Interstitial condensation due to air leakage: A sensitivity analysis.

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ABSTRACT

This paper presents an approach to evaluate the sensitivity of a roof design to condensation problems, given the uncertainty to achieve continuity of airtightness in practice. The approach consists of a repeated number of simulations with a 2D heat, air and vapour transfer model to predict the variation in roof moisture performance due to various discontinuities in roof geometry. The set of discontinuities is calibrated by comparing measuring data of roof airtightness to simulation results. On the basis of the methodology, the paper explores the effectiveness of different measures to reduce the sensitivity of cavity insulated roofs to condensation problems.
The results show that even when a roof design complies with condensation control standards, a lightweight system remains sensitive to condensation problems as a result of air leakage through the discontinuities, joints and perforations, common to most existing construction methods. The sensitivity of a roof to interstitial condensation due to air leakage essentially depends on the heat and vapour transfer properties and design of the layers outside of the thermal insulation (roofing and underlay

KEYWORDS

Air leakage, condensation, heat air and vapour transfer, roof, sensitivity

INTRODUCTION

The basics of condensation control in insulated building components in cold climates is physically well understood. On the one hand airtight construction is necessary to prevent leakage of humid indoor air to the colder side of the thermal insulation layer as a result of air pressure differences across the envelope. On the other hand the vapour transfer properties of the material layers at both sides of the thermal insulation should be tuned in order to control the diffusion of water vapour into the envelope under vapour pressure differences. In lightweight construction both requirements are conventionally met by applying a vapour retarder (plastic film or kraft paper) at the warm side of the envelope which should be sealed at joints and intersections to achieve airtightness.
However, even when a vapour retarder is applied in lightweight building components, condensation problems still occur in practice as a result of air leakage through unintended gaps and perforations common to most existing construction methods. Due to human errors in design and construction, the continuity of the vapour retarder (aka air barrier) is often not achieved and the sound moisture performance of the envelope is at risk. Therefore a methodology is needed to evaluate and reduce the effects of potential discontinuities. To decide on the necessity and the ways of improving the condensation control system, such a methodology should consider the uncertainty to achieve continuity of airtightness in building practice and account for air leakage in the moisture performance analysis of the building envelope.

This paper presents an analysis method to evaluate the sensitivity of lightweight systems to condensation problems as a result of discontinuities, based on a semi-stochastic approach to moisture performance analysis and the application of heat, air and vapour transfer models (Janssens 1998). In the first part of the paper this approach is briefly discussed and applied to cavity-insulated tiled roofs. The second part explores the influence of different measures on the sensitivity of the roof design to condensation problems due to air leakage. The following parameters are studied: the thermal and diffusion resistance of the roofing system, the diffusion resistance of the vapour retarder and the thermal resistance of the insulation.

METHODOLOGY

Assessment Method

A failure effect analysis method has been developed to define the sensitivity of a roof system to condensation problems due to air leakage. The method consists of a repeated number of 2D steady-state heat air and vapour transfer simulations to predict the variation in moisture performance as a result of discontinuities in geometry. The variation of the effective air permeance due to unintended defects has been considered the only source of uncertainty in the analysis. The other loading and design variables, such as the indoor climate parameters and the material properties, have been assumed to be comparatively well definable for each project. The uncertainties in geometry and airtightness are modelled by the introduction of various defect combinations in the envelope geometry. The set of defects is calibrated by comparing measuring data with the predicted variation in roof air permeance as a result of the defects. A steady-state moisture performance analysis for a typical cold spell has been proposed as a first-order assessment of the risk of interstitial condensation due to air leakage. The calculation model 2DHAV for coupled heat, air and vapour transfer (Janssens 2001a) is used to predict the variation of condensation amounts in a specific envelope design at certain indoor conditions due to the various defect combinations. The reliability of the condensation control system is then defined as the fraction of calculation results with condensation amounts smaller than a predefined limit state. The complementary fraction is a measure for the risk of failure of the system. The onset of drainage of condensate has been formulated as criterion, with a limit state value of 0.1 kg/m^2. A more detailed discussion of the methodology may be found in Janssens and Hens (1998) and Janssens (2001b).

Case description

The methodology is applied to a tiled insulated compact roof, with an eaves to ridge length of 4.5 m, and a slope of 30°. The roof consists of a roofing system with tiles and a common plastic underlay (diffusion thickness $\mu d = 2$ m), a fibre glass thermal insulation (thickness 12 cm), a kraft paper vapour retarder ($\mu d = 5$ m) and a gypsum board internal lining. The design complies with existing standards for the control of condensation by diffusion (eg DIN 1981). The U-value of the roof is 0,27 W/(m^{2}K). Table 1 lists the cold spell design climate conditions for Ukkel, Belgium, together with the inside conditions used in the analysis. Table 2 defines the set of intended and unintended air gaps in the roof assembly which are used in the failure effect analysis. Intended gaps are considered to be part of the system (overlaps in the underlay, vented cavities,…), unintended gaps are the consequence of defects in continuity (joints between boards, cracks,…). The calculation is repeated with introduction of all combinations of the set of 8 unintended defects (256 possible combinations) and the results are statistically processed. A calculation grid of 1183 nodes is used (13x91).

TABLE 1: Climate conditions (weekly mean values)

Boundary	Temperature	Vapour pressure	Surf. coefficient	Net radiation	Air pressure*
Inside	20°C	1170 Pa	8 $W/(m^2K)$	-	2.5 Pa
Outside (Ukkel)	-2.5°C	470 Pa	17 $W/(m^2K)$	-30 W/m^2	0 Pa

* Reference pressure at eaves level; a hydrostatic pressure gradient is accounted for.

TABLE 2: Set of intended and unintended air gaps.

	Layer	Width	Position	Comment
IN	ROOFING LAYER	5 x 1.5 mm	Every 1.15 m	Joints between sheets/boards (5 in total)
		5 mm	Above insulation	Incompatibility of insulation and framing dimensions
UNINTENDED	THERMAL INSULATION	5 mm	Top	Discontinuity at ridge
		5 mm	Bottom	Discontinuity at eaves
		3 x 2.5 mm	Every 1.2 m	Joints between boards (3 in total)
		5 mm	Below insulation	Discontinuity between insulation and internal lining
	INTERNAL LINING (inc. vapour retarder)	1 mm	Top	Unsealed junction at ridge
		1 mm	Bottom	Unsealed junction at eaves
		2 x 0.5 mm	Twice every 1.5m	Cracks at both sides of joist or at partition wall
		2 x 0.5 mm		

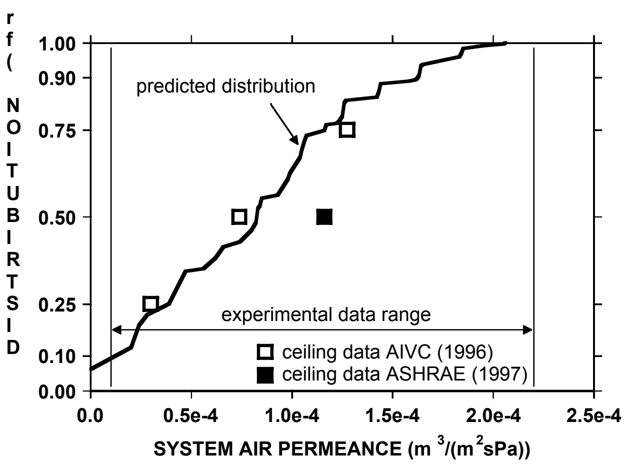

FIGURE 1: Comparison between predicted distribution and experimental data of system air permeance

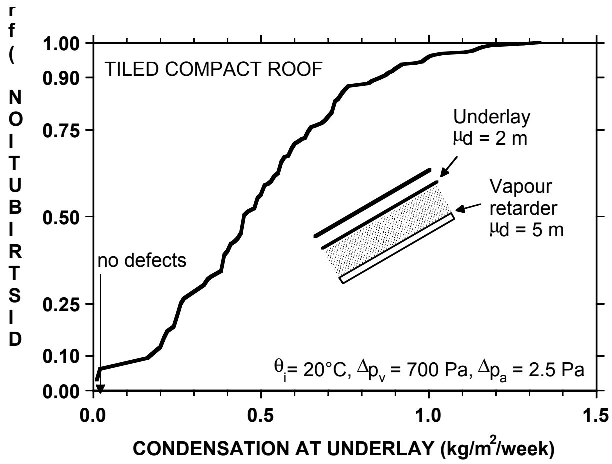

FIGURE 2: Predicted distribution of condensation amount at underlay surface (surface-averaged value)

The calculation result is represented by means of the cumulated distribution function, defining the fraction of calculation results falling below a certain value. Figure 1 shows the predicted distribution of the system air permeance. As the figure demonstrates, the distribution covers the range of experimental permeance data of roof systems of common practice. This indicates that the set of defects defined in Table 2 is representative of the uncertainty in geometry and continuity in building practice.

The predicted distribution of the surface-averaged condensation amount in the roof is presented in Figure 2. The result illustrates that even small defects in the envelope layers may jeopardise the roof moisture performance. As a result of defects in the internal lining and vapour retarder, the condensation quantities may increase to two orders of magnitude above the condensation mass in a roof without defects. The roof design in this study is very sensitive to condensation problems due to air leakage: over 90% of the defect combinations causes a transgression of the limit state criterion of 0.1 kg/m^2.

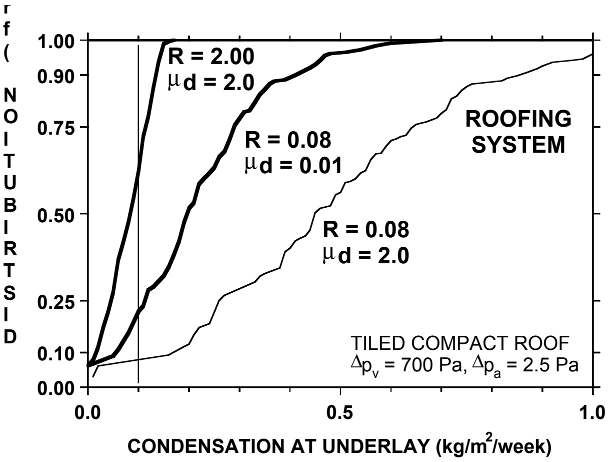

FIGURE 3: Effect of vapour permeable or thermally insulating roofing system on condensation at underlay

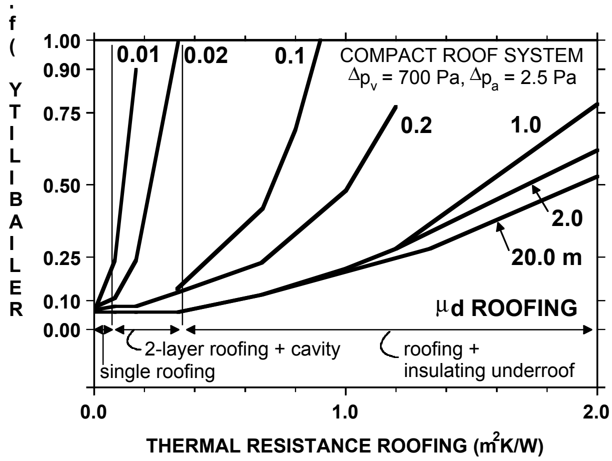

FIGURE 4: Combined effect of vapour permeable and insulating roofing systems on system reliability

PARAMETER STUDY

Thermally insulating and vapour permeable roofing systems

The failure effect analysis described in the previous section is successively performed for various values of the heat and vapour transfer properties of the layers at the outside of the thermal insulation. In the following discussion the total of these layers is referred to as the 'roofing system'. Three types of roofing systems are distinguished, depending on the total thermal resistance: systems with a single roofing (eg corrugated plates), systems with a two-layered roofing separated by an air cavity (eg tiles with underlay) and systems with an insulating underroof (eg extruded polystyrene board on top of the roof framing).
Figure 3 compares the predicted distribution of the condensation rate in the tiled compact roof discussed in the previous section with two alternatives. The first is a roofing system with a decreased diffusion resistance (μd = 0.01 m), representative of a roofing system with tiles and a spunbonded, so-called breathing underlay film. The second is a roofing system with an increased thermal resistance (R = 2 m^{2}K/W), representative of a system with insulating underroof Due to these measures, the predicted condensation flow rates substantially decrease compared to the reference case, as well as the variance of the distributions. This way it is possible to create a less sensitive roof design, which restricts the variation of surface-averaged condensation amounts due to unintended defects to the limiting characteristic of 0.1 kg/m^2.

Figure 4 illustrates how the reliability of the roof design is affected by the combined thermal resistance and diffusion thickness of the roofing system. A roofing system combining a small diffusion thickness (μd ≤ 0.02) with a thermal resistance as small as that of an air cavity, is very effective in improving condensation control reliability. For vapour retarding roof coverings, an insulating underroof with a high thermal resistance is needed to improve the reliability to the same level. However, the reliability of systems with a single roofing layer (small thermal resistance) is not improved by decreasing the diffusion thickness of the roofing. Apparently a vapour permeable roofing system is unable to reduce the condensation risk without a minimum thermal resistance.

These results are quite logical from a physical point of view. Because of the unintended defects in the envelope layers the access of water vapour into the roof system increases, mainly by air leakage from inside to outside. In this case condensation at the inner surface of the roofing system may only be reduced or prevented when the vapour access into the component is balanced by the removal of vapour from the condensing surface to the outside.

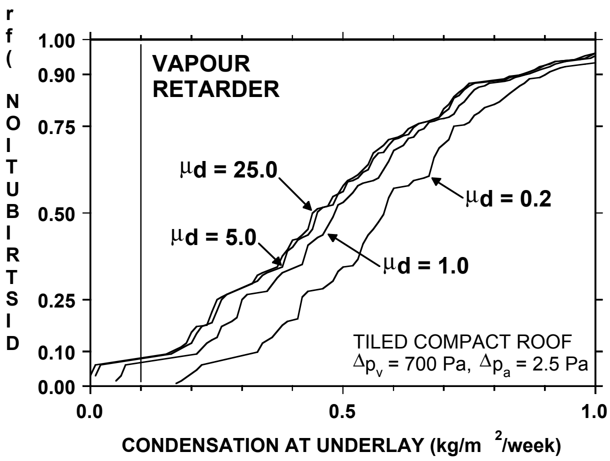

FIGURE 5: Effect of diffusion thickness of vapour retarder on condensation amounts at underlay surface

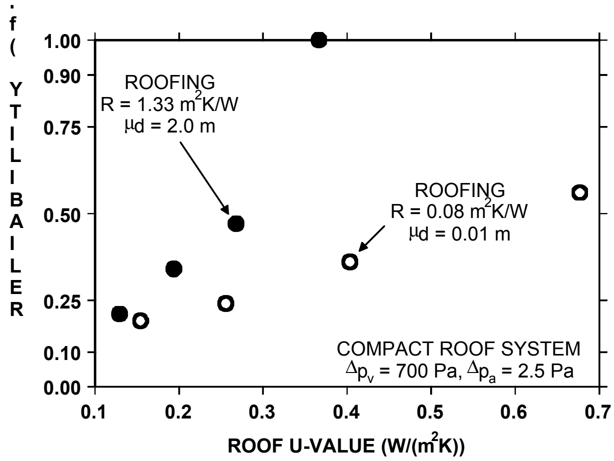

FIGURE 6: Effect of roof thermal quality on condensation control reliability

The vapour removal rate depends on the diffusion resistance of the layers at the outside of the condensing surface, and on the drying potential of the roof defined by the difference between the saturation vapour pressure at the condensing surface and the vapour pressure of the outside air. Since the saturation vapour pressure is a function of the temperature of the condensing surface, the vapour removal rate also depends on the thermal resistance of the roofing system. However, the diffusion resistance of the roofing system only affects the vapour removal when the drying potential is positive, this is when the temperature of the condensation plane is larger than the dew point of the outside air. This condition may not be met during cold weather when on average the long-wave radiation to the sky outweighs the solar radiation and the exterior roof surface may be cooled below the outside air temperature. Thus only when a minimum portion of the thermal resistance of the building component is located outside of the condensing surface (approximately 0.05 m^2K/W), may the vapour removal be enhanced by a lower diffusion resistance of the roofing system.

Effect of vapour retarders and thermal quality

The previous analysis has demonstrated the possibilities to reduce the sensitivity of a roof design to condensation problems by the application of vapour permeable and thermally insulating roofing systems. In this section the influence of the heat and vapour transfer properties of the materials inboard of the roofing system are investigated (vapour retarder, thermal insulation).

As may be expected, the failure effect analysis shows the insensitivity of the roof moisture performance to the vapour diffusion resistance of the vapour retarder. Figure 5 compares the predicted distributions of the condensation rate in the tiled compact roof for different values of this property. The result confirms that the quality of the vapour retarder is of no consequence to the control of interstitial condensation in a lightweight roof when the achievement of its continuity is uncertain. Once the diffusion thickness of the vapour retarder is larger than 1.0 m, the predicted distribution of condensation rates essentially remains unaltered. A diffusion thickness of the order of 1 m is achieved by most finishing layers (paint, wall paper,...).

Figure 6 shows the predicted condensation control reliability as a function of the thermal quality of the roof for a roofing system with a vapour permeable underlay and a system with insulating underroof. In both cases the reliability decreases with higher thermal quality. This indicates that standard condensation control methods which performed satisfactorily in roofs with higher U-values, are not adequate when thermal insulation requirements for the building envelope become more rigid.

Considering the influence of the roof thermal quality on the temperature of the condensing surface and on the drying potential of the roof, it may be surprising that the system reliability of the roof design with vapour permeable underlay is not more affected by changes in U-value. An explanation for this result is found in the nature of air leakage through gaps. In the vicinity of the air flow path, the temperature of the condensing surface is determined more by the airborne heat transfer than by the heat conducted through the roof system. Especially the vapour permeable roofing systems benefit from the locally increased drying potential associated with a higher roofing temperature. As a result, the reliability of the condensation control system is less dependent on the thermal quality of the roof than may be expected.

CONCLUSIONS

This paper presented and applied a semi-stochastic method of moisture performance analysis to study the sensitivity of lightweight roof systems to condensation problems in cold climates, given the uncertainty to achieve continuity of airtightness in building practice. The study defined air leakage as a significant cause of condensation problems in roofs of this type. The analysis showed that the sensitivity for condensation due to a lack of continuity of airtightness in a cavity insulated roof essentially depends on the properties and design of the roofing system, which contains all the layers outside of the structural cavity. The layers located at the inside of the roofing system (eg vapour retarder) have a minor influence on the condensation risk.

The analysis demonstrated the effectiveness of two measures to reduce the sensitivity of a roof design to condensation problems: increasing the thermal resistance of the roofing system and enhancing the removal of vapour from the inner surface of the roofing system to the outside, by using a vapour permeable underlay. The second measure is effective only if a minimum portion of the roof thermal resistance is located outboard of the structural cavity. The research also demonstrated that roofs with higher thermal quality are more sensitive to condensation problems due to a lack of airtightness. This indicates that the introduction of thermal insulation requirements should go hand in hand with upgraded guidelines for condensation control.

REFERENCES

DIN 4108. (1981). *Wärmeschutz im Hochbau* (Energy conservation in highrise buildings, in German). Teil 1-5. Ausgabe August 1981. Deutsches Institut für Normung e.V.

Janssens, A. (1998). *Reliable Control of Interstitial Condensation in Lightweight Roof Systems, Calculation and Assessment Methods*. Doctoral dissertation K.U.Leuven, Faculteit Toegepaste Wetenschappen, ISBN 90-5682-148-2, 217 pp.

Janssens, A. and Hens, H. (1998). Condensation risk assessment. *Thermal Performance of the Exterior envelopes of Buildings VII*: Conference Proceedings. ISBN 1-883413-70-2, ASHRAE Special Publications, Atlanta, GA. 199-206.

Janssens, A. (2001a). Advanced numerical models for hygrothermal research: 2DHAV model description. *Moisture analysis and condensation control* (H.R. Trechsel, editor). ASTM Manual 40. American Society for Testing and Materials, West Conshohocken, PA, USA, ISBN 0-8031-2089-3, 177-178.

Janssens, A. (2001b). Reliable control of interstitial condensation in lightweight roof systems. *Air Information Review*, Vol. 22, nr. 4, p. 11 (abstract), AIVC CD (full publication, 190 pp.).