower than 30-years average value for a specific location. Five different locations in the Central Europe were chosen for the numerical simulations. These locations were: Wien (A), Gratz (A), Krakow (Pl), Holzkirchen (D), and Hof (D). The climate parameters for each location are placed in *Appendix C*.

As it was impossible to get climate data for the Czech Republic, several locations in the Czech Republic are compared with the selected location. These data are in *Table 4.8* and they are sorted by mean outdoor air temperature. The data for the Czech Republic are from the Czech Hydrometeorological Institute as 30-years mean values. The selected locations with locations from the Czech Republic can be also found on the geographical map, see *Figure 4.4*.

Table 4.8. Comparison of outdoor climate conditions for several central European locations. Highlighted locations are used for the numerical simulation

Location	Altitude	Mean temperature	Min/Max temperature	Mean relative humidity	Min/Max relative humidity	Rain sum
	m.a.s.l	[°C]	[°C]	[°C]	[°C]	[mm/a]
Wien (A)	198	10,4	-10,9/32,4	73	24/99	625
Gratz (A)	366	9,7	-11,2/31,4	77	24/99	807
Praha, Karlov (CZ)	261	9,4	-	-	-	447
Brno, Tuřany (CZ)	241	8,7	-	-	-	490
Krakow (PI)	237	8,3	-20,1/31,0	78	22/100	661
Ostrava, Mořnov (CZ)	251	8,2	-	-	-	701
České Budějovice (CZ)	388	8,2	-	-	-	583
Praha, Ruzyně (CZ)	364	7,9	-	-	-	526
Liberec (CZ)	398	7,2	-	-	-	803
Cheb (CZ)	471	7,2	-	-	-	560
Holzkirchen (D)	680	6,6	-20,1/32,1	81	24/98	1185
Přibyslav (CZ)	530	6,6	-	-	-	675
Hof (D)	567	6,1	-16,9/28,9	81	27/100	881



Figure 4.4. Geographical map of the Central Europe; Green points – locations used for the numerical simulation, Red points – location in the Czech Republic

4.1.4.4 Time Period of Numerical Simulations

Each numerical simulation for one roof assembly with outdoor and indoor conditions will be made for five years. The initial day is always the 1st of October according to ČSN EN ISO 13788 (2002).

4.1.4.5 Surface Transfer Coefficients

Heat transfer coefficients

The interior heat transfer coefficient is constant for simulations,

$$\alpha_i = 4,0 \text{ W /}(m^2 K) \quad (4.1)$$

The exterior heat transfer coefficient is constant for simulation without long-wave and short-wave radiation (top layers is used)

$$\alpha_e = 19,0 \text{ W /}(m^2 K) \quad (4.2)$$

In cases when top layer is not used, the exterior heat transfer coefficient depends on wind velocity according to the following equation,

$$\alpha_e = 1,6v_{wind} + 11,0 \quad (4.3)$$

where

- α_e is the exterior heat transfer coefficient [W/(m²K), and
- v_{wind} is the velocity of wind [m/s].

Moisture transfer coefficients

Moisture transfer coefficients are neglected for all calculations because their influence on results is less than 1%.

4.1.5 Determination of Moisture Requirements for Roof Assemblies

There are several criteria for moisture transport in compact membrane roofs. These criteria are described in details in *Chapter 2.1.2 Moisture Criteria for Failures of Compact Flat Roofs*. For numerical simulations, I chose the following moisture requirements for compact membrane roof assemblies.

4.1.5.1 Moisture Requirements According to CSN 730540-2(2007)

Requirement 1:

CSN 730540-2 (2007) says: “Moisture balance at the end of the year must be without any condensation deposit that would continually increase moisture content in the structure. So, year condensation deposit must be lower than evaporation potential of the structure”.

I have slightly changed this requirement to the following version because from physical point of view it is difficult to determine when condensation occurs inside building materials and components.

“Moisture content must not continually increase inside compact roof assemblies. That means that, moisture content in roof assembly at the end of the year must not be higher than moisture content at the beginning of the same year”

Requirement 2:

CSN 730540-2 (2007) says: “Year condensation deposit M_c inside the structure must be reduced for compact membrane roofs, according to following condition (lower value):

$$M_c \leq 0,1 \text{ kg/m}^2 \cdot a \quad \text{or} \quad (4.4)$$

$$M_c \leq 3\% \text{ of square density of the material where condensation occurs} \quad (4.5)$$

Again, I have slightly changed the requirement to the following version:

“The maximum increase of moisture content M_c inside the structure must be reduced for compact membrane roofs, according to following condition (lower value):

$$M_c \leq 0,1 \text{ kg/m}^2 \cdot a \quad \text{or} \quad (4.6)$$

$$M_c \leq 3\% \text{ of square density of the material where condensation occurs} \quad (4.7)$$

These requirements are expressed graphically in *Figure 4.5*.

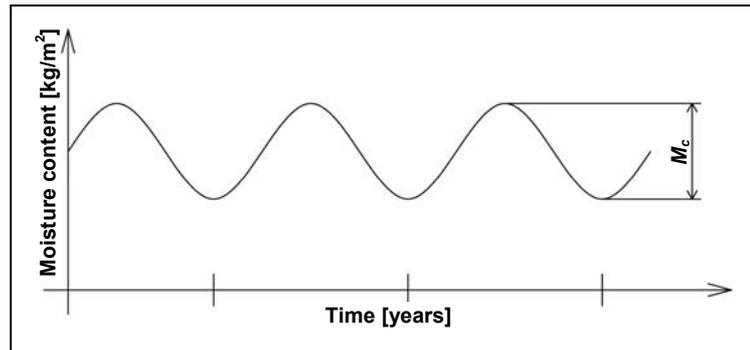


Figure 4.5. Moisture requirements for compact roof assemblies according to CSN 730540-2 (2007) or DIN 4108-3 (2001)

4.1.5.2 Moisture Requirements According to DIN 4108-3 (2001)

Requirement 1:

The first requirement is the same as the requirement according to CSN 730540-2 (2007). “Moisture content must not continually increase inside compact roof assemblies. So, moisture content in the roof assembly at the end of the year must not be higher than moisture content at the beginning of the same year”.

Requirement 2:

According to DIN 4108-3 (2001): “if winter interstitial condensation occurs in wall or roof assemblies the maximum condensation deposit M_c should not exceed $1,0 \text{ kg/m}^2$. If interstitial condensation occurs in non capillary-active materials, the maximum condensation deposit M_c should not exceed $0,5 \text{ kg/m}^2$ ”.

Again, I have slightly changed the wording of the requirement to the following version:

“If winter interstitial condensation occurs in wall or roof assemblies the maximum increase of moisture content M_c should not exceed $1,0 \text{ kg/m}^2$. If interstitial condensation occurs in non capillary-active materials, the maximum increase of moisture content M_c should not exceed $0,5 \text{ kg/m}^2$ ”.

The both requirements are expressed in *Figure 4.5*.

4.1.5.3 Moisture Requirements According to the Author

As the Czech and German standard requirement on moisture transport within building envelopes do not have any support in technical literature I decided to suggest my own requirements for moisture transport inside compact roof assemblies. The first requirement is similar to CSN and DIN standards. I added that the requirement must include each roof layer and the effect of increase moisture content inside each roof layer caused by initial moisture content is not taken into account.

The second requirement follows the experience of Tobiasson (1994) and Kutnar (2005) and says that a high level of moisture content in roof assemblies does not significantly affected the lifetime of the roofs. I defined the maximum level of moisture content as the level that decreases the insulation ability of the insulation layer to 85% of its dry value.

Requirement 1:

“Moisture content must not continually increase inside the whole compact roof assembly and also inside each roof layer. So, moisture content in the whole roof assembly and also inside each roof layer at the end of year must not be higher than moisture content at the beginning of the same year. The effect of increase moisture content due to initial moisture content might be excluded”.

Requirement 2:

“Moisture content inside thermal insulation layer must not decrease insulation ability of insulation material up to 15%. So, the maximum moisture content inside insulation materials must be lower than moisture content that reduces insulation ability to 85% of its dry value”.

The maximum moisture content that reduces insulation ability to 85% is expressed in *Table 4.9* for insulation materials that were used for the numerical simulations. Two author’s requirements are expressed graphically on *Figure 4.6*.

Table 4.9. Hygrothermal properties of insulation materials

Material	thermal conductivity	thermal conductivity	Maximum moisture content in material [kg/m ³]	Source
	dry material $\lambda_{(100\%)}[W/(m.K)]$	wet material $\lambda_{(85\%)}[W/(m.K)]$		
expanded polystyrene	0,04	0,046	78,6	Cammerer & Achziger (1985)
mineral insulation board	0,04	0,046	75,0	IEA Annex 21

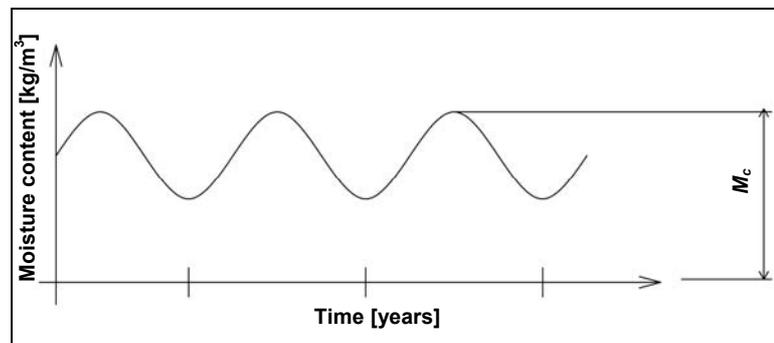


Figure 4.6. Author’s requirements for moisture content in thermal insulation layer inside compact membrane roof assemblies

4.1.6 Simulation Procedure

First of all, numerical simulations were done for twelve different flat compact roof assemblies with the help of the Künzeli numerical model. Vapour retarder was not used in these roof assemblies. Five sets of outdoor climate conditions in the Central Europe and only one set of indoor conditions were used for the simulations. The simulations were done for five years with the beginning on the 1st October.

Total moisture content in the roof assemblies was observed. The main focus was on moisture content in thermal insulation materials because these materials are placed below waterproof membrane and therefore interstitial condensation occurs there. The results of simulations were compared to two different standard and author's requirements mentioned in the previous subchapter. Each roof assembly was evaluated according to these requirements.

The second step of the simulation procedure was to find the influence of thickness of a thermal insulation layer on moisture transport. Numerical simulation was done for the same roof assembly with four different thicknesses of the thermal insulation layer. The calculations were done only for one set of outdoor climate condition. Moisture content was observed in the thermal insulation layer where interstitial condensation occurs. All cases of numerical simulations were evaluated according to two standard and author's requirements.

The last step of the simulation procedure was to compare roof assemblies with and without vapour retarder. Numerical simulations were done for two different roof assemblies and for two sets of outdoor climate conditions. The results of numerical simulations are presented in the following section.

4.1.7 Results of the Simulations

Results of numerical simulations are presented in this section. These results are separated according to each individual roof assembly and according to different steps of simulation procedure.

4.1.7.1 Roof Assemblies – 0AP and 1AP

Roof assembly 0AP or 1AP means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- A – waterproof membrane has a low diffusion resistance
- P – expanded polystyrene was used as thermal insulation material

Moisture content M_c as $[\text{kg}/\text{m}^3]$ in thermal insulation material during five years time period calculated for five different locations is presented in *Figure 4.7*.

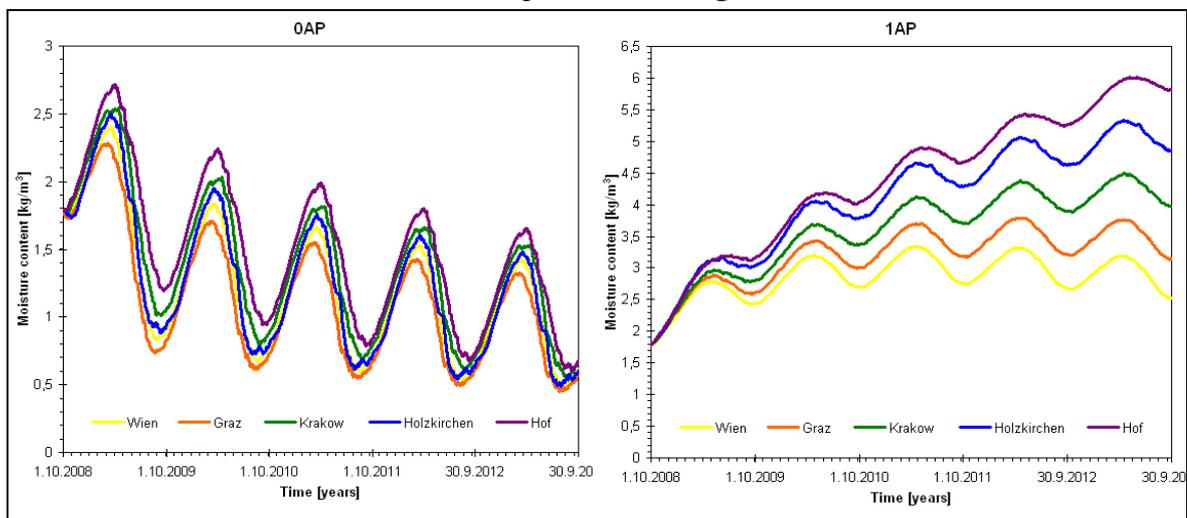


Figure 4.7. Moisture content $[\text{kg}/\text{m}^3]$ in thermal insulation material during five years time period calculated for five different locations. Left – 0AP roof assembly. Right – 1AP roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation period. The maximum increase of moisture content was calculated only when moisture content in the thermal insulation layer decreased during the whole calculation period. These results are presented in Table 4.10.

Table 4.11 presents how the roof assemblies fulfilled standard and author’s requirements on moisture transport within roof assembly.

Table 4.10. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c during the fifth year [kg/m ²]										
Roof assembly: 0AP					Roof assembly: 1AP					
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof	
0,21	0,20	0,22	0,23	0,23	0,13	0,13	-	-	-	

Table 4.11. Does the roof assembly fulfil the standard and author’s requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Roof assembly: 0AP					Roof assembly: 1AP				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No

4.1.7.2 Roof Assemblies – 0BP and 1BP

Roof assembly 0BP or 1BP means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- B – waterproof membrane has a high diffusion resistance
- P – expanded polystyrene was used as thermal insulation material

Moisture content M_c as [kg/m³] in thermal insulation material during five years time period calculated for five different locations is presented in Figure 4.8.

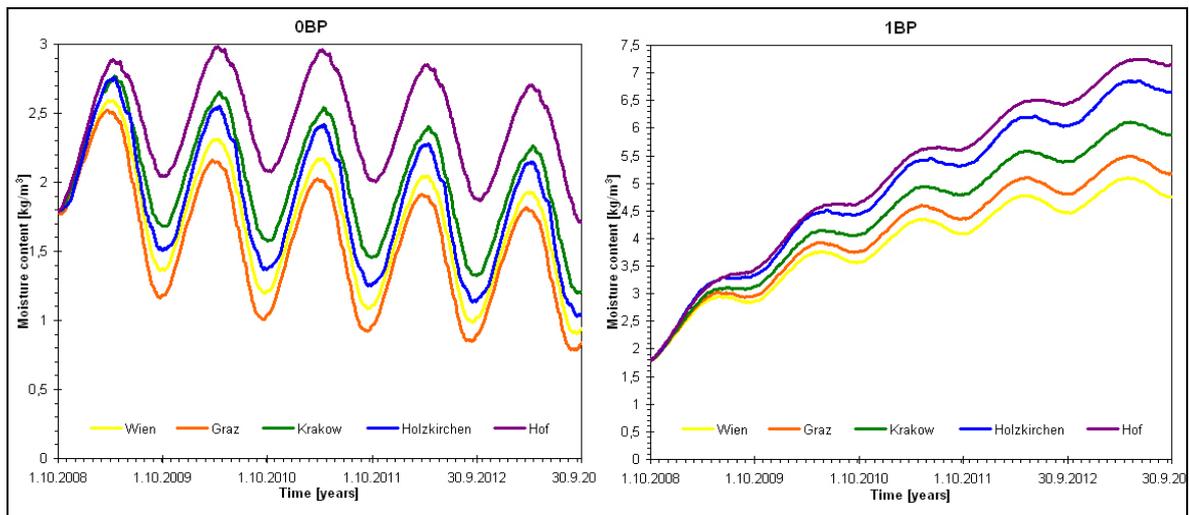


Figure 4.8. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0BP roof assembly. Right – 1BP roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation. The maximum increase of moisture content was calculated only when moisture content in thermal insulation layer decreased during the whole calculation period. These results are presented in *Table 4.12*.

Table 4.13 presents how the roof assemblies fulfilled standard and author's requirements on moisture transport within roof assembly.

Table 4.12. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]										
Roof assembly: 0BP					Roof assembly: 1BP					
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof	
0,23	0,23	0,23	0,24	0,20	-	-	-	-	-	

Table 4.13. Does the roof assembly fulfil the standard and author's requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Roof assembly: 0BP					Roof assembly: 1BP				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

4.1.7.3 Roof Assemblies – 0CP and 1CP

Roof assembly 0CP or 1CP means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- C – waterproof membrane has a very high diffusion resistance
- P – expanded polystyrene was used as thermal insulation material

Moisture content M_c as [kg/m³] in thermal insulation material during five years time period calculated for five different locations is presented in *Figure 4.9*.

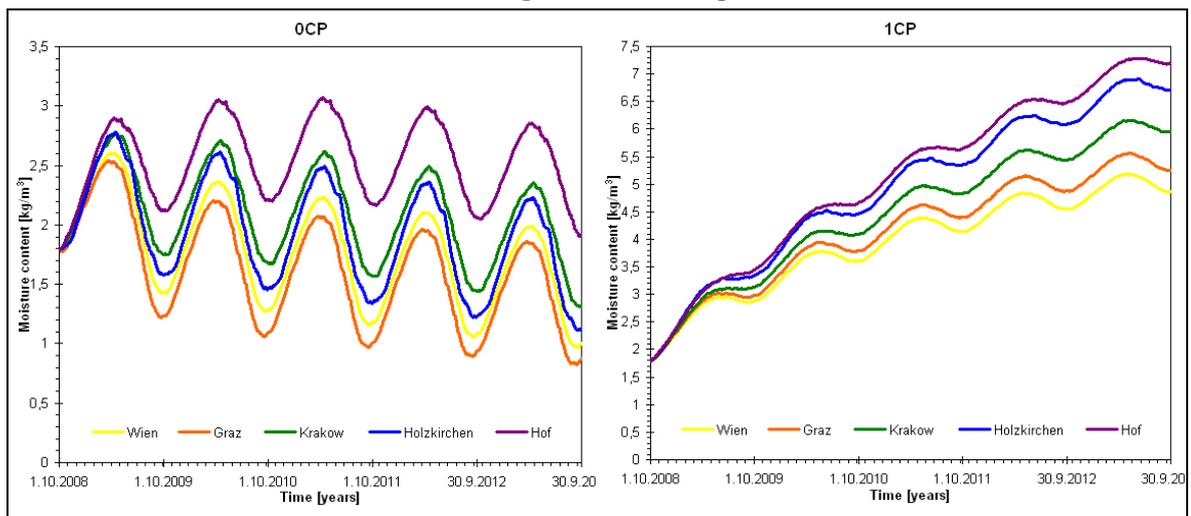


Figure 4.9. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0CP roof assembly. Right – 1CP roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation. The maximum increase

of moisture content was calculated only when moisture content in thermal insulation layer decreased during the whole calculation period. These results are presented in *Table 4.14*.

Table 4.15 presents how the roof assemblies fulfilled standard and author's requirements on moisture transport within roof assembly.

Table 4.14. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations.

Maximum increase of moisture content M_c in the fifth year [kg/m ²]										
Roof assembly: 0CP					Roof assembly: 1CP					
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof	
0,22	0,23	0,22	0,24	0,19	-	-	-	-	-	

Table 4.15. Does the roof assembly fulfil the standard and author's requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements.

Location/ Requirements	Roof assembly: 0CP					Roof assembly: 1CP				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

4.1.7.4 Roof Assemblies – 0AW and 1AW

Roof assembly 0AW or 1AW means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- A – waterproof membrane has a low diffusion resistance
- W – mineral wool insulation was used as thermal insulation material

Moisture content M_c as [kg/m³] in thermal insulation material during five years time period calculated for five different locations is presented in *Figure 4.10*.

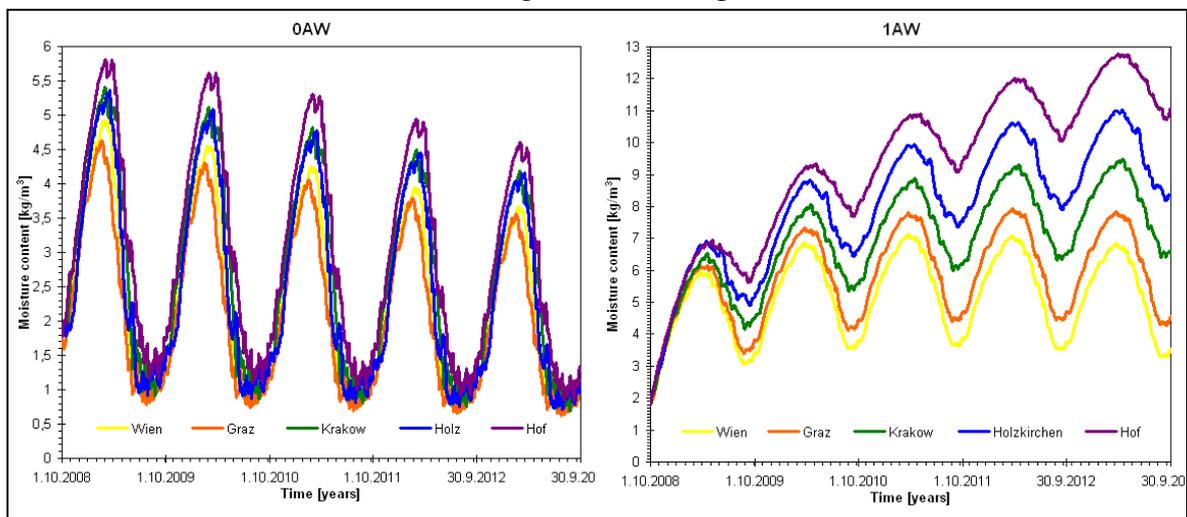


Figure 4.10. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0AW roof assembly. Right – 1AW roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation. The maximum increase of moisture content was calculated only when moisture content in thermal insulation layer decreased during the whole calculation period. These results are presented in *Table 4.16*.

Table 4.17 presents how the roof assemblies fulfilled standard and author’s requirements on moisture transport within roof assembly.

Table 4.16. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]										
Roof assembly: 0AW					Roof assembly: 1AW					
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof	
0,72	0,70	0,83	0,82	0,88	0,80	0,82	-	-	-	

Table 4.17. Does the roof assembly fulfil the standard and author’s requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Roof assembly: 0AW					Roof assembly: 1AW				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	No	No	No	No	No	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No

4.1.7.5 Roof Assemblies – 0BW and 1BW

Roof assembly 0BW or 1BW means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- B – waterproof membrane has a high diffusion resistance
- W – mineral wool insulation was used as thermal insulation material

Moisture content M_c as [kg/m³] in thermal insulation material during five years time period calculated for five different locations is presented in Figure 4.11.

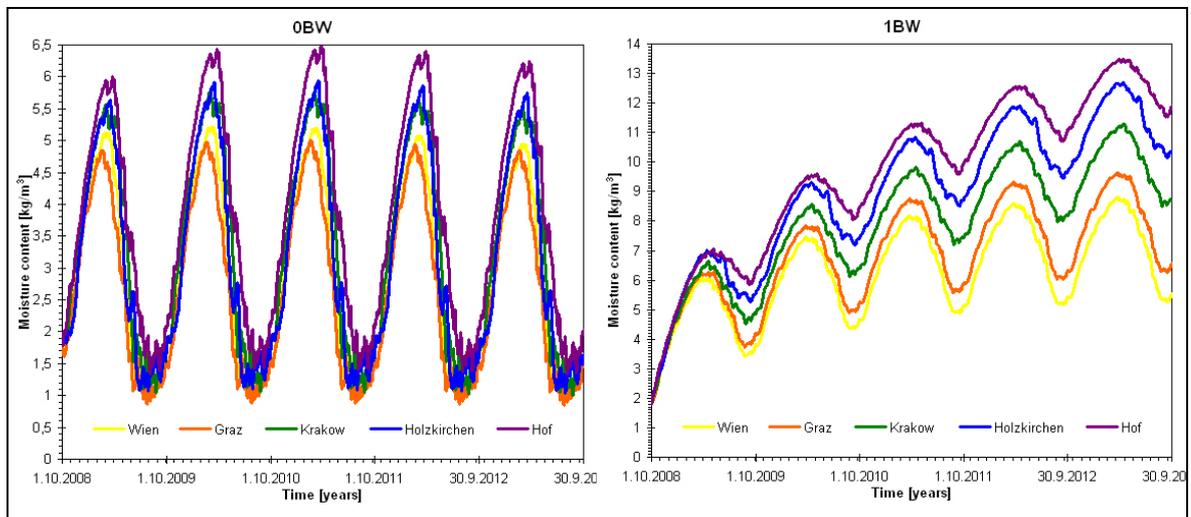


Figure 4.11. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0BW roof assembly. Right – 1BW roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation. The maximum increase of moisture content was calculated only when moisture content in thermal insulation layer decreased during the whole calculation period. These results are presented in Table 4.18.

Table 4.19 presents how the roof assemblies fulfilled standard and author’s requirements on moisture transport within roof assembly.

Table 4.18. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]									
Roof assembly: 0BW					Roof assembly: 1BW				
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
0,96	0,96	1,08	1,12	1,17	-	-	-	-	-

Table 4.19. Does the roof assembly fulfil the standards and authors requirement for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Roof assembly: 0BW					Roof assembly: 1BW				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	No	No	No	No	No	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

4.1.7.6 Roof Assemblies – 0CW and 1CW

Roof assembly 0CW or 1CW means:

- 0 – calculation was made with long- and short-wave radiation
- 1 – calculation was made without long- and short-wave radiation
- C – waterproof membrane has a very high diffusion resistance
- W – mineral wool insulation was used as thermal insulation material

Moisture content M_c as [kg/m³] in thermal insulation material during five years time period calculated for five different locations is presented in Figure 4.12.

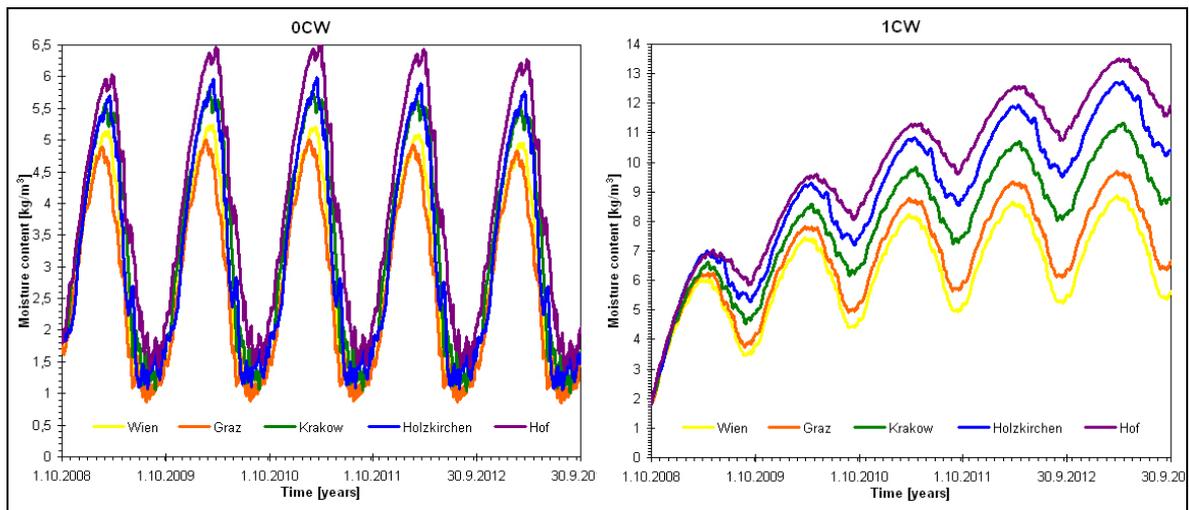


Figure 4.12. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0CW roof assembly. Right – 1CW roof assembly

The maximum increase of moisture content [kg/m²] in the whole thermal insulation layer was recalculated as the maximum positive change of moisture content M_c [kg/m³] in thermal insulation material during the fifth year of the calculation. The maximum increase of moisture content was calculated only when moisture content in thermal insulation layer decreased during the whole calculation period. These results are presented in Table 4.20.

Table 4.21 presents how the roof assemblies fulfilled standard and author’s requirements on moisture transport within roof assembly.

Table 4.20. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]									
Roof assembly: 0CW					Roof assembly: 1CW				
Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
0,97	0,95	1,08	1,13	1,17	-	-	-	-	-

Table 4.21. Does the roof assembly fulfil the standard and author's requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Roof assembly: 0CW					Roof assembly: 1CW				
	Wien	Graz	Krakow	Holzkir.	Hof	Wien	Graz	Krakow	Holzkir.	Hof
CSN	No	No	No	No	No	No	No	No	No	No
DIN	No	No	No	No	No	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

4.1.7.7 Influence of Insulation Thickness on Moisture Transport

As thermal insulation layer has the same thickness for all previous cases I decided to make another calculation with different thicknesses of the thermal insulation layer. I chose one roof assembly (AW) and one set of outdoor climate conditions (Krakow). I observed if thickness of insulation layer had significant influence on moisture transport in roof assemblies. I used four different thicknesses of thermal insulation layer (240mm, 180mm, 120mm and 60mm) for the calculations.

The results of numerical simulation are presented in *Figure 4.13* as moisture content M_c [kg/m³] in the thermal insulation layer. *Table 4.22* presents the maximum increase of moisture content M_c [kg/m²] during the fifth year of the calculation period and *Table 4.23* evaluates roof assemblies according to standard and author's requirements on moisture transport within roof assemblies.

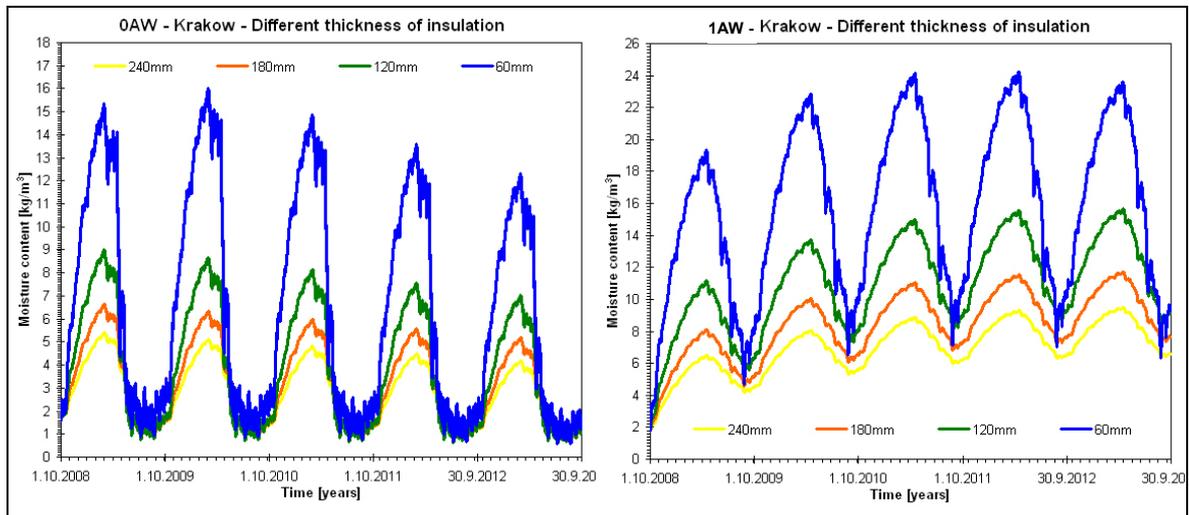


Figure 4.13. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Left – 0AW roof assembly. Right – 1AW roof assembly

Table 4.22. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]							
0AW – Krakow – Different thickness of insulation layer				1AW – Krakow – Different thickness of insulation layer			
240mm	180mm	120mm	60mm	240mm	180mm	120mm	60mm
0,83	0,81	0,77	0,70	-	-	-	1,00

Table 4.23. Does the roof assembly fulfil the standard and author’s requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	0AW – Krakow				1AW – Krakow			
	Different thickness of insulation layer				Different thickness of insulation layer			
	240mm	180mm	120mm	60mm	240mm	180mm	120mm	60mm
CSN	No	No	No	No	No	No	No	No
DIN	No	No	No	No	No	No	No	No
Author	Yes	Yes	Yes	Yes	No	No	No	Yes

4.1.7.8 Influence of Vapour Retarder on Moisture Transport

The last set of results compares moisture transport in compact membrane roof assemblies with and without vapour retarder. I chose two different roof assemblies (AW – roof assembly with waterproof membrane that has a low diffusion resistance, and CW – roof assembly with waterproof membrane that has a very high diffusion resistance). Numerical simulations were done for two outdoor climate conditions (Graz, Holzkirchen). Roof assemblies without vapour retarder were compared to the same roof assemblies in which vapour retarder was placed between the thermal insulation layer and the concrete slab.

The results of the numerical simulations, when short and long wave radiation is taken into account, are presented in Figure 4.14 as moisture content M_c [kg/m³] in the thermal insulation layer. Table 4.24 presents the maximum increase of moisture content M_c [kg/m²] during the fifth year of the calculation period and Table 4.25 evaluates roof assemblies according to standard and author’s requirements on moisture transport within roof assemblies.

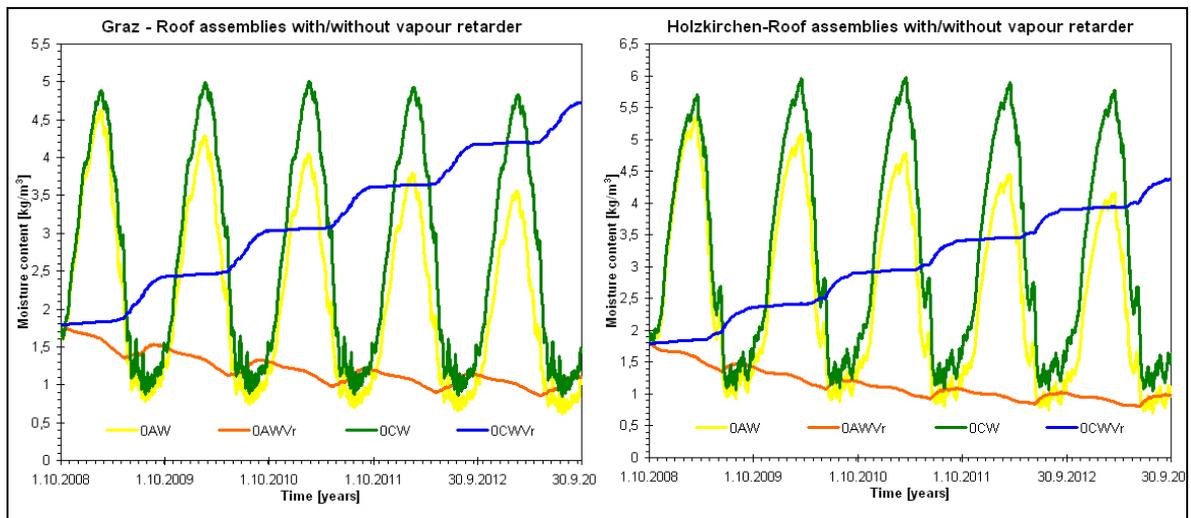


Figure 4.14. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Long and short wave radiation is taken into account. Left – Roof assemblies in Graz location. Right – Roof assemblies in Holzkirchen location

Table 4.24. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies and for two different locations during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]							
Graz				Holzkirchen			
Roof assemblies with/without vapour retarder				Roof assemblies with/without vapour retarder			
0AW	0AWVr	0CW	0CWVr	0AW	0AWVr	0CW	0CWVr
0,70	0,06	0,95	-	0,82	0,05	1,13	-

Table 4.25. Does the roof assembly fulfil the standard and author's requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Graz Roof Assemblies with/without vapour retarder				Holzkirchen Roof Assemblies with/without vapour retarder			
	0AW	0AWVr	0CW	0CWVr	0AW	0AWVr	0CW	0CWVr
	CSN	No	Yes	No	No	No	Yes	No
DIN	No	Yes	No	No	No	Yes	No	No
Author	Yes	Yes	Yes	No	Yes	Yes	Yes	No

The results when short and long-wave radiation is not taken into account are presented in Figure 4.15. Again Table 4.26 presents the maximum increase of moisture content M_c [kg/m²] during the fifth year of the calculation period and Table 4.27 evaluates roof assemblies according to standard and author's requirements on moisture transport within roof assemblies.

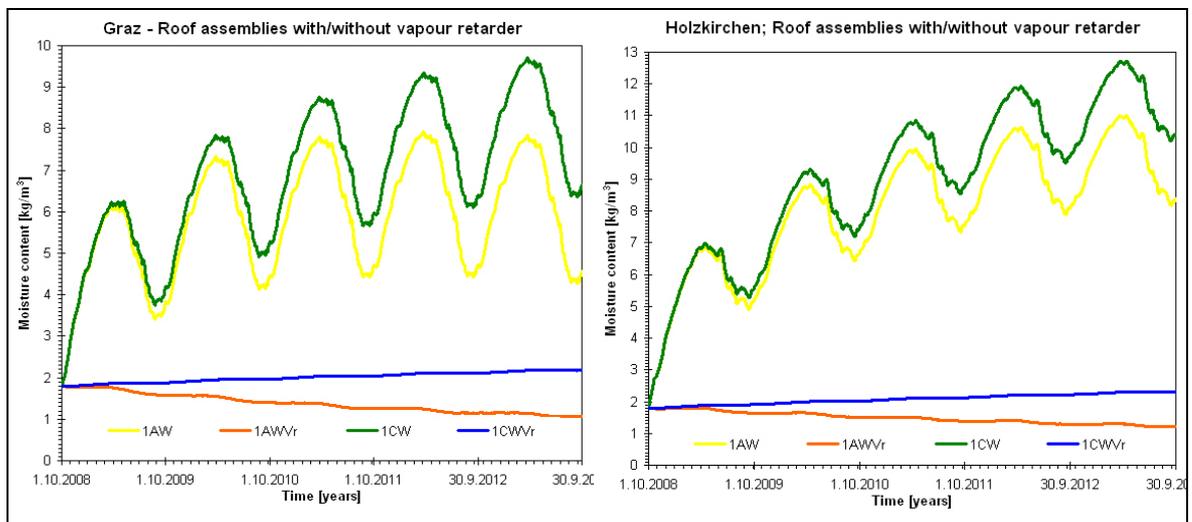


Figure 4.15. Moisture content [kg/m³] in thermal insulation material during five years time period calculated for five different locations. Long and short wave radiation is taken into account. Left – Roof assemblies in Graz location. Right – Roof assemblies in Holzkirchen location

Table 4.26. Maximum increase of moisture content [kg/m²] in thermal insulation layer for two roof assemblies and for two different locations during the fifth year of calculations

Maximum increase of moisture content M_c in the fifth year [kg/m ²]							
Graz				Holzkirchen			
Roof assemblies with/without vapour retarder				Roof assemblies with/without vapour retarder			
1AW	1AWVr	1CW	1CWVr	1AW	1AWVr	1CW	1CWVr
0,82	0,00	-	-	-	0,01	-	-

Table 4.27. Does the roof assembly fulfil the standard and author's requirements for moisture transport? Yes – the roof assembly fulfils the requirements. No – the roof assembly does not fulfil the requirements

Location/ Requirements	Graz Roof Assemblies with/without vapour retarder				Holzkirchen Roof Assemblies with/without vapour retarder			
	1AW	1AWVr	1CW	1CWVr	1AW	1AWVr	1CW	1CWVr
	CSN	No	Yes	No	No	No	Yes	No
DIN	No	Yes	No	No	No	Yes	No	No
Author	Yes	Yes	No	No	no	Yes	no	No

4.1.7.9 Evaporation Potential

The last set of numerical simulations was done to find how much moisture can be evaporated from compact membrane roof assemblies if vapour retarder is presented. Several authors Tobiasson (1994), Künzel (1998) and others say that vapour retarder and waterproof membrane creates a moisture trap because moisture content (e.g. as the fraction of rain), that gets into compact roof assembly with vapour retarder, cannot be released and accumulates inside the roof assembly.

One roof assembly (AWVr) and two locations (Graz, Holzkirchen) were chosen for the numerical simulations. These numerical simulations were done with moisture source. This moisture source represents moisture content that can get into the roof assembly for example as rain by leakage in waterproof membrane. This example can occur in old roof systems but it should not occur in a new roof system because new waterproof membranes must be compact without any perforation.

The moisture source was placed in thermal insulation layer beneath the waterproof membrane and it was calculated as percentage of precipitation in a specific location. The maximum amount of moisture content as fraction of rain in [%] or as fraction of rain in [kg/(m².a)] that can be still evaporated from the roof assembly during a year cycle is presented in *Table 4.28*.

Table 4.28. The maximum amount of moisture content that can be still evaporated from roof assembly in a concrete location

Location	Graz – Rain sum 807mm per year		Holzkirchen - Rain sum 1185mm per year	
	0AWVr	1AWVr	0AWVr	1AWVr
Roof Assembly				
Maximum Fraction of Rain in Roof Assembly [%]	0,012	0,007	0,010	0,004
Maximum Fraction of Rain in Roof Assembly [kg/(m ² .a)]	0,097	0,056	0,119	0,047

4.1.8 Discussion

Several interesting things arise from numerical simulations of moisture transport in compact membrane roof assemblies.

All twelve roof assemblies without vapour retarder fulfil the author’s requirements on moisture transport when short and long-wave radiation was taken into account. None of the twelve roof assemblies fulfils the Czech standard requirements and only assemblies with expanded polystyrene as thermal insulation fulfil the German standard requirements on moisture transport within roof assemblies.

If short and long-wave radiation is not taken into account the author’s and DIN requirements are fulfilled only for roof assemblies where waterproof membrane with a low diffusion resistance is applied and only for two the warmest geographical locations (Wien and Graz).

None of the twelve roof assemblies fulfils the Czech standard requirements on moisture transport within roof assemblies. The main reason is that the requirement for the amount of condensation deposit inside a roof assembly is too strict, compared to the author’s and DIN requirements.

The maximum increase of moisture content (maximum condensation deposit) during a year cycle depended mainly on used thermal insulation material. The maximum increase of moisture content in roof assemblies, in which expanded polystyrene was used as thermal insulation material, was around 0,23kg/m², but the maximum increase of moisture content

during a year cycle was between 0,7 kg/m² to 1,13 kg/m² for roofs where mineral wool insulation was used as material for the thermal insulation layer. This was the reason, why roof assemblies with mineral wool insulation did not fulfil the DIN requirements on moisture transport. The difference can be seen on *Figure 4.7* and *Figure 4.10*, where the same roof assemblies except the thermal insulation layer are compared.

Another interesting fact is that different diffusion properties of waterproof membrane do not have such an important influence on moisture transport within roof assemblies like diffusion properties of thermal insulation material. *Table 4.29* shows the maximum increase of moisture content during the fifth year of the calculation for six different roof assemblies. The geographical location is Krakow and it is the same for all these assemblies. The results show that bigger difference across the values applies to the assemblies with different thermal insulation layer than the assemblies with different waterproof membrane.

Table 4.29. Maximum increase of moisture content M_c during the fifth year of the calculation for six roof assemblies in Krakow

Roof assembly	0AP	0BP	0CP	0AW	0BW	0CW
Maximum increase of moisture content M_c in the fifth year [kg/m ²]	0,22	0,23	0,22	0,83	1,08	1,08

Moisture content in thermal insulation layer in all cases was a much lower than the author's requirement for moisture content in insulation materials.

The first twelve sets of numerical simulations show that if short and long-wave radiation is neglected the temperature gradient is the main potential for moisture transport in roof assemblies. If short and long-wave radiation is taken into account the main potential for moisture transport is again temperature gradient but caused by the radiation.

The second set of results shows that the thickness of the thermal insulation layer does not play a significant role on moisture transport. Moisture content in insulation material increases with decreasing thickness of thermal insulation layer in compact membrane roof assembly but the amount of moisture increase per square metre during a year cycle decreases as can be seen in *Figure 4.13* and *Table 4.22*.

The third set of results shows several interesting things. Vapour retarder used in compact membrane roof assemblies does not always help to reduce moisture content in the insulation layer. The roof assembly (0CW locations Graz and Holzkirchen) shows worse results with the vapour retarder than without the vapour retarder, see *Figure 4.14*. Moisture content accumulates inside the roof assembly during summer periods when the direction of moisture transport is opposite and it directs from the outdoor environment to the indoor environment. Then during winter period, moisture content inside the roof assembly has no chance to evaporate and during next summer period it increases again.

Vapour retarders reduce the oscillation of moisture content in thermal insulation layer during a year cycle and also reduce moisture content inside roof assemblies especially if short and long wave radiation is not taken into account, see *Figure 4.15*.

Only roof assemblies with vapour retarders (0AWVr, 1AWVr) fulfil the Czech standard requirements for moisture transport in roof assemblies in locations Graz and Holzkirchen, see *Table 4.25* and *Table 4.27*.

The evaporation potential of compact membrane roof assemblies with vapour retarders is very low as can be seen in *Table 4.28*. The maximum moisture content as percentage of precipitation, which can evaporate from the roof assemblies, is around 0,01%. This small amount of moisture content means that when a leakage appears in waterproof membrane, moisture content is accumulated in the roof assembly and only small amount is evaporated.

The evaporation potential rises twice if short and long-wave radiation is taken into account. In the conclusion of this discussion, several comments must be added:

- 1) All results presented in this chapter are only results of the numerical simulations. They only predict and simulate the reality but they are not real. Nowadays, the Künzels numerical model is one of the best numerical models in the World for coupled heat and moisture transport through composite building envelopes but I am sure that in the future better and more accurate model will be found and the results will be more precise.
- 2) All calculations were done with initial moisture content in some of the building materials. This initial moisture content describes better the reality and it is on the safety side, but it is neglected in technical standard. Initial moisture content in building materials can affect the results in such a way that the results of numerical simulations do not correspond with results that are calculated with the help of standard methods especially the amount of increase of moisture content during a year cycle.
- 3) Only one indoor climate conditions were used for all numerical calculations. These indoor climate conditions correspond to conditions in dwelling houses but for other type of houses, different indoor climate conditions should be used.
- 4) Building materials and products were chosen for the numerical simulations in such a manner to represent the wide range of building products and materials that are commonly used in compact membrane roofs but it is impossible to make the simulation for all products. That is the reason why, for example, one supporting structure – a concrete slab – was used for all numerical calculations. Simultaneously, one building products can have several different hygrothermal properties as can be seen in *Table 4.6*. I would like to stress in this paragraph that it is impossible to make simulations for all building products and materials and their different hygrothermal properties.
- 5) All calculations in this chapter were made for roof assemblies in a common roof plane, not for roof building details. The building details are not solved in this Thesis although they are usually the weakest point of the building design.

4.1.9 Conclusion

In the first part of this chapter, I described some problems of the Glaser methods - simple calculation methods for heat and moisture transport through building envelopes. Nowadays, these calculation methods are used in most cases although they neglect several physical phenomena. That was the main reason why I decided to make numerical simulations of coupled heat and moisture transport through compact membrane roof assemblies with the help of the Künzels numerical model.

The results of the simulation show that the dominant potential for moisture transport is temperature gradient that is caused by short and long-wave radiation. The radiation is neglected in the simple Glaser methods.

Three different requirements for moisture transport within roof assemblies were compared; two standard requirements (DIN 4108-3 (2001), CSN 730540-2 (2007)) and the author's requirements, that were created on the basis of technical literature. The comparison shows that the Czech standard requirements for moisture transport within building envelope are very strict.

The use of strict Czech standard requirements for moisture transport together with simple calculation methods that neglect short and long-wave radiation causes that vapour retarders must be design in compact membrane roof assemblies.

The results of the simulation showed that compact membrane roof assemblies placed on concrete slabs can be designed without vapour retarders especially if short- and long-wave radiation can be taken into account.

In certain cases, the use of vapour retarders leads to accumulation of moisture content inside building envelopes and may reduce the lifetime of the whole roof assembly. Simultaneously, when vapour retarders are designed together with waterproof membranes, the evaporation potential of the roof is small and the roof assembly creates a moisture trap. This moisture trap can accumulate a huge amount of moisture between vapour retarder and waterproof membrane in cases when waterproof membrane is perforated and rain leaks into the roof assembly.

Vapour retarders can be useful in some cases of compact membrane roof assemblies but in these cases I rather prefer the design of the compact protected membrane roof or the Duo roof.

Chapter 5: Efficient Roof Assembly and Recommendations

5.1 Changes in Compact Roof Design

This and the following chapters compose gained knowledge from the previous technical chapters and bring a new view on a design of compact membrane roofs. In the first part of this subchapter, the order of compact membrane roofs will be discussed in general according to the moisture transport criterion. The second part of this subchapter discusses advantages and disadvantages of each compact roof design.

5.1.1 The Order of Compact Roofs

It is possible to compose many orders of roofs according to different criteria. I will focus only on one criterion – the efficient control of moisture in compact roofs. I choose this criterion because moisture or moisture content is the most common factor that reduces the durability of the whole roof design.

The order of compact membrane roofs according to the moisture control criterion is plotted in *Figure 5.1*.

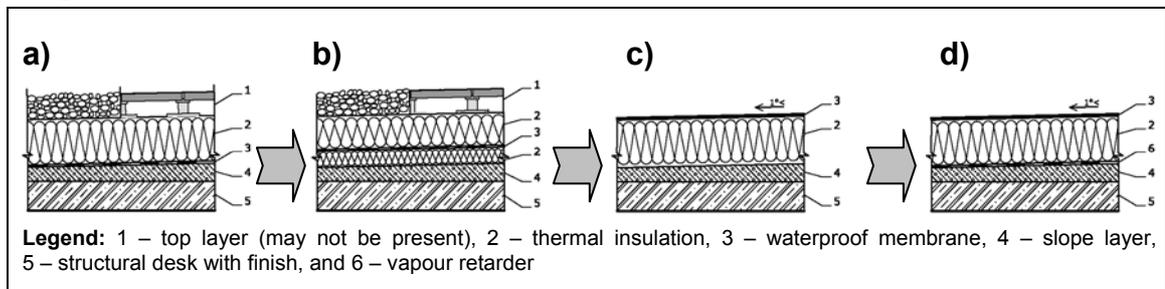


Figure 5.1. The order of compact membrane roofs; a) Protected membrane roof, b) Duo roof, c) Compact membrane roof without vapour retarder, d) Compact membrane roof without vapour retarder

The protected membrane roof is the first in the given order because this roof does not have any problems with interstitial condensation inside the roof assembly and if waterproof membrane is properly applied the roof does not suffer from moisture problems. The effect of rain water on the insulation ability of extruded polystyrene is questioned as it can be found in Tobiasson (1994).

The Duo roof is the second in the given order. The duo roof must be evaluated on moisture transport because if the thickness of the thermal insulation layer below the waterproof membrane is insufficient interstitial condensation occurs and moisture can be accumulated in the roof assembly.

The compact membrane roof without vapour retarder is the third. Interstitial condensation occurs in this roof assembly and that is the reason why the roof has to be evaluated on moisture transport within the assembly. Moisture content caused by interstitial condensation must not accumulate inside the roof assembly during a year cycle and must not cause any degradation of materials. Thermal insulation ability of insulation material must not be reduced under a certain level.

The compact membrane roof with vapour retarder is the last in the given order. This roof assembly has the same problems like the compact membrane roof without vapour retarder but the main reasons why I placed this roof assembly on the last place are:

- 1) Vapour retarder and waterproof membrane create a moisture trap. If water gets into the roof assembly from rain it has no chance to evaporate and it will quickly

accumulate till it will cause some failures. (In compact membrane roof without vapour retarder, a rain leak can be discovered very quickly before it will cause bigger damages.)

- 2) It is difficult to discover a leak in a waterproof membrane because vapour retarder changes the path of liquid and vapour movement inside the roof assembly.
- 3) Vapour retarders and waterproof membranes have to be designed in the roof assembly with certain diffusion properties to prevent moisture from accumulating in the roof assembly.

I agree with the opinion that the compact membrane roof with vapour retarder may behave better than the compact membrane roof without vapour retarder but only in certain cases and if vapour retarders and waterproof membranes are properly performed in the roof assembly. The waterproofing of membranes and the vapour proofing of vapour retarders should be tested before process of approval.

5.1.2 Advantages and Disadvantages of Compact Roof Assemblies

Advantages and disadvantages of compact roof assemblies will be summarized in this subchapter according to different type of the roof assembly.

5.1.2.1 Protected Membrane Roof Assembly

Advantages:

- 1) No problems with interstitial condensation inside the assembly.
- 2) Waterproof membrane is not affected by most of the temperature variations and solar effects. The membrane remains at a relatively constant temperature during day and night or during summer and winter.

Disadvantages:

- 1) Protected membrane roofs cost more than other types of compact roofs because of the higher price of extruded polystyrene and additional cost for ballast or pavers.
- 2) Rain and melt water may effect the insulation ability of extruded polystyrene. Several studies reported different opinions on this problem, i.e. Tobiasson (1994).

5.1.2.2 Duo Roof Assembly

Advantages:

- 1) If enough thickness of thermal insulation is designed above the waterproof membrane the roof assembly has no problems with interstitial condensation.
- 2) Waterproof membrane is not affected by most of the temperature variations and solar effects. The membrane remains at a relatively constant temperature during day and night or during summer and winter.
- 3) This roof assembly is advantageous for renovations because original roof assembly can remain in a place and it can be supplement with new roof layers. A new composed roof assembly must be properly evaluated on moisture transport.

Disadvantages:

- 1) Duo roofs cost more than convention roofs but less than protected membrane roofs.
- 2) The thickness of thermal insulation that is above and below a waterproof membrane has to be properly calculated and designed according to outdoor and indoor climate conditions.

5.1.2.3 Compact Membrane Roof Assembly without Vapour Retarder

Advantages:

- 1) The lowest investment cost compared to other roof assemblies.

Disadvantages:

- 1) The risk of accumulation of moisture inside the roof assembly has to be properly calculated according to outdoor and indoor climate conditions.
- 2) The roof assembly is not suitable for cold climate regions.
- 3) The roof assembly should be designed in cases where short and long-wave radiation can be taken into account.
- 4) Several design principles should be kept for this roof assembly. These principles are discussed in the following chapter in detail.

5.1.2.4 Compact Membrane Roof Assembly with Vapour Retarder

Advantages:

- 1) Lower investment cost than Duo roof assembly or protected membrane roof assembly.
- 2) A vapour retarder reduces moisture content from the interior environment but this has to be properly calculated and evaluated and the vapour retarder has to be without any perforations and properly joined to all openings.

Disadvantages:

- 1) Higher cost than compact membrane roof assembly.
- 2) Stricter demands on perfect performance of vapour retarders and waterproof membranes.
- 3) The risk of accumulation of moisture inside the roof assembly has to be properly calculated according to outdoor and indoor climate conditions.
- 4) Several design principles should be kept for this roof assembly. These principles are discussed in the following chapter in detail.

5.1.3 Conclusion

The main change in compact roof design is that all types of compact roof assemblies can be used in the Central Europe including the compact membrane roof assembly without vapour retarder. The compact membrane roof assemblies without vapour retarder can behave even better in certain cases from a view of moisture transport than the compact membrane roof assemblies with vapour retarder.

All these types of roof assemblies must be properly calculated and evaluated on moisture transport. The limitations for the roof design are proper moisture requirements and indoor and outdoor climate conditions but there are no general rules, when a special type of roof assembly can be used.

5.2 Design of Ideal Compact Roof Assembly

The results from numerical analysis chapter proved that design rules for compact roof assemblies published for example in ČSN 731901 (1999) do not exactly express the conditions when a certain type of a roof assembly should be designed. Each roof assembly must be evaluated according to moisture and heat criteria and then build up. Each roof assembly can be evaluated as the function in which indoor and outdoor climate conditions are the variables,

$$roof = f(i, e) \quad (5.1)$$

where

- roof* is the roof assembly,
- i* is the indoor climate conditions, and
- e* is the outdoor climate conditions.

As it is impossible to determine general rules when a certain type of roof assembly should be designed I decided to write down a recommendation list of design principles for two most critical roof assemblies – the compact membrane roof assembly with vapour retarder and the compact membrane roof assembly without vapour retarder. These recommendations help to design roof assemblies in a more efficient way and to avoid the future failures.

5.2.1 Recommendations - Compact Membrane roof Assembly with Vapour Retarder

Waterproof Membrane

- 1) Waterproof membranes should be provided with slope at least 1° and must be totally sealed against penetration. Totally flat roof is a design mistake.
- 2) Waterproof membranes should have diffusion resistance as low as possible, in order to facilitate evaporation of moisture from a roof assembly as much as possible. That is the reason why single ply membrane systems are preferable to double ply systems or build-up systems. Products made of PVC or VAE are suitable for the compact membrane roofs because these products have a low diffusion resistance. On contrary, products made of PE, FPO or modified bitumen should not be used in compact membrane roofs.
- 3) Thickness of waterproof membranes should be as low as possible from a view of diffusion. On the other hand, waterproof membranes must have such thickness so that it will not be easily punctured. An ideal thickness seems to be about 1,2mm to 1,5mm.

If a vapour retarder is properly sealed against water penetration and thermal insulation material in roof assembly is resisted against moisture (extruded polystyrene) the thickness of waterproof membranes may be lower than 1mm. In

this case, the roof assembly resembles protected membrane roof assembly and the function of the membrane resembles a separation layer.

- 4) If a layer with high diffusion resistance is placed below waterproof membrane an expansion layer must be placed between the layer and waterproof membrane.

Thermal Insulation Layer

- 1) Material for thermal insulation layer does not play an important role in the compact membrane roof assembly with vapour retarder from a moisture point of view because waterproof membrane and vapour retarder have much higher diffusion resistance.
- 2) Thermal insulation material should be placed in the roof assembly in two rows and insulation boards should be placed as close to each other as possible so that thermal and diffusion bridges are minimized.

Vapour Retarder

- 1) Vapour retarder in the compact membrane roof assembly should be designed only as the secondary waterproof system. Therefore, vapour retarder should be provided with slope and connected to a drainage system of the roof.
- 2) Vapour retarder must be untied and properly vapour proofly sealed to all openings. The sealing material must have the same or higher diffusion resistance as the vapour retarder and must also have the same or higher lifetime. Diffusion bridges should not be created.
- 3) Vapour retarder should be placed on the interior side of the roof assembly as much as possible but not below a silicon layer or layers that contains free water.
- 4) Material for vapour retarder should have such diffusion properties so that moisture transport is reduced and moisture does not accumulate inside the roof assembly. The results of experiment showed that bitumen membranes are preferable to foil membranes because they are more resistant against damage.
- 5) Vapour retarder should adhere to the under layer so that multidimensional diffusion of vapour beneath vapour retarder does not occur when vapour retarder is perforated. The expansion layer should not be designed below vapour retarder.

Slope Layer

- 1) Regarding moisture transport, slope layers are not as important as the previous layers of compact membrane roofs. Compact membrane roofs should be evaluated on moisture transport in places where a slope layer has the maximum and minimum thickness of the layer.
- 2) The best solution is to design supporting structures with a slope already. Then the slope layer is not necessary in roof assemblies.
- 3) Lightweight materials with a low thermal conductivity are preferable for the slope layer (e.g. expanded polystyrene or aerated concrete).

Stabilization of the Roof Assembly

- 1) No type of stabilization of the compact membrane roof assembly should create thermal and diffusion bridges. That is the reason why fully adhered systems and stabilization with the help of pavers or ballast of stones should be preferred to mechanically fastened systems.

- 2) If pavers or ballast of stones are used as the stabilization system of the compact membrane roof assembly this layer should be taken into account for the calculation of moisture transport within the roof assembly.
- 3) If fully adhered systems are used for the stabilization of roof assemblies fully spread adhesive layers should be taken into account when moisture transport is calculated.

5.2.2 Recommendations - Compact Membrane Roof Assembly without Vapour Retarder

Waterproof Membrane

- 1) Design principles for waterproof membrane in the compact membrane roof assembly without vapour retarder are the same as for the compact membrane roof assembly with vapour retarder.

Thermal Insulation Layer

- 1) Diffusion resistance of the thermal insulation layer should be as high as possible because a high diffusion resistance reduces vapour transport from the interior environment to the roof assembly. Then the amount of interstitial condensation below waterproof membrane and the risk of degradation of thermal insulation materials are also reduced.
- 2) The order of common used thermal insulation materials from a view of moisture transport is: cellular glass insulation boards, expanded polystyrene boards, polyurethane boards, and mineral insulation boards.
- 3) Thermal insulation boards should be placed in the roof assembly in two rows and insulation boards should be placed as close to each other as possible so that thermal and diffusion bridges are minimized.

Slope Layer and Stabilization of the Roof Assembly

- 1) Design principles for slope layer and for stabilization of the roof assembly in the compact membrane roof assembly without vapour retarder are the same as for the compact membrane roof assembly with vapour retarder.

Chapter 6: Conclusions and Recommendations for Further Work

6.1 Major Findings

These two last chapters summarize the major findings of the Thesis and provide the recommendations for further future scientific work. This chapter finishes the Thesis and presents conclusions according to the individual objectives of the Thesis. Only major finding are presented here, other conclusions can be found in each chapter of the Thesis.

The Thesis brings new knowledge of compact membrane roof design, of moisture and heat transport through building materials and of water vapour permeability measurements. I would highlight the chapter in that the methods of water vapour permeability measurements are discussed. This complex summary has not existed in available technical literature, yet.

The experimental apparatus for water vapour permeability measurement was successfully suggested, built up and described in this Thesis. This apparatus facilitates to measure diffusion properties of thin very low permeable products. The apparatus and the measurement method is unique in the world because it reduces the buoyancy effect and leakage through the sealant. The final results indicate that the experimental apparatus provides very accurate measurements up to the sd-value of 200m, over which the results vary more than 10% within each product.

The unique results of the measurement proved that the sd-value of perforated products with high diffusion resistance significantly decreases with increasing percentage of perforation. The used percentage of perforation was much smaller, and sd-values of products higher than in previous known studies. The results of the measurement proved that perforation of vapour retarders or diffusion bridges must be taken into account when hygrothermal behaviour of building envelope assemblies is simulated.

On the basis of the results, an analytical equation that described vapour transport through thin low permeable products with certain percentage of perforation was suggested. The equation showed a very good agreement with experimental results and also with results from similar known studies. Therefore the model can indicate how much moisture will be transported through perforated low-permeable thin layers such as aluminium sheets or membrane foils. However, the analytical model has limitations that are described in relevant chapter.

The numerical simulations of coupled heat and moisture transport through selected compact membrane roof assemblies were done with the help of the Künzels numerical model that described transport of phenomena more precisely than the Glaser methods. The results of the simulations showed several interesting things. The dominant potential for moisture transport is the temperature gradient that is caused by short- and long-wave radiation. The radiation is neglected in the Glaser (standard) methods.

Three different requirements on moisture transport within building envelopes were compared. The comparison showed that the Czech standard requirements are very strict compared to the others. The strict standard requirements on moisture transport and neglecting short- and long-wave radiation causes that vapour retarders have to be designed in compact membrane roof assemblies.

The results of the simulation showed that compact membrane roof assemblies can be designed without vapour retarders in certain cases especially if short- and long-wave radiation can be taken into account. The use of vapour retarders together with waterproof membrane creates a moisture trap. The evaporation potential of this roof is small and when waterproof membrane is perforated and rain leaks into the roof assembly, a huge amount of

moisture between vapour retarder and waterproof membrane is trapped and accumulates. Accumulation of moisture content inside building envelopes may reduce the lifetime of the whole roof assembly.

The results proved that there are not exact general rules or conditions when a special type of a roof assembly should be designed. Each roof assembly is always unique and it cannot be generalize. Each roof assembly should be properly evaluated according to outdoor and indoor climate conditions by a state-of-art simulation tool that solves coupled moisture, air and heat transport.

The previous chapter brings several new recommendations how to design compact membrane roofs more efficiently from a view of moisture transport. These principles facilitate longer lifetime for the compact membrane roof assemblies.

All objectives of the Thesis were successfully accomplished.

6.2 Recommendations for Further Work

It is difficult to say how the research in building envelope structures will go on. It is more important to say that the research will continue. From my point of view, the main focus will be on materials and the development of new materials with excellent hygrothermal properties like it happened in the recent past, for example, with extruded polystyrene or cellular glass insulation. The main focus will be given on transparent materials and building components as windows or curtain walls because these components are still the weakest point in the building enclosure. The future may bring building envelopes that will be intelligent, self reacting on changes in indoor and outdoor climate conditions. These structures will behave like a human skin. Distribution systems of some media in the envelope will hold a constant indoor environment although outdoor conditions will change quickly. The future brings more specialization in the building design. Some of the designers will focus only on pitched roof assemblies and others on flat roof assemblies. Narrow specialization will bring more efficient structures from a point of view of used materials and energy.

The other focus in the research may be given on experimental methods that will properly measure physical quantities of materials. Physical quantities of materials will not be determined as a constant or a function depending only on one variable. Physical quantities of materials will be determined as a field that will be dependant on several physical quantities of the material and on statistical distribution of these quantities. Lot of new experimental approaches, that will describe materials properties properly, will be discovered.

From my point of view, I see the slowest development in physical methods that describe the reality. This development was very slow in the past and will be slow in future. The physical approach will slowly change from deterministic methods to stochastic methods but the physical bases will remain the same.

References

- ASHRAE (1997). *ASHRAE Handbook, Fundamentals*. Atlanta: ASHRAE.
- ASHRAE 160P. (2006). *Design Criteria for moisture Control in Buildings*. SPC Approved Draft for Publication/Public Review.
- ASHREA (2005). Chapter 23 - Thermal and Moisture Control in Insulated Assemblies-Fundamentals. In *ASHRAE Handbook – Fundamentals (SI)*. Atlanta: ASHRAE
- ASTM E 96/E 96M. (2005). *Standard Test Methods for Water Vapor Transmission of Materials*. West Conshohocken: ASTM International.
- Bauer, W. (1965). Influence of holes on water-vapor permeability of vapor-checking surface layers. In *Symposium Moisture Problems in Buildings*. Helsinki: RILEM-CIB.
- Bazant, Z.P. & Najjar, L.J. (1972). Nonlinear water diffusion in nonsaturated concrete. *Materials and Structures*, 5(25), 3-20.
- Bomberg, M. (1979). Testing Water Vapor Transmission: Unresolved Issues. In H.P. Trechsel & M. Bomberg (Eds), *Water Vapor Transmission Through Building Materials and Systems. Mechanisms and Measurement* (pp.157-167). Philadelphia: ASTM STP.
- Bomberg, M., Pazera, M., Haghghat, F. & Grunewald, J. (2002). Modified cup for testing of water vapour transmission through thick, permeable materials. In *Building Physics 2002. 6th Nordic Symposium* (pp.373-380).
- Branauer, S., Emmett, P.H. & Teller, E. (1938). Adsorption of Gases in Multimolecular Layers. *Journal of Amer. Chem. Soc.* 60(2), 309-319.
- BS 5250 (2002). *Code of Practice for Control of Condensation in Buildings*. BSI.
- BS 6229 (2003). *Flat Roofs with continuously supported covering. Code of Practice*. BSI.
- Burch, D.M. & Desjarlais, A.O. (1995). Water-Vapor Measurements of Low-Slope Roofing Materials. Gaithersburg: NIST 5681.
- Burch, D.M., Thomas, W.C. & Fanney, A.H. (1992). Water Vapor Permeability Measurements of Common Building Materials. *ASHRAE Transaction*, 98(2), 486-495.
- Cammerer, J. & Achtziger, J. (1985). Einfluss des Feuchtegehaltes auf die Wärmeleitfähigkeit von Bau- und Dämmstoffen (Effect of the moisture content on the thermal conductivity of building materials and insulation products). *Kurzberichte aus der Bauforschung* (115), 401-406. [in German]
- Cash, C.G. (1985). Moisture and Build-Up Roofing. In *Proceeding 2nd International Symposium on Roofing Technology* (pp.416-427). Rosemont: National Roofing Contractors Association.
- Chaloupka, K. & Šála, J. (2002). *Ploché střechy a pěnový polystyren, Izolační praxe 3*. (Flat Roofs and expanded polystyrene, Isolation practice). Prague: Association EPS.
- Chaloupka, K. (2003). *Jak parotěsná je parozábrana v ploché střeše?* (How vapour tight is a vapour redarder in a flat roofs?) [online]. Last upgrade 10.12.2003. Link: <<http://www.strechaspecial.cz/text13.html> [in Czech]
- Chang, S.C., & Hutcheon, N.B. (1956). Dependence of Water Vapor Permeability on Temperature and Humidity. *ASHRAE Transaction*, 62(1581), 437-449.

- ČSN 727030 (2000). *Stanovení součinitele difúze vodní páry stavebních materiálů. Všeobecná část.* (Determination of water vapour permeability of building materials. General information). Praha: ČNI. [in Czech]
- ČSN 727031 (1975). *Měření součinitele difúze vodní páry stavebních materiálů metodou bez teplotního spádu.* (Isothermal measurement of water vapour permeability of building materials). Praha: ČNI. [in Czech]
- ČSN 730540 (1964). *Tepelně technické vlastnosti stavebních konstrukcí.* (Hygrothermal Properties of Building Structures). Praha: ČNI. [in Czech]
- ČSN 730540-2 (1994). *Tepelná ochrana budov – Část 2: Funkční požadavky.* (Thermal Protection of Buildings – Part 2: Functional Requirements). Praha: ČNI. [in Czech]
- ČSN 730540-2 (2007). *Tepelná ochrana budov – Část 2: Požadavky.* (Thermal Protection of Buildings – Part 2: Requirements). Praha: ČNI. [in Czech]
- ČSN 730540-3 (2005). *Tepelná ochrana budov – Část 3: Návrhové hodnoty veličin.* (Thermal Protection of Buildings – Part 3: Design value quantities). Praha: ČNI. [in Czech]
- ČSN 730540-4 (2005). *Tepelná ochrana budov – Část 4: Výpočtové metody.* (Thermal Protection of Buildings – Part 4: Calculation Methods). Praha: ČNI. [in Czech]
- ČSN 731901 (1999). *Navrhování střech – Základní ustanovení.* (Roof Design – Basic Provisions). Praha: ČNI. [in Czech]
- ČSN EN 12524 (2001). *Stavební materiály a výrobky – Tepelně vlhkostní vlastnosti – Tabulkové návrhové hodnoty.* (Building materials and products - Hygrothermal properties – Tabulated design values). Praha: ČNI. [in Czech]
- ČSN EN 1931 (2001). *Hydroizolační pásy a fólie – Asfaltové, plastové a pryžové pásy a fólie pro hydroizolaci střech – Stanovení propustnosti vodní páry.* (Flexible sheets for waterproofing. Bitumen, plastic and rubber sheets for roof waterproofing. Determination of water vapour transmission properties). Praha: ČNI. [in Czech]
- ČSN EN ISO 12572. (2002). *Tepelně vlhkostní chování stavebních materiálů a výrobků. Stanovení prostupu vodní páry.* (Hygrothermal Performance of Building Materials and Products – Determination of Water Vapour Transmission Properties). Praha: ČNI. [in Czech]
- ČSN EN ISO 13788 (2002). *Tepelně vlhkostní chování stavebních dílců a stavebních prvků – Vnitřní povrchová teplota pro vyloučení kritické povrchové vlhkosti a kondenzace uvnitř konstrukce – Výpočtové metody.* (Hygrothermal performance of building components and building elements – Internal surface temperature to avoid critical surface humidity and interstitial condensation – Calculation methods). Praha: ČNI. [in Czech]
- Darcy, H. (1856). *Les Fontaines Publiques de ville de Dijon* (Public Fountains in the City of Dijon), Dalmont Paris.[in French]
- de Vries, D.A. (1987). The theory of heat and moisture transfer in porous media revisited. *International Journal Heat and Mass Transfer*, 30(7), 1343-1350.
- Derome, D., Derluyn, D., Zillig, W. & Carmeliet, J. (2008). Model for hysteretic moisture behaviour of wood. In C.Rode (Ed), *Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, Volume 2* (pp. 959-965). Lyngby: Technical University of Denmark.
- DIN 4108-3 (2001). *Wärmeschutz und Energie-Einsparung in Gebäuden - Teil 3: Klimabedingter Feuchteschutz; Anforderungen, Berechnungsverfahren und Hinweise für Planung und Ausführung.* (Thermal protection and energy economy in

- buildings - Part 3: Protection against moisture subject to climate conditions; Requirements and directions for design and construction). [in German]
- Dutt, O., Lavallée, C. & Ashton, H.E. (1994). Infrared Technique as a Research Tool for Measuring Water Vapor Transmission of Roofing Membranes. *Journal of Testing and Evaluation*, 21(3), 199-210.
- Fajkoš A. (1997). *Ploché střechy*. (Flat roofs). Brno: Akademické nakladatelství CERM. [in Czech]
- Fanney, A.H., W.C. Thomas, D.M. Burch & L.R. Mathena, Jr. (1991). Measurements of moisture diffusion in building materials. *ASHRAE Transactions*, 97(2), 99-113.
- Fick, A. (1855). Über diffusion. *Annalen der Physik und Chemie* 94, 59-86. [in German]
- Galbraith, G.H., Kelly, D.J. & McLean, R.C. (2004). Moisture permeability measurements under reduced barometric pressures. *Materials and Structures*, 37(June), 311-317.
- Galbraith, G.H., McLean, R.C., Tao, Z. & Kang, N. (1992). The comparability of water vapour permeability measurements. *Building Research and Information*, 20(5), 364-375.
- Galbraith, G.H., McLean, R.C., Gillespie, I. Guo, J. & Kelly, D.J. (1998). Nonisothermal moisture diffusion in porous building materials. *Building Research & Information*, 26(6), 330-339.
- Glaser, H. (1959). Grapisches Verfahren zur Untersuchung von Diffusionsvorgängen (Graphical Procedure for investigating Diffusion). *Kaltetechnik*, 11, 345-355. [in German]
- Griffin, C.W. & Fricklas R.L. (2006). *Manual of Low-Slope roof systems*. New York: McGraw-Hill.
- Hajšman, L. (2000). *Analýza vlastností soustavy. Obvodový plášť – finální nátěr* (Analysis of component properties. Wall Assembly – Final Finish). PhD Thesis. Prague: Czech Technical University in Prague.
- Hansen, K.K. & Bertelsen, N.H. (1989). Results of a Water Vapor Transmission Round-Robin Test Using Cup Methods. In H.P. Trechsel & M. Bomberg (Eds), *Water Vapor Transmission Through Building Materials and Systems. Mechanisms and Measurement* (pp.91-100). Philadelphia: ASTM STP.
- Hansen, K.K. & Lund, H.B. (1990). Cup Method for Determination of Water Vapor Transmission Properties of Building Materials. Sources of Uncertainty in the Method. In J.V. Thue (Ed), *Proceedings of the 2nd Symposium, Building Physics in the Nordic Countries* (pp.291-298). Trondheim: Tapir Publishers.
- Hedenblad, G. (1996). *Moisture permeability of mature concrete, cement mortar and cement paste*. PhD Thesis. Lund: LTH Lund University.
- Hens, H. (2006). The vapor diffusion resistance and air permeance of masonry and roofing systems. *Building and Environment*, 41, 745-755.
- Hens, H., Janssens, A. & Zheng, R. (2003). Zinc roofs: an evaluation based on test house measurements. *Building and Environment* 38, 795-806.
- Hill, D. (2003). Review of Hygrothermal Models for Building Envelope Retrofit Analysis. *Research Highlights, Canada Mortgage and Housing Corporation*, November, 1-4.
- Hutcheon, N.B. (1989). Forty Years of Vapour Barriers. In H.P. Trechsel & M. Bomberg (Eds), *Water Vapor Transmission Through Building Materials and Systems. Mechanisms and Measurement* (pp.5-7). Philadelphia: ASTM STP.

- ISO 7783-1. (1996). *Paints and varnishes - Determination of water vapour transmission rate – Part 1: Dish method for free films*. Geneva: ISO.
- Joy, F.A. & Wilson, A.G. (1963). Standardization of the Dish Method for Measuring Water Vapour transmission. In *Proceedings of the international Symposium on Humidity and Moisture 4* (pp.259-270). Washington, DC.
- Karagiozis, A., Desjarlais, A. & Salonvaara, M., (2002). Sensitivity of Low Sloped Roofs Designs to Initial Water and Air Leakage. In *Hot and Humid Symposium* (pp. 547 – 554). Houston.
- Karagiozis, A.N. (2001). Advanced Numerical Models for Hygrothermal Research. In H.R. Trechsel (Ed), *Moisture Analysis and Condensation Control in Building Envelopes* (pp.90-106). West Conshohocken: American Society for Testing and Materials.
- Korsgaard, V. & Pedersen, C.R. (1992). Laboratory and Practical Experience with a Novel Water-Permeable Vapour Retarder. In *Proceedings Thermal Envelopes V* (pp. 480-490): ASHRAE.
- Krischer, O. & Kast, W. (1978). *Die Wissenschaftlichen Grundlagen der Trocknungstechnik* (The scientific principles of drying technology). Berlin: Springer-Verlag.[in German]
- Krupka, J. (2005). Kotevní prvky (Anchor elements). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.228-238). Praha: Informační centrum CKAIT. [in Czech]
- Krus, M. (1996). *Moisture Transport and Storage Coefficients of Porous Mineral Building Materials. Theoretical Principles and New Test Methods*. PhD Thesis. Stuttgart: Fraunhofer IRB Verlag.
- Kumaran, M.K. (1998a). Interlaboratory Comparison of the ASTM Standard Test Methods for Water Vapor Transmission of Materials (E96-95). *Journal of Testing and Evaluation*, 26 (2), 83-88.
- Kumaran, M.K. (1998b). An Alternative Procedure for the Analysis of Data from the Cup Method Measurements for Determination of Water Vapor Transmission Properties. *Journal of Testing and Evaluation*, 26(6), 575 – 581.
- Kumaran, M.K. (2001). Hygrothermal Properties of Building Materials. In H.R. Trechsel (Ed), *Moisture Analysis and Condensation Control in Building Envelopes* (pp.29-65). West Conshohocken: American Society for Testing and Materials.
- Kumaran, M.K. (2006). A Thermal and Moisture property Database for Common Building and Insulation Materials. *ASHREA Transactions*, 112(2), 485-497.
- Kumaran, M.K., Lackey, J.C., Normandin, N. & van Reenen, D. (2006). Vapor permeances, air permeances, and water absorption coefficients of building membranes. *Journal of testing and Evaluation*, 34 (3), 241-245.
- Künzel, H.M. & Kiessl, K. (1996). Assessing precipitation heat losses of protected membrane roofs. In *Proceedings IEA-Annex 24 Closing Seminar*. Finland
- Künzel, H.M. (1995). *Simultaneous Heat and Moisture Transport in Building Components. One- and two-dimensional calculation using simple parameters*. PhD Thesis. Stuttgart: Fraunhofer Institute of Building Physics.
- Künzel, H.M. (1998). More Moisture Load Tolerance of Construction Assemblies Through the Application of a Smart Vapor Retarder. In *Proceeding Thermal Envelopes VII* (pp.129-132). Clearwater Beach: ASHRAE.

- Künzel, H.M. (1999). Flexible Vapor Control Solves Moisture Problems of Building Assemblies – Smart Retarder to Replace the Conventional PE-film. *Journal of thermal Envelope and Building Science*, 23(July), 95-102.
- Künzel, H.M. (2005). Adapted vapour control for durable building enclosures. In 10th *International Conference on Durability of Building Materials and Components*. Lyon.
- Künzel, H.M., Karagiozis, A.N. & Holm, A.H. (2001). A Hygrothermal Design Tool for Architects and Engineers (WUFI ORNL/IBP). In H.R. Trechsel (Ed), *Moisture Analysis and Condensation Control in Building Envelopes* (pp.136-151). West Conshohocken: American Society for Testing and Materials.
- Kutnar, Z. (2005). Vývoj skladeb plochých střech – interakce vad a poruch. (Development of Flat Roof Assemblies – interaction defects and failures). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.284-305). Praha: Informační centrum CKAIT. [in Czech]
- Lackey, J.C., Marchand, R.G. & Kumaran, M.K. (1997). A Logical Extension of the ASTM Standard E96 to Determine the Dependence of Water Vapour Transmission on Relative Humidity. In R.S. Graves & R.R. Zarr (Eds), *Insulation Materials: Testing and Applications* (pp. 456-470). Philadelphia: ASTM STP.
- Langlais, C., Silberstein, A. & Sandberg, P.I.(1994). Effect of Moisture on the Thermal Performance of Insulating Materials. In H.R.Trechsel (Ed), *Moisture Control in Buildings* (pp.54-71). Philadelphia: ASTM.
- Lstiburek, J.W. (2002). Moisture control for buildings. *ASHRAE Journal* 44(2), 36-41.
- Lstiburek, J.W. (2004). Understanding Vapor Barriers. *ASHRAE Journal* 46(August), 40-47.
- Luikov, A.V. (1973). Systems of Differential Equations of Heat and Mass Transfer in Capillary-Porous Bodies. *International Journal of Heat, Mass Transfer*, 18,1-14.
- McGlashan, M.L. (1971). *Physicochemical Quantities and Units*. London: The Royal Institute of Chemistry.
- Mrlík, F. (1980). Problémy při výzkumu difúze vodních par ve stavebních materiálech a konstrukcích (Research problems of water vapour diffusion in buildings materials and structures). *Zdravotní technika a vzduchotechnika*, 23(6), 321-337.[in Czech]
- Mrlík, F. (1985). *Vlhkostné problémy stavebných materiálů a konstrukcí* (Moisture problems of building materials and structures). Bratislava: Alfa. [in Slovak]
- Mrlík, F. (1986). *Vlhkostní a tepelné technické konstanty stavebních materiálů a konstrukcí*. (Moisture and Heat Constants of Building Materials and Structures). Praha: VÚPS. [in Czech]
- Mukhopadhyaya, P., Kumuran, M.K. & Lackey, J. (2005). Use of the Modified Cup Method to Determine Temperature Dependency of Water Vapor Transmission Properties of Building Materials. *Journal of Testing and Evaluation*, 33(5), 1-7.
- Novotný, M. & Misar, I. (2003). *Ploché střechy*. (Flat roofs). Praha: Grada Publishing. [in Czech]
- Oláh, J. (2002). História a súčasnosť plochých a šikmých striech (History and Contemporary of Flat and Sloped Roofs). *Střechy, fasády, izolace*, (1),14-15. [in Slovak]
- Oláh, J. (2005a). Základní pojmy. (Basic therms). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.11-15). Praha: Informační centrum CKAIT. [in Czech]

- Oláh, J. (2005b). Historia plochých střechech. (History of Flat Roofs). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.11-15). Praha: Informační centrum ČKAIT. [in Slovak]
- Padfield, T., Peuhkuri, R., Rode C. & Hansen K.K.(2002). Non-Isothermal Water Vapour Transmission through Porous Insulation. In *6th symposium on building physics in the Nordic countries, Part 1: Equipment*. Trondheim.
- Pedersen, C.R. (1990). *Combined Heat and Moisture Transfer in Building Constructions*. Ph.D. Thesis. Lyngby: Technical University of Denmark.
- Peuhkuri, R. (2003). *Moisture Dynamics in Building Envelopes*. PhD Thesis. Lyngby: Denmark Technical University.
- Peuhkuri, R., Rode, C. & Hanssen, K.K. (2008). Non-isothermal moisture transport through insulation materials. *Building and Environment*, 43, 811-822.
- Phillip, J.R. & de Vries, D.A. (1957). Moisture Movement in Porous Media Under Temperature Gradients. *Transactions of the American Geophysical Union* 38, 222-232.
- Rose, B.R. (1997). Moisture control in the Modern Building Envelope: history of the Vapor Barrier in the U.S., 1923-52. *APT Bulletin* 28(4), 13-19.
- Schirmer, R. (1938). Diffusionszahl von Wasserdampf-Luft-Germischen und die Verdampfungsgeschwindigkeit (Diffusion coefficient of water vapour – air mixtures and rate of evaporation). *Beiheft Wrfahrenstechnik*, No.6, 170-177. [in German]
- Schule W. & Reichardt I. (1980). Wasserdampfdurchgang durch Öffnungen (Moisture flux through holes). *Zeitschrift für Warmeschutz, Kälteschutz, Brandschutz, WKSB-Sonderausgabe*, August, 12-16. [in German]
- Schwartz, N.V., Bomberg, M. & Kumuran, M.K. (1989). Water Vapor Transmission and Moisture Accumulation in Polyurethane and Polyisocyanurate Foams. In H.P.Trechsel & M.Bomberg (Eds), *Water Vapor Transmission Through Building Materials and Systems. Mechanisms and Measurement* (pp.63-72). Philadelphia: ASTM STP.
- Schwarz, B. (1971). *Die Wärme- und Stoffübertragung an Aussenwandoberflächen* (Heat and material transfer in outdoor wall surfaces). PhD Thesis. Stuttgart: Stuttgart Technical University. [in German]
- Seiffert, K. (1960). Messungen vom diffusionswiderstandsfaktoren (Measurements of diffusion resistance Factors). *Kaltetechnik*, 12(7), 187-190. [in German]
- Seiffert, K. (1971). *Damp Diffusion and Buildings. Prevention of Damp Diffusion Damage in Building Design*. New York: Elsevier publishing company limited.
- Šilarová, Š. (2005a). Střechy jednoplášťové. (Compact roofs). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.100-116). Praha: Informační centrum ČKAIT. [in Czech]
- Šilarová, Š. (2005b). Stabilizační vrstva (Ballasted layer). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.228). Praha: Informační centrum ČKAIT. [in Czech]
- Slanina, P. & Silarova, S. (2006). Difuzní mosty (Diffusion bridges). *Strechy, fasady, izolace*, 13(4), 66-67. [in Czech]
- Slanina, P. (2004). *Definování parotěsné vrstvy u plochých jednoplášťových střechech. (A definition of a vapour retarder for compact membrane roofs)*. Diploma thesis. Praha: Czech Technical University. [in Czech]

- Spoel van der W. (2003). Water vapour transport through perforated foils. In: J. Carmeliet, H. Hens and G. Vermeir (Eds), *Research in building physics: proceedings of the 2nd International Conference on Building Physics* (pp.207-215). Leuven: Lisse, Exton, Pa, A.A. Balkema.
- STN 73 1901 (2005). Navrhovanie striech – Zakladne ustanovenia. (Roof Design – Basic Provisions). Bratislava: STN. [in Slovak]
- Suprenant, B.A. & Malisch, W.R. (1998). Don't puncture the vapor retarder. *Aberdeen's Concrete Construction*, 43(12), 1071-1075.
- TenWolde, A. (2001). Manual Analysis Tools. In H.R. Trechsel (Ed), *Moisture Analysis and Condensation Control in Building Envelopes* (pp.107-115). West Conshohocken: American Society for Testing and Materials.
- Time B. & Uvsløkk S. (2003). *Intercomparison on measurement of water vapour permeance*. Oslo: Norges byggforskningsinstitutt.
- Toas, M. (1989). Results of the (1985) Round/Robin Test Series using ASTM E96-80. In H.P.Trechsel & M.Bomberg (Eds), *Water Vapor Transmission Through Building Materials and Systems. Mechanisms and Measurement* (pp.73-90). Philadelphia: ASTM STP.
- Tobiason, W. (1989). Vapor Retarder for Membrane Roofing Systems. In *Proceedings, Ninth Conference on Roofing Technology*. Oak Park: National roofing contractors Association.
- Tobiasson, W. (1994). General Considerations for Roofs. In H.R.Trechsel (Ed), *Moisture Control in Buildings* (pp.35-53). Philadelphia: ASTM.
- Tveit, A. (1966). *Measurements of moisture sorption and moisture permeability of porous materials*. Oslo: Norwegian building research institute.
- Tye, R.P. (1994). Relevant Moisture Properties of Building Construction Materials. In H.R.Trechsel (Ed), *Moisture Control in Buildings* (pp.35-53). Philadelphia: ASTM.
- Viitanen H. & Bjurman J. (1995). Mould growth on wood under fluctuating humidity conditions. *Mat. und Org.* 29(1), 27-46.
- Viitanen, H. & Salonvaara, M. (2001). Failure Criteria. In H.R. Trechsel (Ed), *Moisture Analysis and Condensation Control in Building Envelopes* (pp.66-80). West Conshohocken: American Society for Testing and Materials.
- Vykydal, L., Chaloupka, K. & Hanzalová, L. (2005). Hydroizolační vrstva (Waterproofing layer). In L. Hanzalová & Š.Šilarová (Eds), *Ploché střechy* (Flat roofs) (pp.149-192). Praha: Informační centrum CKAIT. [in Czech]
- WTA 6-2-01 (2004). *Simulation of heat and moisture transfer*. Munchen: WTA Publicatons.
- Zarr, R.R., Burch, D.M. & Fanney, A.H. (1995). *Heat and Moisture transfer in Wood-Based Wall Construction: Measured Versus Predicted*. Gaithersburg: NIST Building Science Series 173.

Author's Related Publications

- Slanina, P. & Šilarová, Š. (2008). Moisture transport through perforated vapour retarders, *Building and Environment*, doi:10.1016/j.buildenv.2008.10.006 – IF2007: 0,852
- Slanina, P. & Šilarová, Š. (2008). Measurement of Moisture Transport through Perforated Vapour Barriers. In C. Rode (Ed), *Proceedings of the 8th Symposium on Building Physics in the Nordic Countries* (pp. 785-800), Copenhagen: Technical University of Denmark
- Zirkelbach, D., Künzel, H.M. & Slanina, P. (2008) Einfluss von Undichtheiten bei der Sanierung von Plattenbauten mit Wärmedämm-Verbundsystemen. In J. Gänssmantel et al. (Eds), *WTA Almanach 2008* (pp. 285-297), München: WTA-Publications
- Slanina, P. & Šilarová, Š. (2008). Measurement of Moisture Transport through Perforated Vapour Barriers. *Nordic Journal of Building Physics*, (in print)
- Slanina, P. (2008). Ideální návrh ploché střechy z hlediska šíření vlhkosti. In *Zborník zo sympozia Strechy 2008* (pp. 133-140), Bratislava: Slovak Technical University, Slovak Roofing Guild
- Slanina, P. (2008). Moisture Transport in Flat Roofs with Perforated Vapour Barriers. In *Proceeding of Workshop 2008* (pp.482-483), Prague: Czech Technical University
- Slanina, P. (2007). Moisture Transport in Flat Roofs. In *International Conference VSU 2007 (1)* (pp. II-123-II-129), Sofia, VSU
- Slanina, P. (2007). Difúzní vlastnosti proděravěné parotěsnicí vrstvy. In *Zborník zo sympozia Strechy 2007* (pp. 141-145), Bratislava: Slovak Technical University, Slovak Roofing Guild
- Slanina, P. (2007). Difúzní vlastnosti materiálů a jejich vliv na transport vodní páry – teorie versus tepelně technické normy. In *Spolehlivost, optimalizace a trvanlivost stavebních materiálů a konstrukcí*, Praha: Czech Technical University
- Slanina, P. (2007). Návrh střechy z hlediska transportu vlhkosti. *Prezentace stavebních materiálů (2)*, 79-81
- Slanina, P., Husáková, V., Kalináč, J. & Pokorný, M. (2007). Difúzní vlastnosti materiálů plochých střech a jejich vliv na tepelně technický výpočet. In *Juniorstav 2007* (pp. 39-44), Brno: Technical University
- Slanina, P. (2006). Vlhkostní režim v plochých střechách. In *Zborník zo sympozia Strechy 2006* (pp. 205-209), Bratislava: Slovak Technical University, Slovak Roofing Guild
- Slanina, P. (2006). Difúzní vlastnosti materiálů z pohledu nových tepelně technických norem, In *Tepelná ochrana budov 2006* (pp.153-156), Praha: Contour s.r.o.
- Slanina, P. (2006). Vliv nehomogenit parotěsnicí vrstvy na funkčnost střešních plášťů, In *Poruchy a rekonštrukcie obvodových plášťov a striech 2006* (pp.70-75). Podbánské: Technical University Kosice
- Slanina, P. (2006). Vlastnosti nehomogenních parotěsnících vrstev, In *Spolehlivost, optimalizace a trvanlivost tavebních konstrukcí 2006* (pp. 47-50). Praha: Czech Technical University

- Slanina, P. & Šilarová, Š. (2006). Difúzní mosty. *Střechy, fasády, izolace* (4)13, 66-67
- Slanina, P. (2006). Šíření vlhkosti ve střešních konstrukcích. In *Proceeding of Workshop 2006*, Prague: Czech Technical University
- Slanina, P. (2006). Šíření vlhkosti v jednoplášťových střešních konstrukcích. In *Juniorstav 2006* (pp. 173-177), Brno: Technical University
- Slanina, P. & Šilarová, Š. (2005). Difúzní mosty. In *Zborník zo sympozia Strechy 2005* (pp. 100-103), Bratislava: Slovak Technical University, Slovak Roofing Guild
- Slanina, P. & Šilarová, Š. (2005). Konstruktivní řešení střech, recyklace ve stavebnictví. In *Setkání kateder a ústavů pozemního stavitelství ČR a SR* (pp. 63-64), Prague: Czech Technical University
- Slanina, P. & Šilarová, Š. (2004). Vliv kotvení parotěsnicí vrstvy na její vlastnosti. In *Zborník zo sympozia Strechy 2004* (pp. 100-103), Bratislava: Slovak Technical University, Slovak Roofing Guild
- Slanina, P. (2004). Parozábrany v plochých střechách. *Střechy, fasády, izolace* (10) 11, 40-42
- Slanina, P. (2004). Všeobecně o parozábranách střech. *Střechy, fasády, izolace* (9)11, 76-78
- Slanina, P. (2004). Parotěsná vrstva – terminologie, rozdělení, navrhování. *Tepelná ochrana budov*(3)7, 13-16
- Slanina, P. & Šilarová, Š. (2004). Vliv kotvení parotěsné vrstvy na její vlastnosti. In *Tepelná ochrana budov 2004* (pp.99-103), Praha: Contour s.r.o.

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Appendixes

Appendix A

Measurement protocols

PE - Foil									
Date	Hour	Time [d]	Weight [g]				stage	Av.Temp [°C]	Av.RH [%]
			Sample1	Sample2	Sample3	Sample4			
14.2.2007	12:05	0,0	321,702	319,238	337,760	335,870			
19.2.2007	10:05	4,9	321,711	319,249	337,725	335,832			
22.2.2007	11:30	8,0	321,698	319,238	337,716	335,819	0	0	
26.2.2007	9:55	11,9	321,677	319,214	337,684	335,784		21,95	53,90
1.3.2007	13:25	15,1	321,660	319,197	337,658	335,759		22,37	53,58
5.3.2007	10:35	18,9	321,634	319,173	337,628	335,726		22,44	53,74
8.3.2007	11:10	22,0	321,597	319,134	337,590	335,683	1	22,56	53,70
12.3.2007	15:15	26,1	321,545	319,082	337,544	335,630		22,73	53,81
15.3.2007	10:05	28,9	321,524	319,056	337,516	335,602		23,00	53,83
19.3.2007	10:30	32,9	321,469	319,008	337,461	335,544		23,20	53,93
21.3.2007	10:30	34,9	321,444	318,982	337,436	335,515	3	21,84	53,86
23.3.2007	10:45	36,9	321,411	318,946	337,390	335,469		21,42	54,00
26.3.2007	10:50	39,9	321,352	318,890	337,336	335,412		22,04	53,78
29.3.2007	10:30	42,9	321,291	318,838	337,273	335,345		22,51	53,87
2.4.2007	10:00	46,9	321,220	318,766	337,204	335,271		22,76	53,90
4.4.2007	11:15	49,0	321,153	318,701	337,135	335,203	6	23,47	54,17
6.4.2007	9:35	50,9	321,101	318,642	337,078	335,136		23,36	54,26
10.4.2007	9:20	54,9	320,984	318,530	336,955	335,014		23,65	54,55
13.4.2007	11:05	58,0	320,819	318,369	336,787	334,842	12	24,50	55,10
16.4.2007	9:00	60,9	320,666	318,226	336,634	334,680		24,90	55,46
17.4.2007	9:10	61,9	320,614	318,172	336,577	334,626		25,14	55,03
18.4.2007	10:35	62,9	320,501	318,057	336,461	334,556	24	25,36	55,58
19.4.2007	9:20	63,9	320,411	317,972	336,377	334,463		25,11	55,82
20.4.2007	13:55	65,1	320,295	317,857	336,253	334,336		25,05	55,85

Bitumen membrane										
Date	Hour	Time [d]	Weight [g]				stage	Av.Temp [°C]	Av.RH [%]	A press. [Pa]
			Sample1	Sample2	Sample3	Sample4				
7.5.2007	20:55	0,0	497,922	495,474	485,433	488,955				
10.5.2007	11:02	2,6	497,971	495,520	485,484	489,017				
14.5.2007	9:15	6,5	497,995	495,548	485,512	489,042				
17.5.2007	9:47	9,5	497,987	495,544	485,515	489,051				
21.5.2007	9:35	13,5	497,990	495,548	485,520	489,053				
24.5.2007	9:48	16,5	497,993	495,553	485,521	489,059				
28.5.2007	9:14	20,5	497,989	495,552	485,529	489,060	0	0	0	0
31.5.2007	10:00	23,5	497,967	495,530	485,507	489,045		26,9	60,2	1005
4.6.2007	12:00	27,6	497,944	495,511	485,498	489,029		25,7	59,8	1013
7.6.2007	10:20	30,6	497,945	495,512	485,497	489,035		25,8	59,6	1009
11.6.2007	9:45	34,5	497,925	495,495	485,484	489,016		27,6	59,8	1006
14.6.2007	10:20	37,6	497,904	495,473	485,467	489,001		28,6	59,9	1002
18.6.2007	10:20	41,6	497,887	495,453	485,453	488,984	1p	29,0	60,1	1003
21.6.2007	11:05	44,6	497,868	495,438	485,444	488,980		28,5	60,0	1002
25.6.2007	13:15	48,7	497,850	495,419	485,430	488,954		28,6	60,0	1001
28.6.2007	14:30	51,7	497,833	495,401	485,413	488,943		27,4	60,0	1004
2.7.2007	13:45	55,7	497,820	495,387	485,402	488,935		25,9	59,5	1003
4.7.2007	17:30	57,9	497,809	495,378	485,390	488,927	1n	26,4	59,3	997
8.7.2007	14:25	61,7	497,785	495,353	485,366	488,907		25,7	59,0	1002
12.7.2007	12:30	65,6	497,772	495,339	485,355	488,900		25,3	59,5	1008
16.7.2007	10:25	69,6	497,782	495,354	485,369	488,922		24,6	59,1	1001
19.7.2007	10:25	72,6	497,744	495,310	485,339	488,886		27,0	59,4	1013
23.7.2007	10:45	76,6	497,717	495,279	485,300	488,861		28,0	59,9	1005
26.7.2007	11:25	79,6	497,688	495,250	485,279	488,837		27,4	59,8	1010
30.7.2007	12:50	83,7	497,653	495,213	485,241	488,807		26,2	60,0	1008
2.8.2007	12:50	86,7	497,637	495,195	485,227	488,798	3n	25,0	60,1	1007
6.8.2007	11:10	90,6	497,606	495,167	485,197	488,772		24,9	60,2	1007
9.8.2007	10:10	93,6	497,584	495,141	485,181	488,751		26,0	59,9	1001
14.8.2007	12:55	98,7	497,552	495,107	485,139	488,723		26,3	59,8	1009
21.8.2007	10:10	105,6	497,502	495,050	485,098	488,676		25,7	59,7	998
23.8.2007	14:35	107,7	497,485	495,033	485,073	488,665	6n	25,2	59,8	1008
27.8.2007	12:25	111,6	497,453	494,992	485,034	488,623		25,4	60,1	1016
30.8.2007	14:45	114,7	497,422	494,957	484,993	488,586		25,2	60,2	1010
3.9.2007	15:50	118,8	497,392	494,921	484,951	488,550		23,7	59,9	1004
6.9.2007	14:05	121,7	497,358	494,877	484,914	488,507	12n	22,8	60,1	1013
10.9.2007	10:55	125,6	497,328	494,848	484,890	488,468		22,0	60,1	1009
12.9.2007	12:15	127,6	497,306	494,816	484,866	488,446		22,0	60,0	1019
14.9.2007	11:45	129,6	497,281	494,790	484,836	488,411		22,0	60,0	1014
24.9.2007	14:30	139,7	497,174	494,680	484,728	488,281		22,0	60,0	1012
27.9.2007	16:00	142,8	497,155	494,650	484,704	488,244		22,0	60,0	1009

LD PE foil

Date	Hour	Time [d]	Weight [g]				stage	Av.Temp [°C]	Av.RH [%]	A press. [Pa]
			Sample1	Sample2	Blind test	Sample3				
13.7.2007	16:30	0,0	307,076	301,998	410,654	306,342				
16.7.2007	10:48	2,8	307,088	302,003	410,673	306,343				
19.7.2007	10:40	5,8	307,073	302,000	410,672	306,327				
23.7.2007	11:05	9,8	307,064	301,988	410,687	306,314	0	0	0	0
26.7.2007	11:45	12,8	307,049	301,979	410,688	306,301		27,9	52,2	1010
30.7.2007	13:10	16,9	307,028	301,960	410,691	306,285		26,9	52,2	1008
2.8.2007	13:10	19,9	307,024	301,957	410,698	306,275		25,5	51,7	1007
6.8.2007	11:35	23,8	307,004	301,937	410,700	306,258		25,9	51,6	1007
9.8.2007	10:30	26,8	306,992	301,917	410,706	306,237	1	27,2	51,2	1001
14.8.2007	13:10	31,9	306,965	301,871	410,714	306,196		26,9	51,7	1009
21.8.2007	10:30	38,8	306,934	301,820	410,722	306,145		26,5	51,5	998
23.8.2007	14:50	40,9	306,905	301,785	410,724	306,112	3	25,9	51,5	1008
27.8.2007	12:40	44,8	306,846	301,715	410,722	306,044		26,4	51,6	1016
30.8.2007	15:00	47,9	306,800	301,658	410,719	305,990		26,0	51,3	1010
3.9.2007	16:10	52,0	306,710	301,557	410,718	305,891	6	24,3	51,3	1004
6.9.2007	14:05	54,9	306,651	301,493	410,721	305,829		23,0	51,4	1013
10.9.2007	11:10	58,8	306,583	301,409	410,730	305,751		22,6	51,4	1009
12.9.2007	12:30	60,8	306,538	301,361	410,724	305,702		23,0	51,3	1019
14.9.2007	11:55	62,8	306,457	301,274	410,726	305,615	12	23,4	51,5	1014
24.9.2007	14:20	72,9	306,082	300,879	410,723	305,224		22,1	51,9	1012
27.9.2007	16:50	76,0	305,981	300,772	410,732	305,124		21,4	52,0	1009
1.10.2007	11:21	79,8	305,850	300,628	410,730	304,978		21,7	52,3	1021
9.10.2007	15:26	88,0	305,237	300,002	410,733	304,389	24	22,7	53,2	1020
15.10.2007	15:04	93,9	304,850	299,590	410,727	303,478		21,7	53,4	1015
18.10.2007	16:05	97,0	304,650	299,383	410,720	303,780		21,7	53,8	1016
24.10.2007	15:42	103,0	304,283	298,997	410,725	303,407		21,1	54,0	1015

LD/HD PE foil										
Date	Hour	Time [d]	Weight [g]				stage	Av.Temp [°C]	Av.RH [%]	A press. [Pa]
			Sample1	Blind test	Sample2	Sample3				
13.7.2007	16:15	0,0	306,232	406,504	299,991	299,314				
16.7.2007	10:35	2,8	306,260	406,544	300,017	299,354				
19.7.2007	10:30	5,8	306,290	406,562	300,041	299,363				
23.7.2007	10:50	9,8	306,305	406,588	300,054	299,399				
26.7.2007	11:30	12,8	306,316	406,598	300,071	299,400				
30.7.2007	13:00	16,9	306,319	406,615	300,073	299,410				
2.8.2007	13:00	19,9	306,325	406,623	300,085	299,419				
6.8.2007	11:25	23,8	306,323	406,628	300,079	299,420				
9.8.2007	10:20	26,7	306,328	406,638	300,084	299,419				
14.8.2007	13:05	31,9	306,324	406,652	300,081	299,430				
21.8.2007	10:20	38,7	306,330	406,664	300,087	299,421	0	0	0	0
23.8.2007	14:40	40,9	306,327	406,668	300,085	299,420		25,9	53,1	1008
27.8.2007	12:30	44,8	306,322	406,669	300,083	299,415		26,3	53,1	1016
30.8.2007	14:50	47,9	306,312	406,671	300,069	299,408		25,9	52,8	1010
3.9.2007	16:00	52,0	306,297	406,673	300,051	299,388	1	24,2	52,7	1004
6.9.2007	14:15	54,9	306,286	406,676	300,044	299,381		23,0	52,7	1013
10.9.2007	11:00	58,8	306,272	406,685	300,032	299,369		22,5	52,4	1009
12.9.2007	12:25	60,8	306,268	406,687	300,022	299,357		22,9	52,4	1019
14.9.2007	11:50	62,8	306,238	406,685	299,997	299,335	3	23,3	52,5	1014
24.9.2007	14:25	72,9	306,135	406,693	299,887	299,238		22,0	52,7	1012
27.9.2007	16:00	76,0	306,102	406,700	299,857	299,207		21,4	52,5	1009
1.10.2007	11:20	79,8	306,064	406,696	299,818	299,175		21,7	52,8	1021
9.10.2007	15:28	88,0	305,885	406,690	299,641	298,995	6	22,7	52,9	1020
15.10.2007	15:04	93,9	305,766	406,696	299,513	298,887		21,7	53,0	1015
18.10.2007	16:07	97,0	305,715	406,698	299,461	298,830		21,7	52,9	1016
24.10.2007	15:45	103,0	305,612	406,705	299,349	298,726		21,0	53,0	1015
26.10.2007	10:50	104,8	305,582	406,703	299,320	298,692	12	21,2	53,1	1048
30.10.2007	14:08	108,9	305,432	406,700	299,172	298,540		20,7	53,3	1004
31.10.2007	15:40	110,0	305,394	406,696	299,121	298,493		21,2	52,9	1022
2.11.2007	9:57	111,7	305,324	406,689	299,047	298,429		21,0	53,3	1023
5.11.2007	12:50	114,8	305,196	406,678	298,921	298,296		21,7	53,5	1022
9.11.2007	12:40	118,8	305,078	406,708	298,801	298,180		21,1	53,5	998
13.11.2007	13:55	122,9	304,805	406,709	298,514	297,910	24	20,7	53,9	1001
16.11.2007	12:55	125,9	304,611	406,707	298,332	297,714		20,3	54,4	1018
19.11.2007	17:00	129,0	304,423	406,706	298,133	297,518		20,2	54,3	1010

Bitumen membrane with aluminium sheet

Date	Hour	Time [d]	Weight [g]			stage	Av.Temp [°C]	Av.RH [%]	A press. [Pa]
			Sample1	Blind test	Sample2				
13.7.2007	16:30	0,0	533,004	404,588	545,353	536,387			
16.7.2007	10:48	2,8	533,034	404,598	545,372	536,442			
19.7.2007	10:58	5,8	533,069	404,595	545,395	536,454			
23.7.2007	11:10	9,8	533,084	404,592	545,411	536,501			
26.7.2007	11:50	12,8	533,114	404,588	545,422	536,508			
30.7.2007	13:20	16,9	533,127	404,582	545,428	536,536			
2.8.2007	13:20	19,9	533,145	404,581	545,443	536,551			
6.8.2007	11:35	23,8	533,149	404,572	545,444	536,565			
9.8.2007	10:35	26,8	533,175	404,574	545,462	536,580			
14.8.2007	13:15	31,9	533,189	404,570	545,475	536,615			
21.8.2007	10:35	38,8	533,229	404,563	545,495	536,633			
23.8.2007	14:55	40,9	533,233	404,560	545,497	536,638			
27.8.2007	12:45	44,8	533,245	404,554	545,505	536,639			
30.8.2007	15:05	47,9	533,243	404,540	545,499	536,645			
3.9.2007	16:20	52,0	533,257	404,535	545,504	536,648			
6.9.2007	14:30	54,9	533,259	404,534	545,507	536,658			
10.9.2007	11:15	58,8	533,274	404,533	545,523	536,670			
12.9.2007	12:30	60,8	533,272	404,528	545,516	536,667			
14.9.2007	12:00	62,8	533,279	404,527	545,522	536,674			
24.9.2007	14:20	72,9	533,289	404,512	545,527	536,691			
27.9.2007	15:50	76,0	533,298	404,515	545,538	536,702			
1.10.2007	11:10	79,8	533,309	404,514	545,537	536,700			
9.10.2007	15:28	88,0	533,306	404,492	545,557	536,702			
15.10.2007	15:04	93,9	533,316	404,487	545,555	536,707			
18.10.2007	16:07	97,0	533,314	404,476	545,551	536,706			
23.10.2007	15:43	102,0	533,330	404,483	545,566	536,705			
26.10.2007	10:48	104,8	533,328	404,481	545,569	536,712			

Appendix B

Hygrothermal properties of used materials

A – Low diffusion resistance membrane

Physical quantity	Units	Value
Bulk density	kg/m ³	1000
Porosity	m ³ /m ³	0,0002
Specific Heat Capacity, Dry	J/(kg.K)	1500
Thermal Conductivity, Dry	W/(m.K)	0,16
Water Vapour Diffusion Resistance Factor	-	15000
Thickness	m	0,0012

B – High diffusion resistance membrane

Physical quantity	Units	Value
Bulk density	kg/m ³	1000
Porosity	m ³ /m ³	0,0002
Specific Heat Capacity, Dry	J/(kg.K)	1500
Thermal Conductivity, Dry	W/(m.K)	0,16
Water Vapour Diffusion Resistance Factor	-	150000
Thickness	m	0,0015

C – Very high diffusion resistance membrane

Physical quantity	Units	Value
Bulk density	kg/m ³	1000
Porosity	m ³ /m ³	0,0002
Specific Heat Capacity, Dry	J/(kg.K)	1500
Thermal Conductivity, Dry	W/(m.K)	0,16
Water Vapour Diffusion Resistance Factor	-	50000
Thickness	m	0,01

Vr – Vapour retarder

Physical quantity	Units	Value
Bulk density	kg/m ³	130
Porosity	m ³ /m ³	0,001
Specific Heat Capacity, Dry	J/(kg.K)	2300
Thermal Conductivity, Dry	W/(m.K)	2,3
Water Vapour Diffusion Resistance Factor	-	200000
Thickness	m	0,001

P – Expanded polystyrene

Physical quantity	Units	Value
Bulk density	kg/m ³	30
Porosity	m ³ /m ³	0,95
Specific Heat Capacity, Dry	J/(kg.K)	1500
Thermal Conductivity, Dry	W/(m.K)	0,04
Water Vapour Diffusion Resistance Factor	-	50
Thickness	m	0,24

Thermal conductivity – moisture dependence
(Cammerer & Achtziger (1985))

Water content [kg/m ³]	Thermal conductivity [W/(m.K)]
0	0,04
10	0,04
20	0,04
50	0,042
100	0,049
200	0,071
300	0,1
400	0,14
500	0,18
600	0,24
700	0,31
800	0,4
900	0,52
950	0,6

W – Mineral insulation board

Physical quantity	Units	Value
Bulk density	kg/m ³	60
Porosity	m ³ /m ³	0,95
Specific Heat Capacity, Dry	J/(kg.K)	850
Thermal Conductivity, Dry	W/(m.K)	0,04
Water Vapour Diffusion Resistance Factor	-	1,3
Thickness	m	0,24

Thermal conductivity – moisture dependence
(IEA Annex 21)

Water content [kg/m ³]	Thermal conductivity [W/(m.K)]
0	0,04
10	0,04
20	0,041
50	0,043
100	0,049
200	0,07
300	0,1
400	0,15
500	0,2
600	0,27
700	0,35
800	0,44
900	0,55
950	0,6

Concrete slab

Physical quantity	Units	Value
Bulk density	kg/m ³	230
Porosity	m ³ /m ³	0,18
Specific Heat Capacity, Dry	J/(kg.K)	850
Thermal Conductivity, Dry	W/(m.K)	1,6
Water Vapour Diffusion Resistance Factor	-	180
Thickness	m	0,150

Moisture storage function

Hedenblad (1996)

RH [-]	Water content [kg/m ³]
0	0
0,05	27
0,1	32
0,15	34
0,2	35
0,3	37
0,4	40
0,5	48
0,6	58
0,7	72
0,8	85
0,9	100
0,95	118
1	150

Liquid transport coefficient – suction

Hedenblad (1996)

Water content [kg/m ³]	DWS [m ² /s]
0	0
72	$7,4 \cdot 10^{-11}$
85	$2,5 \cdot 10^{-10}$
100	$1,0 \cdot 10^{-9}$
118	$1,2 \cdot 10^{-9}$

Liquid transport coefficient – redistribution

Hedenblad (1996)

Water content [kg/m ³]	DWW [m ² /s]
0	0
72	$7,4 \cdot 10^{-12}$
85	$2,5 \cdot 10^{-11}$
100	$1,0 \cdot 10^{-10}$
118	$1,3 \cdot 10^{-10}$

Thermal conductivity – moisture dependence

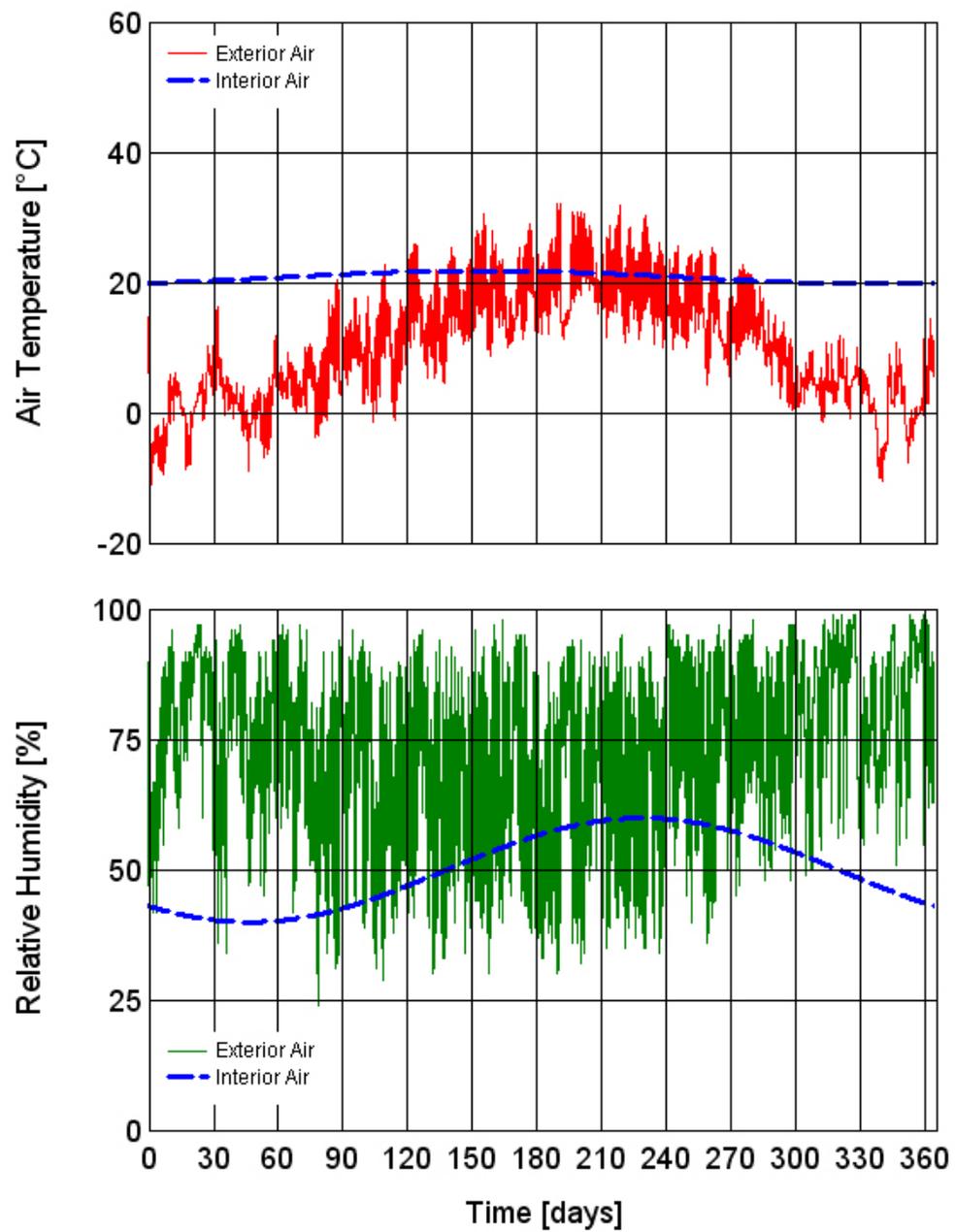
Hedenblad (1996)

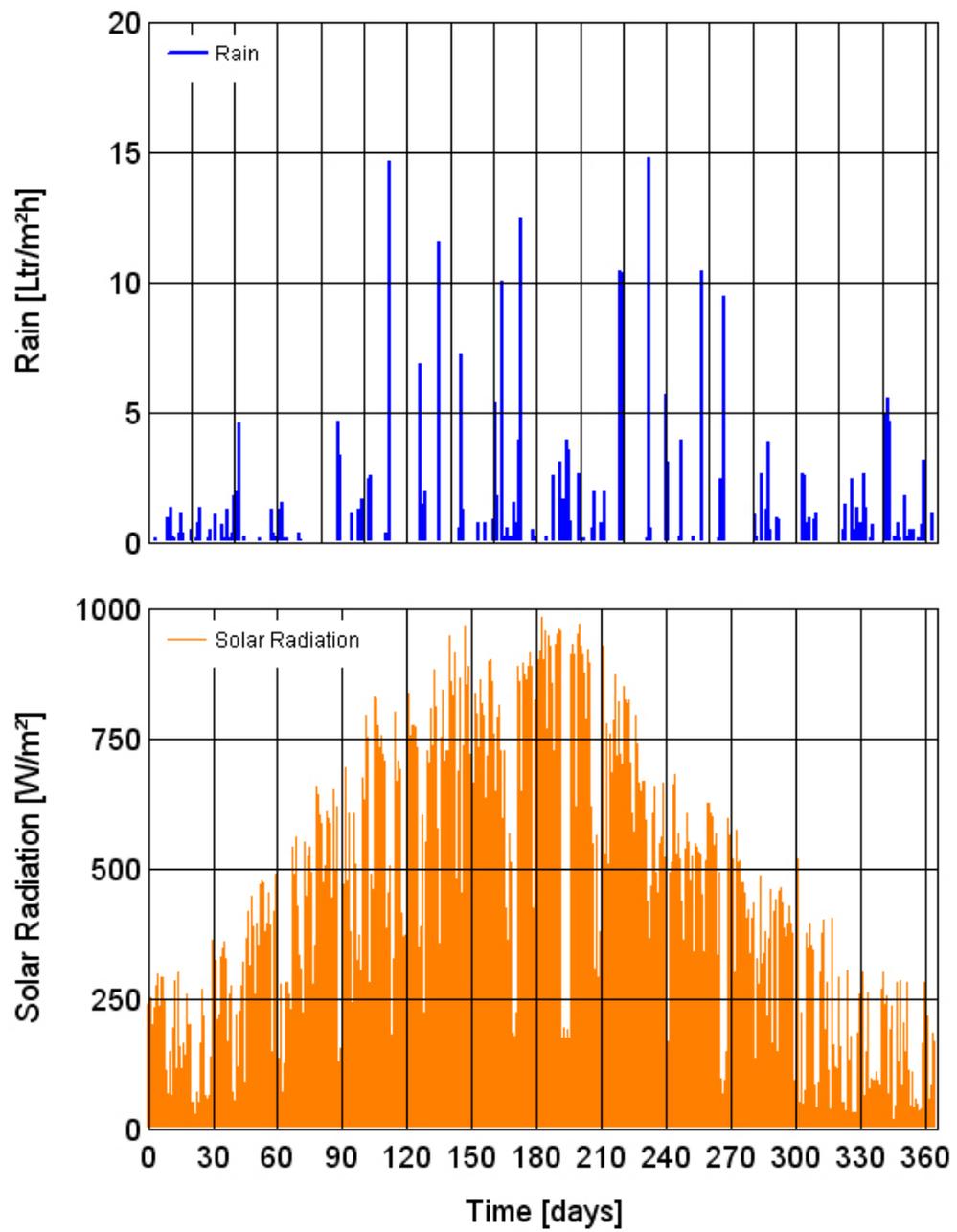
Water content [kg/m ³]	Thermal conductivity [W/(m.K)]
0	1,6
180	2,602

Appendix C

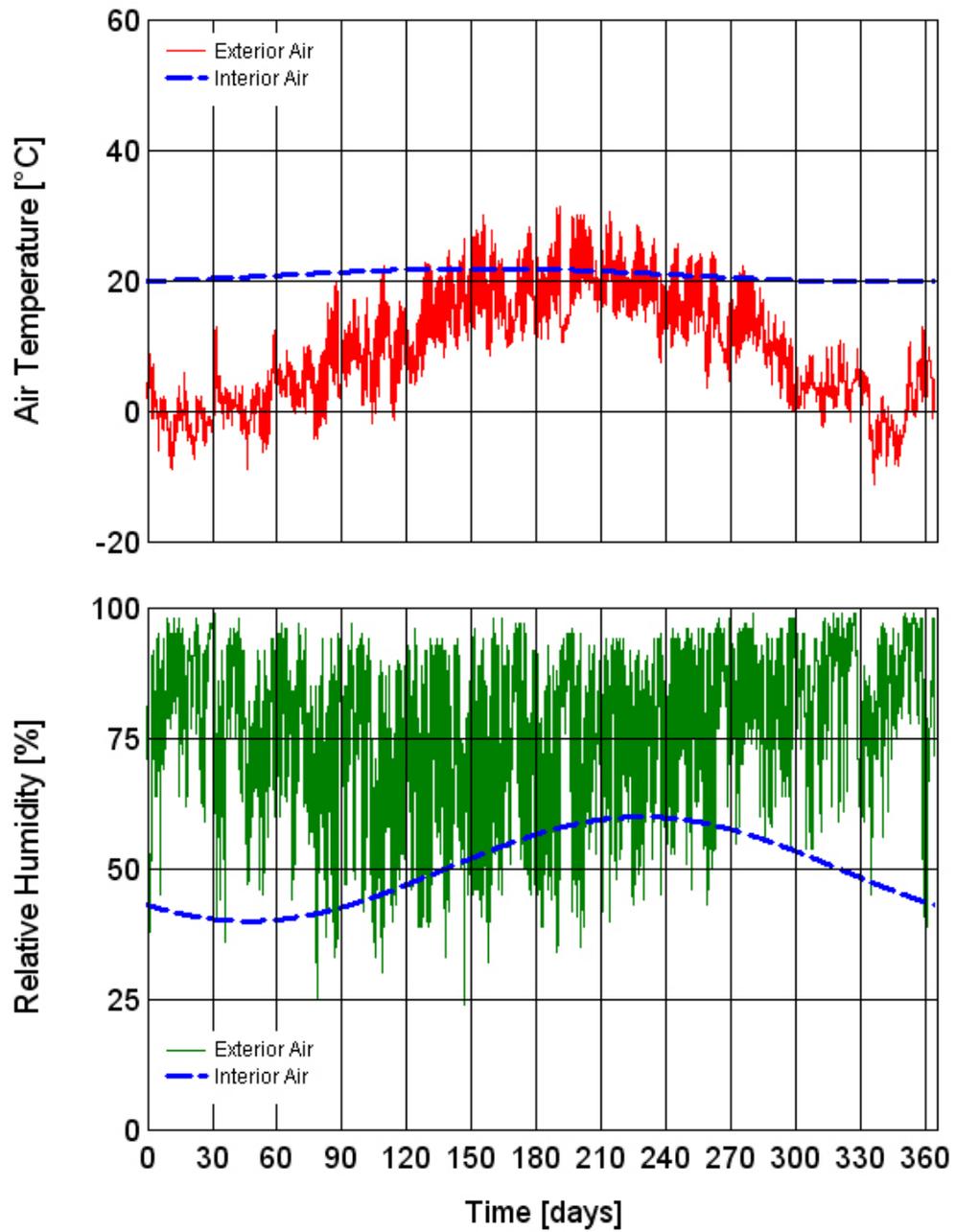
Outdoor and indoor climate conditions

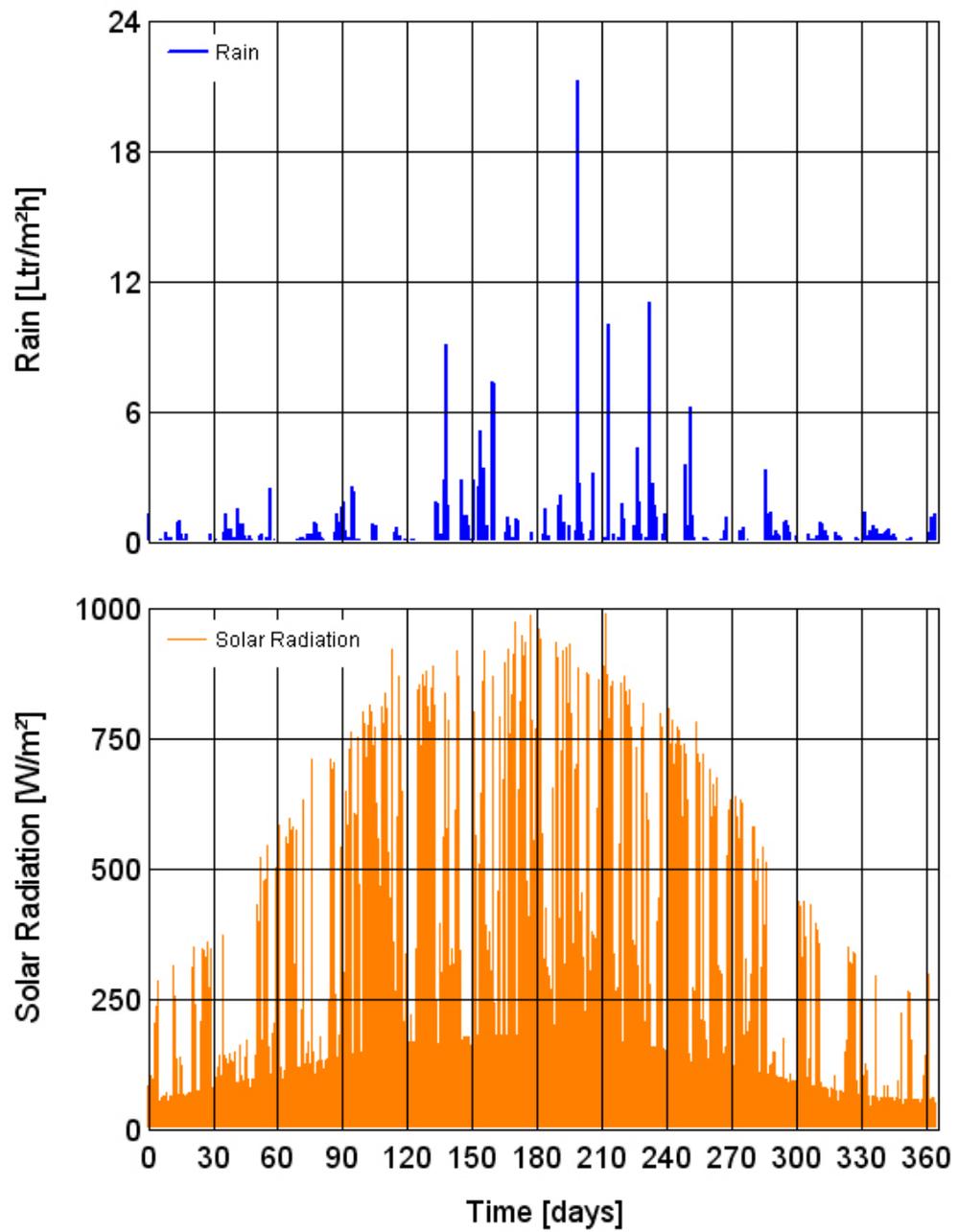
Wien



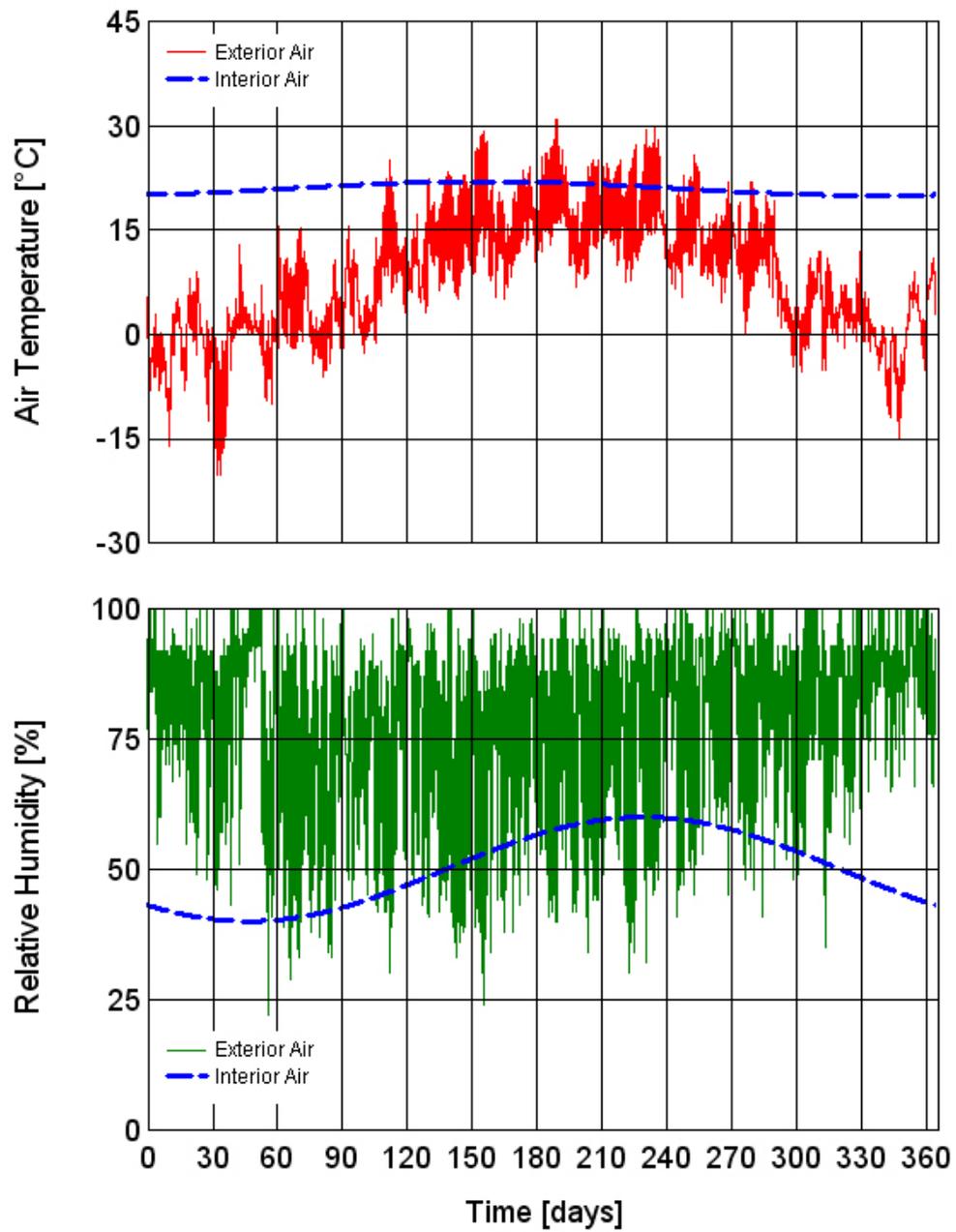


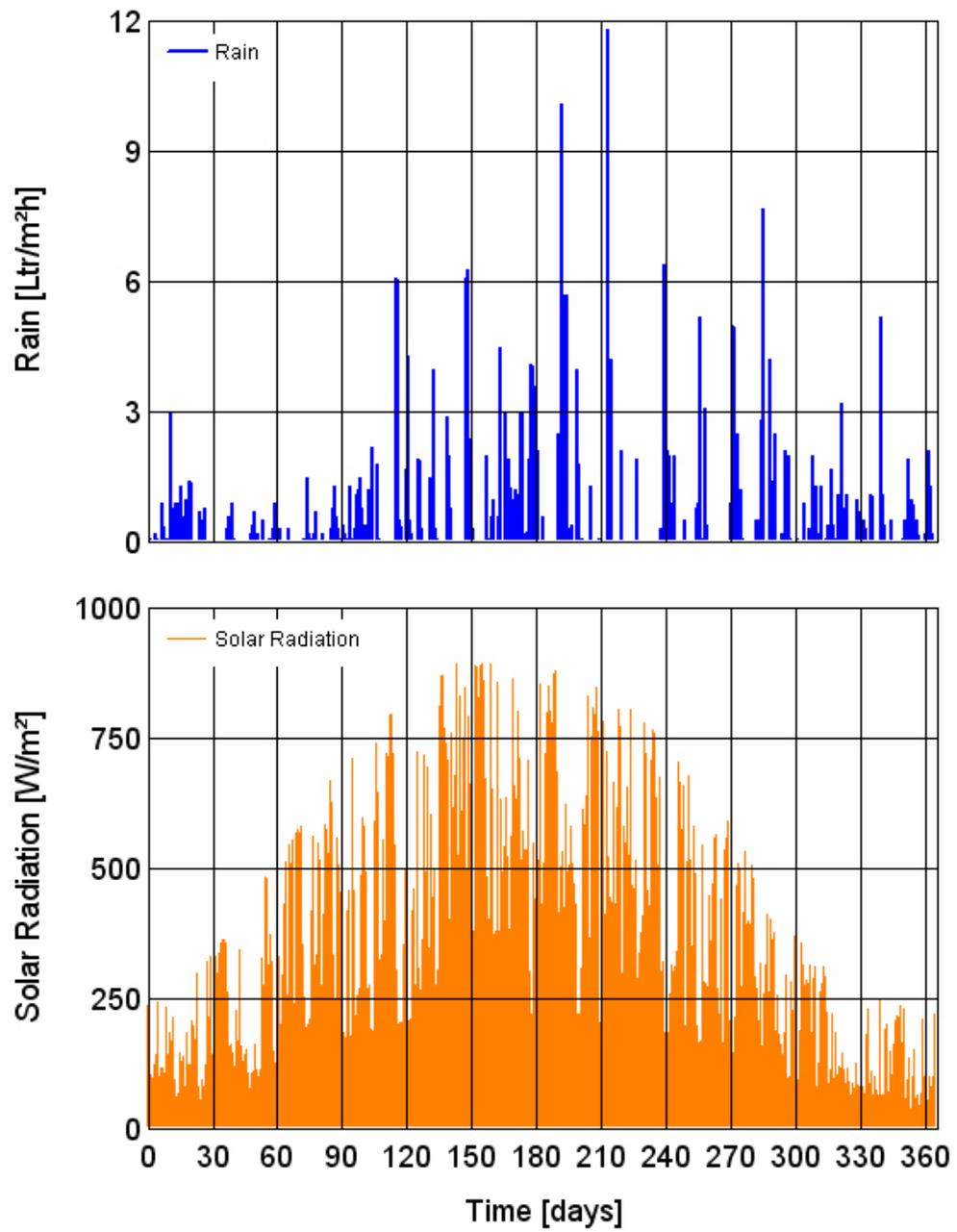
Graz



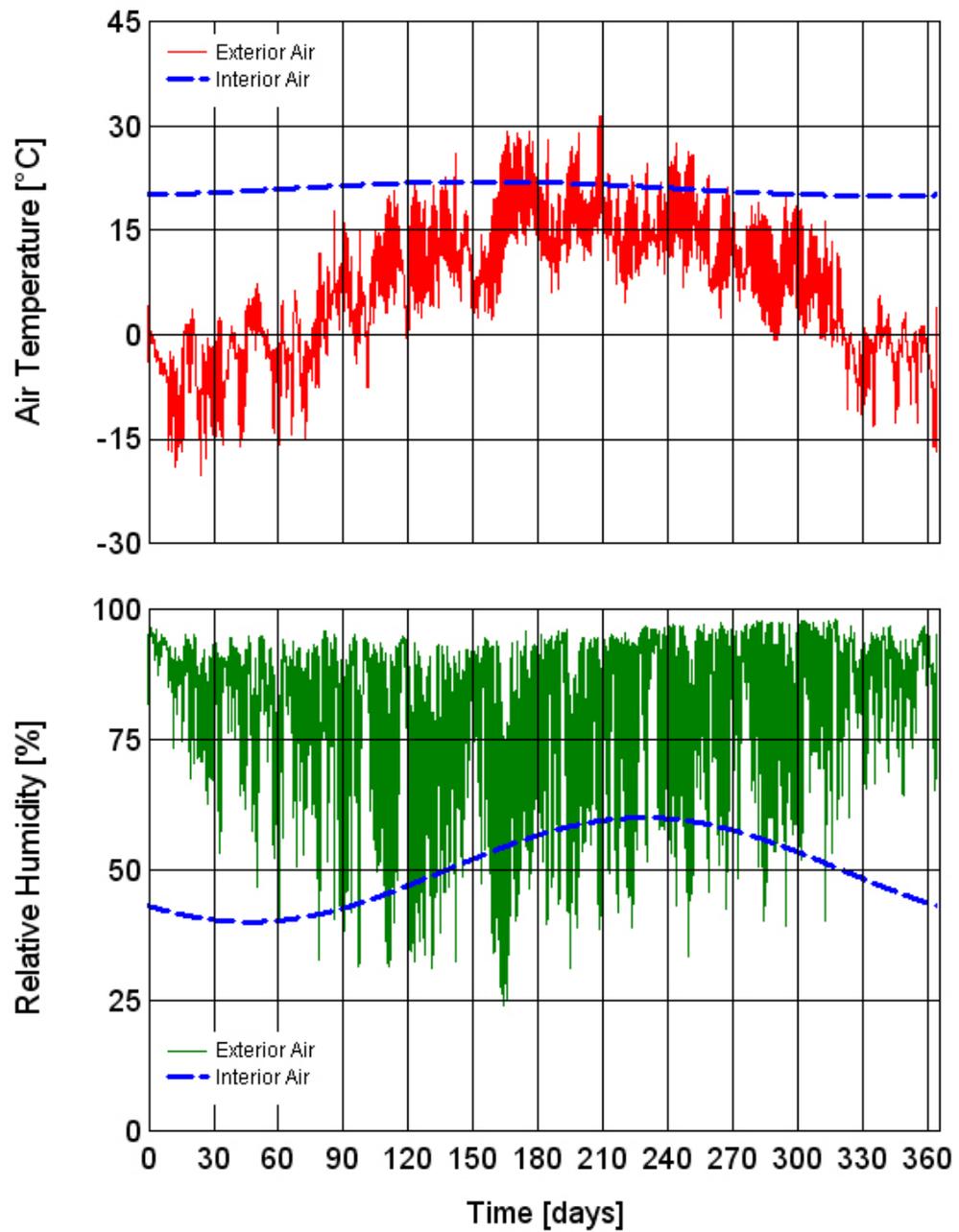


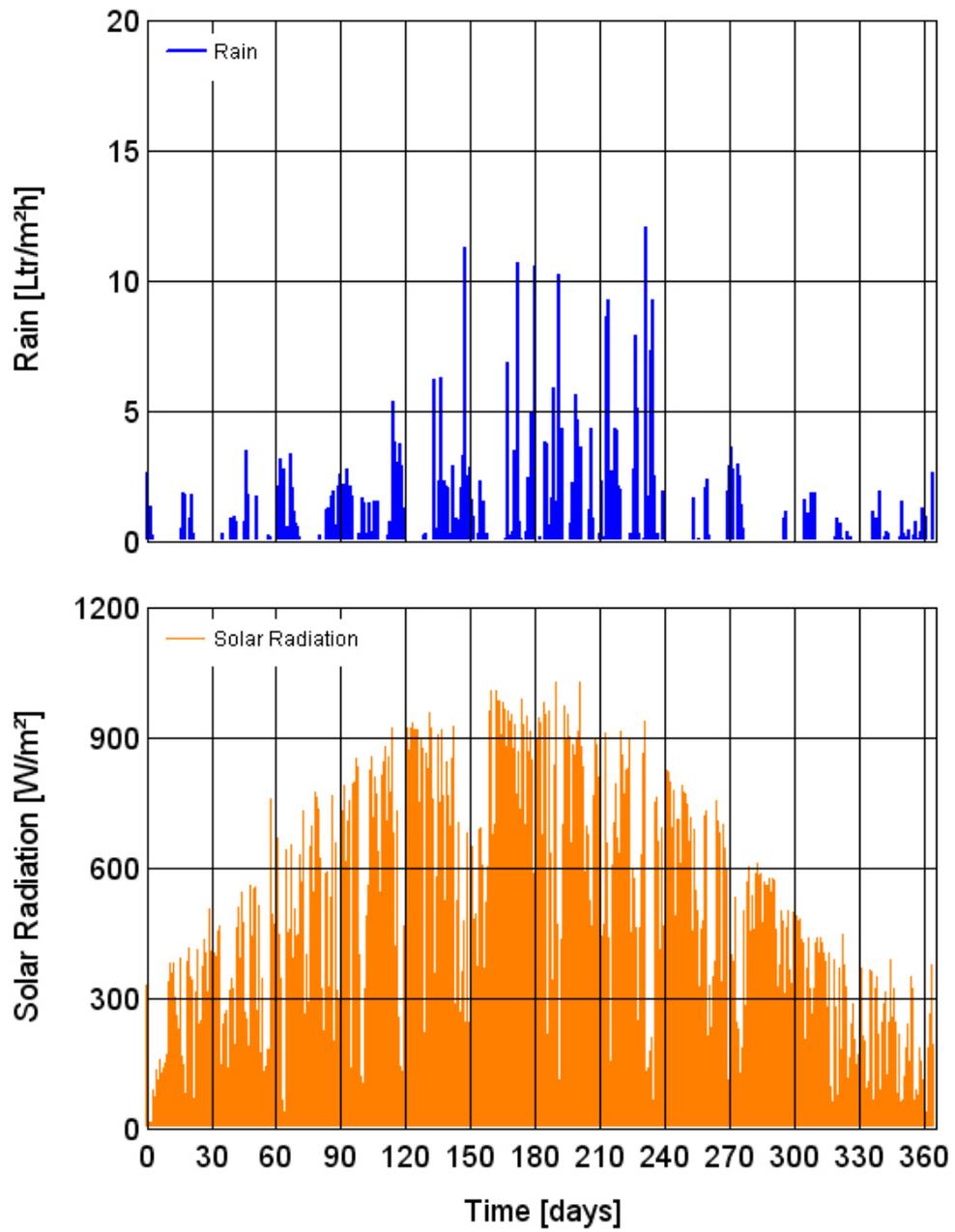
Krakow





Holzkirchen





Hof

