THE INFLUENCE OF AIR PERMEABILITY AND TYPE OF UNDERLAY ON THE HYGROTHERMAL PERFORMANCE OF AN INCLINED ROOF

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ABSTRACT

The airtightness of inclined roofs is important in order to avoid hygrothermal problems and to guarantee the durability of the construction itself. Previous research in building physics showed that perfect airtightness of inclined roofs is difficult to achieve and maintain. In practice, air transport through the construction, i.e. in/exfiltration, cannot be avoided due to for example imperfections or bad workmanship. The heat and moisture conditions in the building component are strongly influenced by advection, i.e. air transport through the building component, resulting from air pressure differences between the indoor and outdoor environment.

Current models to predict heat, air and moisture (HAM) conditions in building components assume uniform boundary conditions, both for the temperature and relative humidity imposed at the internal and external surface of the building component. In such models, the heat and moisture fluxes due to advection are generally not considered. A more detailed description and prediction of the influence of the air transport through the building component on the HAM conditions in the building component would be desired.

In the work presented in this paper, the hygrothermal performance of an inclined roof is analyzed while taking into account the air transport through the construction. An airflow model is used to describe the advective transport through the building component. The airflow model is integrated into an existing HAM building component model. The analysis focuses on a case study which is based on a common roof design in Western Europe. Three configurations consisting of a vapour-retarding underlay foil (which was applied in the past), vapour-open underlay, and a fibre cement board underlay are investigated.

KEYWORDS

Moisture control, hygrothermal performance, vapour advection.

INTRODUCTION

Building energy consumption and sustainability are currently one of the most important issues worldwide. Improved energy performance of buildings cannot be achieved by additional insulation and more energy efficient building systems only. The airtightness of the building envelope has a major influence on a building's energy performance, thermal comfort, indoor air quality, and moisture damages [1]. Hence, sufficient airtightness is required to guarantee the adequate hygrothermal performance of a building and to avoid moisture problems.

In light-weight constructions, an airtight building envelope is usually realised by an interior air barrier system. The most important property of the air barrier is its continuity. Ensuring continuity in order to prevent (advective) airflow through the building component requires sealing of all the joints and intersections of this layer. In cold and moderate climates, such as in North-West European areas, the layer often combines the function of air barrier with the function of vapour retarder.

In current building practice, it is labour intensive and often difficult to construct a perfectly continuous air barrier, due to a large number of internal joints, intersections, and perforations, e.g. for electrical and plumbing services. Often air leakages due to unintended gaps and perforations cannot be avoided and moisture problems may develop due to these air leakages. Since the compliance with air leakage criteria in building practice is uncertain, it is important to include control measures in the envelope design to prevent severe moisture problems when the continuity of airtightness is not achieved. Such measures could reduce the effects of potential air leakages on the moisture performance of the building envelope.

For inclined roofs, several guidelines for condensation control have been developed, mainly influenced by national regulations. Guidelines for the selection of the air/vapour barrier, are based on the vapour diffusion resistance factor (μd_i) of the air/vapour barrier, and of the roof underlay (μd_e). A proper combination of the air/vapour barrier and the roof underlay is achieved as a function of the indoor environmental conditions. In Belgium, selection criteria have been published by Meert [2] and Janssens [3]. Similarly, German guidelines have been reported by the Fraunhofer Institute for Building Physics [4] [5], and in the German standard [6]. The guidelines are based on numerical studies where the influence of (advective) vapour flow on the interstitial condensation risk in an inclined roof is investigated while assuming steady-state boundary conditions. Moreover, a maximum allowable condensation due to air transport of respectively 200 g/m^2 roof area [3] and 250 g/m^2 roof area [5] [6] is assumed. In case the predicted condensate is exceeded, the component is expected to fail and the construction is not recommended.

While hygrothermal simulation models nowadays use transient boundary conditions for the indoor and outdoor climatic conditions, i.e. indoor and outdoor air temperature and relative humidity, solar and longwave radiation, and rain loads, advective airflows, i.e. the airflows through the building component, are often neglected. And, if the model takes into account in/exfiltration through a building component, the airflow is often assumed to be constant and steady-state. In reality, however, the airflow is strongly dependent of the wind induced pressure differences between inside and outside, and thus changing with time. Neglecting these transient influences, may lead to inaccuracies in the predicted hygrothermal conditions in the building component, resulting in an under- or overprediction of the hygrothermal conditions in the building component, and consequently damage and/or degradation of the construction may occur.

It is the objective of this paper to study the influence of transient (advective) airflow through a roof construction on the hygrothermal conditions in the component. A case study which is based on a common roof design in Western Europe is selected for analysis. Three configurations consisting of a vapour-retarding underlay foil, a vapour-open underlay, and a fibre cement board underlay are investigated. The hygrothermal conditions in the roof are simulated using the Delphin 5 software for transient heat, air and moisture transfer in building components [7] [8]. The hygrothermal performance of the different configurations is analyzed based on the predicted condensate that is generated during a year, the total moisture content in the construction evaluated over 4 years, and the maximum moisture content in the wood construction.

ANALYSIS AND METHODS

A common roof design in Western Europe is selected as a base case for analysis of the hygrothermal conditions. The roof contains the following layers (from outside to inside): concrete tiles on laths and battens, an underlay, 120mm of fibre glass insulation between the rafters (50x120mm), a vapour retarder, and painted gypsum board. The analyzed roof construction is presented in Figure 1. The roof is 1.8m wide and 4.55m long per pitch and oriented northeast with a slope of 30^o. Additional information on the topology of the building can be found in [9]. The underlay (Figure 1) is installed directly on top of the insulation, continuously form eave to eave, with a sealed overlap. The design thermal properties of the roof are calculated based on the thermal conductivity of the applied building materials. Moreover, the design U-value of the roof corresponds to 0.27 W/(m^2K).

A more detailed description of the composition of the roof is presented in Table 1. Three configurations consisting of a vapour-retarding underlay foil, a vapour-open underlay, and a fibre cement board underlay are investigated. Regarding new buildings, the use of a vapour-open underlay foil as a protection for the insulation has become common practice in current residential construction. Moreover, considering the renovation of a roof construction, it may be possible that the underlay consists of a vapour-retarding underlay foil (which was used in the past). Alternatively, a capillary-active roof underlay, for example fibre cement board, could be applied. In this study, the influence of different roof underlays on the hygrothermal performance of the roof is investigated. Table 2 presents the material properties of the applied building materials. The air permeability of the fibre cement board is based on the measurements reported in Langmans et *al.* (2010) [10], while the air permeability of the other building materials are based on [11].

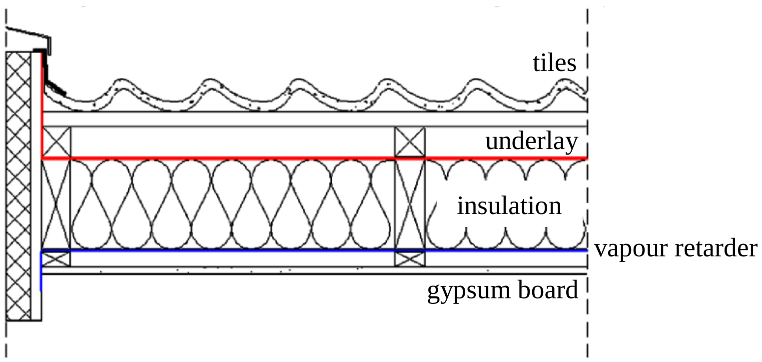

Figure 1: Roof construction with insulation between the rafters (and on top of the purlines)

Roof construction	**#1 - Vapour retarding underlay**	**#2 - Vapour-open underlay**	**#3 - Capillary-active underlay**
	Concrete tiles	Concrete tiles	Concrete tiles
Underlay	Vapour retarding foil	Vapour-open foil	Fibre cement board (3mm)
Insulation	Fibre glass (120mm)	Fibre glass (120mm)	Fibre glass (120mm)
Finishing layer	Painted gypsum board + vapour barrier (μd_i=2m)	Painted gypsum board + vapour barrier (μd_i=2m)	Painted gypsum board + vapour barrier (μd_i=2m)

Table 1: Analyzed roof constructions

	Thickness	Thermal conductivity	Vapour permeability	Air permeability (without joints)
	d [m]	λ [W/mK]	μ [-]	K_a [m s^{-1}Pa^{-1}]
Underlay foil:				
- vapour retarding	0.001	-	2000	$28.6 \cdot 10^{-7}$
- vapour-open	0.001	-	20	$28.6 \cdot 10^{-7}$
Fibre cement board	0.003	0.25	80	$6.4 \cdot 10^{-7}$
Fibre glass	0.12	0.035	1.5	
Vapour retarder	0.002	-	1000	$5.0 \cdot 10^{-7}$
Gypsum board	0.01	0.1	10	$6.9 \cdot 10^{-7}$

Table 2: Material properties

Hygrothermal modelling

A hygrothermal model of the presented roof construction has been developed using the hygrothermal software Delphin 5, which is an envelope model for the coupled simulation of heat, air, and moisture transport in a building component [7] [8]. First of all, the developed hygrothermal model has been verified using experimental data which has been obtained within the framework of a Belgian project on moisture problems in roof constructions [9]. Second, the model has been simulated during four years. External boundary conditions are applied using the Test Reference Year (TRY) for Belgian (Brussels) outdoor climatic conditions. Indoor environmental conditions are applied according to the Belgian classification for indoor climatic conditions. The indoor air temperature in the building is represented by Equation 1 and lies above 18^{o}C during the entire year. The boundary conditions for the partial vapour pressure of the indoor air for respectively Belgian climate classes II (CC2) and III (CC3), are presented in Table 3 [2] [12].

Equation 1

$$T_i = \max(18; 8 + 0.8T_e)$$

where T_i and T_e are the indoor and outdoor air temperature [^{o}C] respectively.

Climate class	**Type of building**		**Partial vapour pressure difference between the indoor and outdoor air [Pa]**
CC2	Buildings with moderate vapour production and more than sufficient ventilation	Large houses, schools, shops, etc.	$< 436 - 22T_e$
CC3	Buildings with significant vapour production and moderate ventilation	Small houses, restaurants, etc.	$< 713 - 22T_e$

Table 3: Belgian classification of indoor climate classes [2]

Airflow modelling

The air pressure difference across the construction is the driving force for the airflow through the construction. Air pressure differences are caused by buoyancy (stack effect), wind forces, pressure differences due to mechanical ventilation systems, open fireplaces, etc. The pressure difference across the construction is represented by Equation 2

Equation 2

$$\Delta p_a = C_p \rho_o \frac{U_h^2}{2} + \rho_o g H \frac{T_i - T_o}{T_i} + \Delta p_I$$

where Δp_a represents the total air pressure difference across a leak [Pa], C_p is the wind surface pressure coefficient [-], ρ_o the outdoor air density [kg/m^3], U_h the wind velocity [m/s], which is often taken at building height h [m] in the undisturbed upstream flow, g the gravitational acceleration [m/s^2], H the height above the reference plain [m], T_i and T_o represent the indoor and outdoor air temperature respectively [K], and Δp_I is the pressure that acts to balance inflows and outflows, including mechanical system flows [Pa].

In this study, only the pressure differences due to the stack effect and the wind forces are considered, since a mechanical ventilation system is not present in the building considered. The relative importance of wind and stack pressures in a building depends on the building height, internal resistance to vertical airflow, location and airflow resistance characteristics of envelope openings, local terrain, and the immediate shielding of the building. The wind pressure on the building envelope is usually expressed by pressure coefficients (C_p). Pressure coefficients on building facades are influenced by a wide range of parameters. As it is practically impossible to take into account the full complexity of C_p variation, building simulation models generally incorporate it in a simplified way. An intensive overview of wind pressure coefficient data in building energy simulation and air-flow network programs is reported by Cóstola (2009) [13].

Wind pressure coefficients for the building considered have been calculated using the web-based application C_p Generator, based on the geometry of the building, the building’s surroundings, and sheltering [14]. The resulting C_p coefficients served as an input for the hygrothermal simulation model (Equation 2).

The airflow through a crack is approximated by the quadratic expression represented by Equation 3 [15]

Equation 3

$$\Delta p_a = \frac{12\mu z}{wd^3} Q + \frac{\rho C}{2d^2 w^2} Q^2$$

where Δp_a is the air pressure difference across the crack [Pa], μ the dynamic viscosity [kg/(ms)], ρ the air density [kg/m^3], Q the air flow rate through the crack [m^3/s], and z, w, d, respectively the length, width, and height of the crack [m]. The parameter C is well approximated by $C = 1.5 + n_b$, where n_b is the number of right-angle bends in the crack [15].

In practice, detailed information on crack sizes and their distribution in buildings is limited. Leakage characteristics are generally expressed as an effective leakage area without specifying crack dimensions. Given the difficulty of this characterisation, the airflow through the roof construction is considered using a more general approach based on the overall air permeability of the roof construction (K_a). The resulting airflow through the roof is governed by Equation 4.

Equation 4

$$V_a = K_a(\Delta p_a)^n$$

where V_a is the airflow through the building component [$m^3/(m^2\ s)$], K_a is the airflow coefficient [m^3/m^2sPa], representing the air permeability of the building component, and n is the flow exponent, which in general has a value between 0.5 and 1.0, depending on the characteristics of the airflow.

Parameter analysis

Several values for the air permeability (K_a) of the roof construction have been investigated representing an airtight roof construction as well as a roof incorporating a relatively large number of leakages. Based on the observations obtained from literature [3] [16], typical values for the air permeability of the roof construction are applied for the different indoor environmental conditions (Table 4). The hygrothermal response of the roof is simulated using the presented values for the total air permeability of the roof, applied to the presented roof construction.

Table 4: Total air permeability of the roof construction

Cases	K_a [$\cdot 10^{-4}$ m^3/m^2sPa]
1	0.2
2	0.3
3	0.4
4	0.5
5	1.1
6	1.6
7	2.2

The resulting hygrothermal model incorporates the transient moisture sources due to the airflow through the roof construction calculated based on Equation 4. Depending on the specific air permeability of the component K_a and the environmental conditions around the building component, the hygrothermal conditions in the component are evaluated.

RESULTS

Figure 2 presents the predicted condensate per m^2 roof area during the second year of simulation, respectively between October 1 and June 1. Moreover, the figure presents the total moisture content in the roof construction over 4 years. In the figure, a comparison between a vapour retarding underlay, vapour-open underlay, and capillary-active underlay is shown. The roof constructions are susceptible to indoor climate class 2 and have an air permeability of $0.2\cdot 10^{-4}$ $m^3/(m^2sPa)$. The figure shows that the roof construction with a vapour-retarding underlay is relatively sensitive to condensation, i.e. a maximum of approximately 700 g/m^2

condensate is developed, while the condensation occurring in the roof constructions with a vapour-open and capillary-active underlay is negligible. In addition, Figure 2 shows that the predicted total moisture contents in the vapour-retarding roof are relatively high compared to the moisture content observed for the other two roof constructions.

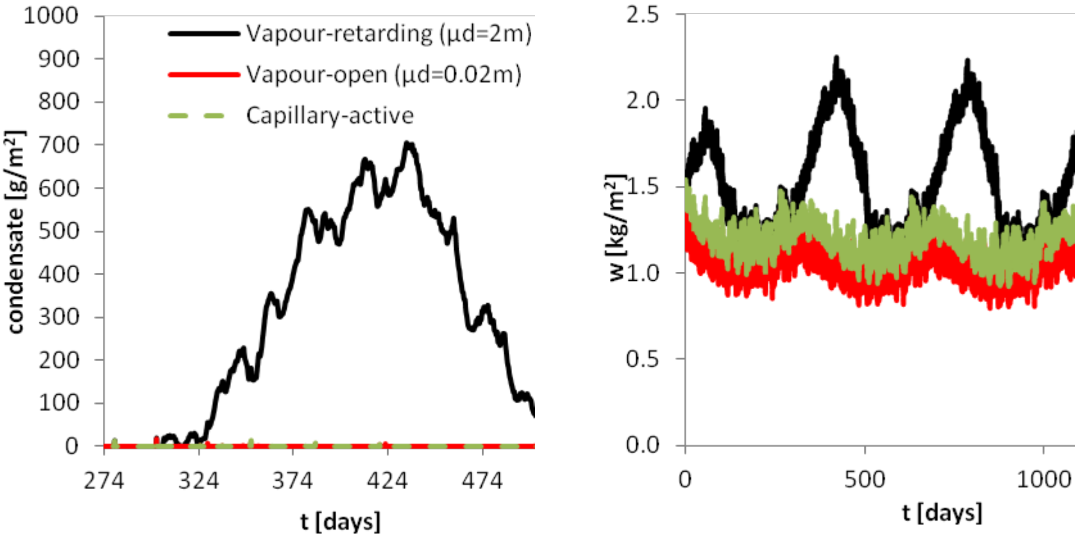

Figure 2: Predicted condensation [g/m^2] and moisture content [kg/m^2] in the roof construction for different construction configurations susceptible to indoor climate class 2 and an air permeability of $0.2\cdot10^{-4}$ m^3/(m^{2}sPa)

In Figure 3, the hygrothermal performance of a roof configuration with a vapour-open roof underlay and a capillary-active underlay are compared. The figure shows a roof susceptible to respectively indoor climate class 2, having an air permeability of $1.6\cdot10^{-4}$ m^3/(m^{2}sPa), and indoor climate class 3, having an air permeability of $0.5\cdot10^{-4}$ m^3/(m^{2}sPa). The figure shows that a roof with a capillary underlay is relatively sensitive to condensation induced by the airflow through the roof construction compared to the roof with the vapour-open underlay.

Figure 3 also shows a relatively large moisture content in the roof construction with a capillary underlay. It is obvious that the relatively high moisture content is caused by the ability of the capillary-active underlay to buffer moisture. Moreover, both roof designs are able to dry during summer and moisture accumulation over time does not occur.

The hygrothermal performance of the different configurations has been analyzed based on the condensate that is generated during winter after 3 years, the total moisture content after 1 year and after 4 years, and the maximum moisture content in the wood construction observed during the 4th year of simulation. The simulation results are summarized in respectively Table 5, Table 6, and Table 7.

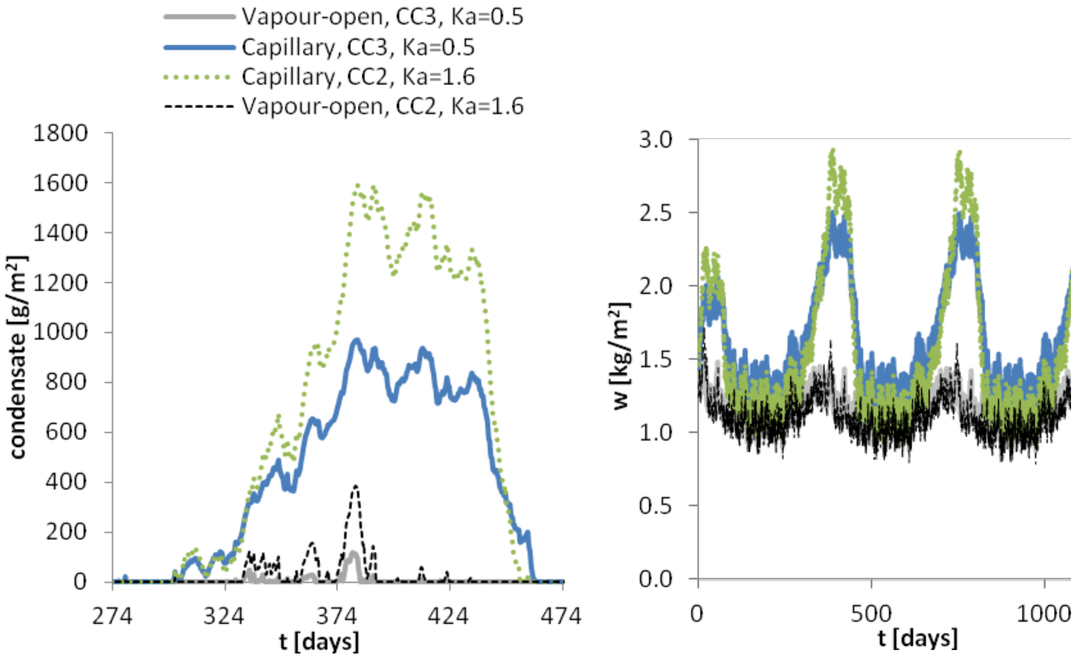

Figure 3: Simulation results for roof constructions with a vapour-open and a capillary-active underlay susceptible to respectively indoor climate class 2 and 3, and with an air permeability $[K_a \cdot 10^{-4}]$ of $0.5 \cdot 10^{-4}$ $m^3/(m^2sPa)$ and $1.6 \cdot 10^{-4}$ $m^3/(m^2sPa)$

Roof construction	**#1 - Vapour retarding**		**#2 - Vapour-open**		**#3 - Capillary-active**	
	CC 2	**CC 3**	**CC 2**	**CC 3**	**CC 2**	**CC 3**
·10-4 m^3/(m^{2}sPa)	C [kg/m^2]	C [kg/m^2]	C [kg/m^2]	C [kg/m^2]	C [kg/m^2]	C [kg/m^2]
0.2	0.70	4.03	0.02	0.03	0.03	0.04
0.3	5.66		0.03	0.03	0.04	0.16
0.4			0.03	0.05	0.07	0.40
0.5			0.03	0.12	0.15	0.97
1.1			0.16	1.20	0.92	3.24
1.6			0.39	3.62	1.59	9.58
2.2			0.79	7.38	2.77	13.83

Table 5: Predicted maximum condensate (C [kg/m^2]) in a winter season after 3 years

Roof construction	**#1 - Vapour retarding**				**#2 - Vapour-open**				**#3 - Capillary-active**			
	CC 2		**CC 3**		**CC 2**		**CC 3**		**CC 2**		**CC 3**	
·10-4 m^3/(m^{2}sPa)	**W_{1y}**	**W_{4y}**	**W_{1y}**	**W_{4y}**	**W_{1y}**	**W_{4y}**	**W_{1y}**	**W_{4y}**	**W_{1y}**	**W_{4y}**	**W_{1y}**	**W_{4y}**
0.2	1.85	1.82	2.89	4.37	1.15	1.12	1.23	1.21	1.32	1.28	1.45	1.42
0.3	3.27	5.76			1.16	1.13	1.26	1.23	1.37	1.33	1.60	1.57
0.4					1.17	1.14	1.29	1.27	1.41	1.38	1.81	1.79
0.5					1.18	1.14	1.37	1.35	1.50	1.46	2.23	2.22
1.1					1.41	1.38	3.69	3.69	2.38	2.35	6.11	6.12
1.6					1.62	1.59	5.41	5.42	2.89	2.86	8.06	8.08
2.2					1.41	1.38	3.69	3.69	2.38	2.35	6.11	6.12

Table 6: Predicted moisture content [kg/m^2] in the roof construction after 1 year (w_{1y}) and after 4 years (w_{4y})

Roof construction	**#1 - Vapour retarding**		**#2 - Vapour-open**		**#3 - Capillary-active**	
	CC 2	**CC 3**	**CC 2**	**CC 3**	**CC 2**	**CC 3**
·10-4 $m^3/(m^2sPa)$	**u_{4y}**	**u_{4y}**	**u_{4y}**	**u_{4y}**	**u_{4y}**	**u_{4y}**
0.2	17.0	21.1	17.0	19.0	16.1	16.6
0.3	22.3		17.5	19.1	16.3	16.9
0.4			18.1	19.1	16.5	17.1
0.5			18.3	19.1	16.7	17.3
1.1			19.1	19.2	16.9	17.5
1.6			19.5	19.2	17.4	17.9
2.2			19.7	19.2	17.6	18.1

Table 7: Predicted maximum moisture content [%-mass] in the wood construction during the 4th year of simulation

Regarding the vapour retarding roof underlay, Table 5 shows relatively large amounts of condensate for relatively small airflows through the construction. Moisture accumulation in case with a vapour retarding underlay is already observed at a relatively small air permeability of the roof construction. Therefore, the performance of the roof construction has not been analyzed for an air permeability of $0.4 \cdot 10^{-4}$ $m^3/(m^2sPa)$ and higher.

With respect to the capillary underlay, Table 5 shows that this roof configuration seems to be more sensitive to condensation compared to a vapour-open roof underlay. In addition, the simulation results presented in Table 6 show that relatively high total moisture contents are observed in the capillary-active roof, while the total moisture content in the vapour-open roof construction is lower. As has been mentioned previously, relatively high moisture contents are found in the roof with the capillary-active underlay and can be attributed to the moisture buffering ability of the roof underlay. Moreover, the predicted moisture content of the wood structure (Table 7) shows to be relatively low in the roof with the capillary-active underlay compared to the vapour-open roof. In summary, the simulation results show that the application of a capillary-active roof underlay results conditions which could be considered as more favourable hygrothermal conditions with respect to the moisture content of the wood.

DISCUSSION

Based on the simulation results, upper limits for the air permeability of the roof construction can be developed. Previously, guidelines for the air permeability of inclined roofs have been presented by Janssens (2005) [3]. These guidelines are presented in Table 8. It should be noticed that a roof with a capillary-active underlay has not been subject of Janssens' study.

Roof construction	**#1 - Vapour retarding**	**#2 - Vapour-open**
Indoor climate class	Janssens (2005) [3]	Janssens (2005) [3]
II	0.2	0.3
III	0.1	0.2

Table 8: Upper limits for the air permeability (K_a) [3]

Regarding the upper limits for the air permeability of a vapour retarding roof, the investigations show that the results of the present study and Janssens' study are comparable. In both studies, it is observed that a roof with a vapour-retarding underlay is sensitive to interstitial condensation, resulting in potential moisture accumulation and moisture problems.

A roof construction incorporating a vapour retarding roof underlay is not recommended. And, if a vapour retarding underlay is installed (for example in case of a building renovation without the possibility to replace the existing underlay), special attention should be paid to the air tightness of the roof construction.

With respect to the roof construction with a vapour-open underlay, Janssens [3] indicated relatively low upper limits for the critical air permeability, while the critical upper limits for the air permeability resulting from this study seem to be less strict. The results from the present study showed that moisture accumulation does not take place for air permeabilities larger than the limits reported by Janssens [3]. Additional research should be carried out in order to verify the research results and to make these generally applicable.

The critical upper limits of the air permeability for a roof with a capillary-active underlay are relatively high, compared to a vapour-open roof underlay. Due to the moisture buffering capacity of the fibre cement board, the moisture content of the wood construction is relatively small, which can be considered as more favourable hygrothermal conditions.

CONCLUSION

The influence of the airtightness of an inclined roof construction on the hygrothermal performance has been investigated. It was the objective of this paper to study the influence of transient (advective) airflow through a roof construction on the hygrothermal conditions in the component.

The main conclusion is that an inclined roof incorporating a vapour-open or capillary-active underlay is less sensitive to air leakages, for example due to poor workmanship, compared to a vapour retarding underlay. From this point of view, it is recommended to avoid the application of a vapour retarding underlay. When this kind of underlay is present, e.g. in a renovated building, special attention should be paid to the realisation of good air tightness. Moreover, it can be noted that this type of product has nearly disappeared from the Belgian construction market.

The study also showed that in the analyzed cases the application of a capillary-active underlay results in more favourable hygrothermal conditions and may increase the durability of the component. The capillary-active roof underlay has the potential to buffer moisture and to reduce the risk for condensation in the roof construction. Moreover, a capillary-active roof underlay makes the roof construction less susceptible to interstitial condensation and moisture accumulation and is from this point of view an indirect ‘safety’ against bad-workmanship.

As a practical guideline, it is recommended that inclined roofs should be as tight as possible. Potential moisture problems in inclined roofs are nearly only caused by air leakages at the level of the vapour retarder and are generally not influenced by the performance of the vapour retarder itself, as far as a vapour retarder is installed effectively. For new building constructions, the use of vapour-open underlay is recommended. This kind of product has also the advantage to be more tolerant to poor workmanship regarding the air tightness.

The research results presented in this paper are based on a case study of a building component using numerical simulation. The reader should notice that it may be questionable to what extent the numerical research results can be generalized. Other aspects as the type of insulation, the performance of the insulation, or the type of vapour-retarder have not been considered in this study. A more detailed research and investigation of the influence of these parameters combined with the influence of the (advective) airflow through inclined roof constructions is desired.

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