How to construct a domestic pitched roof with high thermal quality?

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ABSTRACT

The paper at hand collects research findings on the impact of air flow on the thermal performance of pitched roof assemblies. Air flows in these components are typically a mixture of: 1) in/exfiltration, 2) natural convection and 3) wind-washing. In the current building practice the necessity of an air barrier to guarantee the thermal and hygric performance of roofs is well established. Yet the need for a continuous wind barrier to avoid wind-washing of the insulation layer is still often underestimated in practice. In addition the literature review shows that already small leakage paths around the insulation layer may induces an important reduction of the thermal performance due to buoyant driven air loops which is often overlooked in today's building methods. Based on the findings in the literature the present article puts forward guidelines on how to construct pitched roofs with a robust high thermal performance.

KEYWORDS

Wind-washing, natural convection, pitched roofs, guidelines, literature review

1 INTRODUCTION AND PROBLEM STATEMENT

A sound thermal insulation is one of the key factors to reduce the energy use of new and existing buildings. Consequently most European member states increased the U-value requirements for opaque building components to values of 0.25 W/m²K or even better. These requirements are typically evaluated in the design phase: the theoretical performance of the building component is calculated based on the thickness and thermal conductivity of the composing layers. It is however well-known that the actual achieved thermal performance is not only a matter of the thickness of the insulation layer. Other phenomena than pure heat conduction can strongly spoil the performance on site (a.o. Hens et al. 2007, Janssens & Hens 2007, Lowe et al. 2007).

For pitched roofs air movement through the building component is considered as the malefactor, often resulting in an on-site thermal quality much lower than the design value. Recently the British Board of Agrément, one of UK's leading certification bodies, published a report on the air movement and thermal performance of pitched roof constructions (BBA, 2012). The results and conclusions were based on experimental research in laboratory conditions making use of a modified Hot Box. By comparing the thermal performance as a function of imposed air speed at the cold side of the roofs of three so-called 'standard build practice' roof configurations, a significant performance gap was observed for all roof types. On average across all three configurations, a 90% increase was reported between calculated and measured U-value at higher wind speeds. Most striking in this study are not the obtained

results as such – similar results have been reported in previous studies –, but the fact that the pitched roof constructions tested are considered as standard building practice. The huge impact of air movement on the actual thermal performance of building enclosures has been studied extensively for decades. Already in 1989 Powell et al. published a literature survey on the influence of air movement on the effective thermal resistance of porous insulations. Ever since, several studies investigated the effect of different air movement patterns on the thermal performance and durability of (mainly lightweight) building components (e.g. Brown et al. 1993, Di Lenardo 1995, Uvlsok 1996 and Janssens & Hens 2007). Several of those studies, resulted in guidelines and performance requirements of the composing material layers (a.o. NBC 1995, Straube and Burnett 2011, Uvsløkk et al. 2010). However, it seems that these (fragmented) recommendations did not led to a roof construction resilient to air flow effects in day to day building practice.
Therefore, the current article reviews previous research work on air movement in light weight building components in general and pitched roofs in particular. In this study we focus on lightweight insulated sloped roofs, consisting of a wooden framing structure, insulated by filling the structural cavity in between the framing. Based on the literature, the first part of this paper reiterates the common air flow patterns and their effect on the heat transmission losses. In the second part, the observed findings are compiled in specific performance requirements and guidelines for good building practice for a pitch roof construction. When following these guidelines, the performance gap can be minimized and the actual thermal performance of the roofs will be in line with the design values.

2 COMMON AIR FLOW PATTERNS AND THEIR EFFECT ON THERMAL PERFORMANCE

The impact of air movement on the thermal performance of lightweight building components has been extensively studied in the literature. For pitched roofs, three different kind of air flow patterns have to be accounted for:

- air leakage (diffuse and concentrated)
- natural convection
- wind washing

The first corresponds to forced convection due to deficiencies in – or even the lack of – an airtight layer. As a result pressure differentials across the building envelope (be it induced by an indoor-outdoor temperature difference, by wind or by mechanical ventilation) will force the air to flow through the building component. For pitched roofs forced exfiltration conditions are most dominant, resulting not only in increased heat losses, but often also in moisture problems (Janssens & Hens, 2007, Langmans et al. 2013). The second pattern causes a reduced thermal performance of the building component due to free heat convection as a result of buoyancy driven air rotation in and around the insulation layer. Driving force is the temperature difference across the building component. The last air flow pattern, wind washing, results from the fact that commonly no stringent airtightness requirements are put forward for the exterior protective layer (the underlay). As a result, even with a good overall airtightness achieved, exterior air may flow through air permeable insulation materials, again jeopardizing the designed thermal quality.

Figure 1 shows the different kind of air movements observed in sloped roofs: air leakage (diffuse and concentrated), natural convection in and around the insulation layer, and wind washing. Though these mechanisms typically occur as mixed processes, the next sections will try to quantify the impact of each of the different air flow patterns. Based on a literature review, the present article will conclude on the necessary requirements to avoid these air movements.

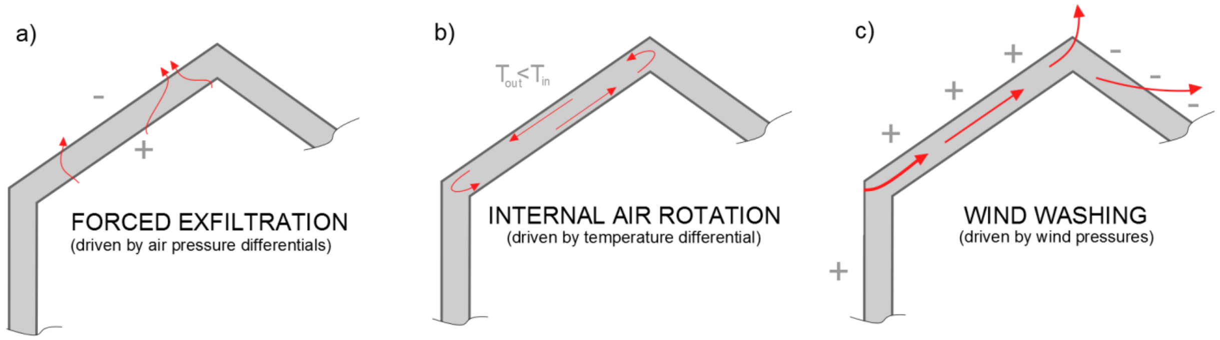

Figure 1: Possible air flow phenomena reducing the thermal performance of pitched roofs: a) forced exfiltration through the pitched roof, b) internal air rotation in and around the insulation layer and c) wind-washing of the insulating layer.

2.1 Forced exfiltration

Most straightforward form of air transport within sloped roofs is forced convection. This occurs when an air pressure differential is established across a building component including air leakages. The overall air pressure difference across the roof is induced by wind, temperature differences and/or mechanical ventilation. The distribution and order of magnitude of the leakage paths within the pitched roof determines the resulting air flow pattern. Desmarais et al. (2000) conducted a detailed laboratory investigation in which they distinguished between: a) long paths, b) concentrated paths and c) distributed (diffuse) leakage paths. The shape of the air flow pattern highly influences the impact on the thermal performance of the building component. A concentrated air flow path will for example correspond to higher heat losses than a distributed air flow path with the same overall air leakage level.

In- and exfiltration in light weight building components can be readily avoided by installing a continuous airtight layer, commonly called the air barrier. Because in practise air barriers consist of different elements and joints, Straube and Burnett (2011) propose to use the term air barrier system. Already in 1985, Di Lenardo et al. prescribed target values for the air permeability of air barrier systems, including anticipated joints and perforations. At that moment, an upper limit of $2.7\ 10^{-6}\ m^3/(m^2sPa)$ was put forward for an air barrier system including joints. This value was based on numerical simulations for the Canadian climate, considering both limit state values for moisture accumulation as well as an increase of the conductive heat transfer (up to 15%) due to air leakages. This value has been tightened by Straube and Burnett (2011), proposing an upper limit of $1.3\ 10^{-6}\ m^3/(m^2sPa)$. Apart from the requirements for the overall airtightness of the air barrier system, they stress the importance of other criteria, such as continuity, strength, durability and stiffness.

2.2 Internal air rotation

Most of the existing studies on natural convection in light weight building components are related to stud walls. Apart for an inclination angle, the composition of pitched roofs is very similar to stud walls. As a consequence the research results regarding internal air rotations in stud walls can be easily transformed to pitched roofs taking into account the inclination angle.

The first studies investigating the effects of air movement on the thermal performance of permeable insulation systems occurred in the late fifties in Norway (Lorentzen & Brendeng 1959). These experimental studies demonstrated that low density insulations may lead to convection loops in and around the insulation layer, significantly reducing its thermal performance. Hereafter many authors have examined the same effect for various configurations and temperature differences across the components (e.g. Bankvall 1972, Silberstein et al. 1990, Klarsfeld & Combarnous 1980, Lecompte 1989, Dyrbøl et al. 2002). A first comprehensive literature review on this topic has been written by Powell et al. (1989). Their review mainly distinguishes between two configurations, studied at that time: (1) a cavity filled with an open porous insulation material and (2) an air cavity partly filled with a thermal insulation layer.

In summary, the studies under review, generally conclude that the impact of natural convection on the thermal performance is limited when at least one of the adjacent layers is airtight, air gaps along the interface between the sheathing and insulation are avoided and sufficiently dense insulation materials (>20-30 kg/m3) are applied.

2.3 Wind washing

The previous section restricted the discussion to internal air rotations effects, presuming an ideal situation in that the insulation layer is closed between two airtight layers. Nevertheless, in reality the exterior protective layer (wind barrier) is most often not sufficiently airtight. As a consequence exterior air may flow through permeable insulation materials driven by pressure gradients on the building envelope. First laboratory investigations on the thermal impact of wind-washing emerged in Scandinavia by Timusk et al. (1991) and Uvsløkk (1996). Timusk et al. (1991) performed experiments on full-scale corners of wood frame walls exposed to wind conditions. They found that defects in the wall sheathing resulted in a significant decrease of its thermal performance. Later, Uvsløkk (1996) conducted full-scale laboratory measurements on wind-washing effects in timber frame walls. The applied exterior pressure difference, based on in situ measurements, was realized by imposing a pressure difference at the walls cladding in and outlet. Based on these measurements, Uvsløkk (1996) proposed a maximum overall air permeability of the wind barrier system of 14 10^{-6} $m^3/(m^2 sPa)$. Ojanen & Kohonen (1995), at their turn, found similar threshold values by numerical simulation. These additional simulation results illustrated that compartmentation of the insulation layer reduced wind-washing. As a consequence, Ojanen & Kohonen (1995) suggested a maximum air permeance of 10 10^{-6} $m^3/(m^2 sPa)$ when strong corner convection is possible and 25 10^{-6} $m^3/(m^2sPa)$ when the building envelope is divided in separate structures.

In addition to these laboratory measurements, Janssens & Hens (2007) studied windwashing effects on in situ pitched roofs in Belgium. They examined the overall air flow patterns with tracer gas tests and temperature and heat flux sensors installed at three heights. Results revealed a clear correlation between the exterior wind speeds and the reduction of the thermal performance. Most significant impact on the thermal performance was located at the level of the ridge. The measured reduction of the overall thermal resistance of roofs for a wind of 4 m/s coming from a direction perpendicular to the roof was 10% for entirely insulated elements (compact roofs) and 40% for partly insulated roof elements (vented roofs). Based on these in situ measurements Janssens & Hens (2007) recommended to seal underlay materials in duo-pitched roofs to improve their air permeance levels to the proposed values of Uvsløkk (1996) and Ojanen & Kohonen (1995). These postulated recommendations notwithstanding, the vast majority of the current building practice still not seals the wind barrier to prevent wind-washing.

3 PRACTICAL GUIDELINE FOR PITCHED ROOFS

The literature review in the previous section revealed that the thermal performance of pitch roofs may be significantly affected by air flow patterns. At the same time, based on their findings, several researchers put forward some guidelines and performance targets to make the roofs less vulnerable to air flow effects. This section compiles for each of the air flow patterns all outcomes to come up with general guidelines on how to construct a pitch roof with a robust thermal performance.

First of all, to **avoid air leakage**, the construction should contain a continuous airtight layer, the so-called air barrier system. This air barrier system has to preclude in- and exfiltration through the roof component. As upper limit a maximum air permeability of 1.3 10^{-6} $m^3/(m^2 sPa)$ can be maintained. Note however, that in addition to the airtightness of the material layer (which can easily be measured and achieved (e.g. Langmans et al. 2010), the continuity of the air barrier system is of far more importance, guaranteeing an overall airtightness of the system including joints, overlaps,… Therefore, a typical interior finishing as for instance coated gypsum board (that easily fulfils the air permeability requirements) is often not considered sufficient since achieving continuity is hard at service penetrations, wall-roof interfaces, etc.. Furthermore, cracks in the inner lining might appear due to wind gust loads on the roof. That is why, common guidelines propose to separate the interior lining and air barrier system, and to install them at different positions to avoid damage of the air barrier system when perforating the lining. In European countries often an air-vapour barrier system is used at the warm side of the insulation to avoid both air leakage through the component, as well as vapour diffusion and convection. Alternatively, a warm roof construction (similar to a flat roof design) could be applied, in which the location of the air (vapour) barrier system, insulation and outside finishing is placed on top of the structural sheathing and framing.

Once forced exfiltration is excluded by a sound air barrier system, it is important to **avoid air rotation by natural convection** within the roof component. Section 2.2 has shown that the thermal resistance of insulation layers can be significantly degraded by natural convection. Convection loops were found to be highly triggered by air cavities or even small air gaps between insulation layer and boundary surface (e.g. Brown (1993) and Janssen (1997)). Therefore, a tight contact between insulation and both interior and exterior surface will be important to reduce the risk on air rotation. This asks for a compact roof. But even when air gaps along underlay and interior air barrier system are avoided, internal air loops through low-density fibrous insulation layers may occur (Powell et al., 1989). To reduce the impact of natural convection, Langmans (2013) proposes the application of denser insulation materials (> 20 kg/m^3). Also blown in insulation was found to be more resilient to air looping than insulation blankets. Not only is the risk on small air gaps lower when insulation is blown into the compartment, often also higher insulation densities are applied.

Last, but not least, and unfortunately often overlooked, wind-washing should be avoided. Even with an interior air barrier system fulfilling passive house standards[1], cold outside air might penetrate in the insulation layer due to wind induced forced convection and leave the construction again at another position, but now as warm air. Pitched roofs are rather susceptible to windwashing as wind will induce steep pressure gradients along the roof sides. To avoid this, an additional air barrier is foreseen at the outside, the so-called wind barrier. Following Uvslokk (1996) and Ojanen & Kohonen (1995) an upper limit of 10-15*10^{-6} $m^3/(m^2 sPa)$ is put forward for the air permeability of the wind barrier. Most roof underlay materials fulfil these requirements and can take up the role of wind barrier. In addition to the air permeance requirements of the underlay, the field study of Janssens & Hens (2007) stressed the importance of a continuous wind barrier. This is important, as for its original

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[1] Passive house standard explicitly require an overall building airtightness of n_{50}=0.6 1/h

function of drainage plane, no sealed joints were requested, but an overlap sufficed. The airtight continuity of the underlay often results in adapted building details. Whereas a continuous wind barrier is feasible in the roof surface itself, it is harder to achieve at eave and ridge joints.. In the eave detail a pre-installed airtight strip is used to make a continuous airtight connection between wind barrier and interior air barrier system, securing the insulation layer for wind-washing.

4 DISCUSSION & CONCLUSIONS

Contrary to the recent conclusions of the (BBA, 2012) in which a significant performance gap was observed for all kind of warm roof constructions, the previous section illustrated that it is possible to construct a well-performing and robust pitched roof with high thermal quality and resilient to air flow patterns. To do so, the following advices should be taken into account:

- To avoid wind washing and air looping, create a compact roof, i.e. fill the cavity between the underlay and the air and vapour barrier over the total height of the rafters and use an insulation material with a high enough density (> 20 kg/m³) and some compressibility.
- Apply a continuous air (and vapour) barrier system at the inside of the insulation layer, in order to assure the airtightness of the roof construction when the internal lining is perforated. The overall air permeability of the air barrier system should be lower than 1.3 10^{-6} m³/(m²sPa). Furthermore, make sure that the internal lining and air barrier are at different positions, so that the lining can be perforated without damaging the air barrier.
- Apply a sufficiently airtight underlay (air permeance < 10-15 10^{-6} m³/(m²sPa)) with sealed joints (or airtight tongue and groove system). Pay attention to an airtight detailing of the eaves and the ridge.
- To increase the thermal quality even more, the cavity between air and vapour barrier and interior lining can be insulated. Air flow has hardly any impact on the thermal performance of this cavity and the extra insulation layer gives additional support to the air barrier system, increasing its lifetime and durability.

5 REFERENCES

Bankvall, C. (1972), *Natural convective heat transfer in insulated structures*, PhD thesis, Division of building technology, Lund institute of technology, Sweden, Lund, Sweden.

BBA (2012) Air movement and thermal performance – An investigation into the effect of air movement on the thermal performance of domestic pitched roof constructions. British Board of Agrément, Technical Report nr. 1

Brown, W. C., Bomberg, M. T., Ullett, J. M. & Rasmussen, J. (1993), *Measured thermal resistance of frame walls with defects in the installation of mineral fibre insulation*, Journal of Building Physics 16(4), 318–339.

Desmarais, G., Derome, D., & Fazio, P. (2000). *Mapping of air leakage in exterior wall assemblies*. Journal of Building Physics, 24, 132–154.

Dyrbøl, S., Svendsen, S. & Elmroth, A. (2002), *Experimental Investigation of the Effect of Natural Convection on Heat Transfer in Mineral Wool*, Journal of Building Physics 26(2), 153–164.

Hens, H., Janssens, A., Depraetere, W., Carmeliet, J., Lecompte, J. (2007). *Brick Cavity Walls: a Performance Analysis Based on Measurements and Simulations*, Journal of Building Physics, 31 (2), 95-124.

Hens (2003). *Interstitial condensation due to air Leakage: a sensitivity analysis*. Journal of Thermal Envelope and Building Science, 27(1), 15–29.

ISO 10456:2007. Building materials and products -- Hygrothermal properties -- Tabulated design values and procedures for determining declared and design thermal values

Janssen, H. (1997), *Thermal performance of highly insulated wood frame walls*, Master thesis, Norwegian University of Science and Technology, Norway.

Janssens, A., & Hens, H. (2003). *Interstitial condensation due to air Leakage: a sensitivity analysis*. Journal of Thermal Envelope and Building Science, 27(1), 15–29.

Janssens, A. & Hens, H. (2007), *Effects of wind on the transmission heat loss in duopitched insulated roofs: A field study*, Energy and Buildings 39(9), 1047–1054.Janssens, A., & Hens,

Kalamees, T., & Vinha, J. (2003). *Hygrothermal calculations and laboratory tests on timber-framed wall structures*. Building and Environment, 38(5), 689–697.

Klarsfeld, S. & Combarnous, M. (1980), *Analyse des transferts thermiques convectifs dans les isolants poreux perméables*, Revue generale de thermique 228, 977–983.

Langmans, J., Klein, R., Roels, S. (2012). *Hygrothermal risks of using exterior air barrier systems for highly insulated light weight walls: A laboratory investigation*. Building and Environment, 56 (10), 192-202.

Langmans, J., Klein, R., & Roels, S. (2012). *Hygrothermal risks of using exterior air barrier systems for highly insulated light weight walls: a laboratory investigation*. Building and Environment, 56(10), 192–202.

Langmans, J., Klein, R., & Roels, S. (2010). *Air Permeability Requirements for Air Barrier Materials in Passive Houses*. In International Symposium on Building and Ductwork Air-tightness. Copenhagen, Denmark: Energie + Umwelt Zentrum.

Lecompte, J. (1989), *The influence of natural convection on the thermal quality of insulated cavity walls constructions (in Dutch)*, PhD thesis, Departement of Civil Engineering, KU Leuven, Belgium.

Lorentzen, G. & Brendeng, E. (1959), *On the influence of free convection in insulated vertical walls*, in ‘10th International congress of refrigeriation’, p. 294.

National Building Code of Canada 1995, Institute for Research in Construction, National Research Council Canada, Appendix A-9.25.1.2.

Powell, F., Krarti, M. & Tuluca, A. (1989), *Air movement influence on the effective thermal resistance of porous insulations: a literature survey*, Journal of Building Physics 12(3), 239–251.

Riesner, K. (2003), *Natural convection in exterior walls (in German)*, Phd thesis, Univeristy of Rockstock, Germany.

Rousseau J. (1998). *Air permeance of Building Materials, Research Highlights*. Technical Series: 98-109. (Available on http://www.cmhc.ca/publications/en/rh-pr/tech/98109.htm)

Timusk, J., Seskus, A. & Ary, N. (1991), *The control of wind cooling of wood frame building enclosures*, Journal of buildings Physics 15(1).

Uvsløkk, S. (1996), *The Importance of Wind Barriers for Insulated Timber Frame Constructions*, Journal of Building Physics 20(1), 40–62.

Straube, J. 2011. *High Performance Building Enclosures*. Somerville, MA: Building Science Press

Silberstein, A., Langlais, C. & Arquis, E. (1990), *Natural convection in light fibrous insulating materials with permeable interfaces: onset criteria and its effect on the thermal performances of the product,* Journal of Building Physics 14(1), 22–42.

Silberstein, A., & Hens, H. (1996). *Effects of air and moisture flows on the thermal performance of insulations in ventilated roofs and walls*. Journal of Building Physics, 19(4), 367–385

Wahlgren, P. (2007). *Overview and literature survey of natural and forced convection in attic insulation*. Journal of Building Physics, 30(4), 351–370.