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THE HYGROTHERMAL BEHAVIOUR OF SLOPED ROOFS

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ABSTRACT

There is a widespread conviction that, to avoid moisture damage in insulated sloped roofs, they should be ventilated under the roof covering and between the thermal insulation and the underroof. However, recent research shows that the assumptions behind - an airtight, vapour retarding roof covering, a longitudinal air flow in the cavities, a surface temperature of the covering always higher than the outside temperature and diffusion as the only vapour transfer mechanismus - oversimplify things. In fact, most coverings are air open, vapour flow is convection rather than diffusion linked and undercooling must be taken into account. The first fact makes venting features in the covering superfluous, the two last aggravate, rather than ameliorate the hygrothermal reaction of vented roofs and suggest a better section alternative: the sandwich solution

1. INTRODUCTION

In most countries, tile and slate manufacturers and roofers defend the vented sloped roof: the necessity of outside air ventilation under the tiles or slates and between the underroof and the insulating layer. Product development is governed by it - venting tiles, venting ridges -, standardisation too, imposing batten heights, venting sections, the use of venting tiles..a.o.
However, from a physics point of view, that conviction isn't so sound, two questions remaining unanswered: does one really need special features to induce ventilation under a tiled or slated deck, and, is ventilation necessary or, worse, could it harm rather then ameliorate the hygric behaviour of the roof?

To clarify both questions, a longlasting stepwise research was set up : first analysing damage cases, then studying the vapour resistance and air tightness of layers and whole roof sections, next looking to the undercooling phenomenon and to interstitial condensation as a function of vapour and air pressure differences and last, testing solutions under real weather conditions, a step still going.

2. A SHORT OVERVIEW OF THE VENTILATION THEORY (1)

The traditional way of looking to ventilation is based on a simple model: in each cavity with in and outlets, there's a longitudinal airflow, resulting in an exponential temperature in- or decrease from the outside temperature at the inlet to a value, nearer to the non vented cavity equilibrium temperature $\theta_{c\infty}$, the longer the cavity and the lower the air velocity:

$$\theta_c = \theta_{c\infty} + (\theta_e - \theta_{c\infty}).\exp[(R_1+R_2).x/(R_1.R_2.1200.v.b)] \qquad \text{(eq 1)}$$

with: $$\theta_{c\infty} = (R_1.\theta_e + R_2.\theta_i)/(R_1+R_2) \qquad \text{(eq 2)}$$

Also an exponential vapour pressure course developes:

$$p_c = p_{c\infty} +(p_e - p_{c\infty}).\exp[462.T_c.(Z_1+Z_2).x/(Z_1.Z_2.v.b)] \qquad \text{(eq 3)}$$

with: $$p_{c\infty} = (Z_1.p_e + Z_2.p_i)/(Z_1+Z_2) \qquad \text{(eq 4)}$$

In these equations, R_1 and R_2 are the thermal resistances (m^2K/W) and Z_1 and Z_2 the diffusion resistances (m/s), of the in- and outside parts alongside the cavity, b is the width of the cavity (m), v the air velocity (m/s), x the lenght coordinate (m), θ_i the inside temperature (°C), θ_e the outside temperature (°C), p_i the inside vapour pressure (Pa), p_e the outside vapour pressure (Pa).and $p_{c\infty}$ the non vented cavity equilibrium vapour pressure (Pa) (figure 1).

Winterly condensation problems arise, when the vapour pressure in the cavity p_c equals the saturation pressure against or in the outside part. That reality becomes more probable, the better insulated the sloped roof (if R_1 increases, then $\theta_{c\infty}$ becomes lower , see eq 2).

Diminuishing the condensation probability is possible, or by increasing the ventilation flow (a wider cavity, more in and outlet area, a higher air velocity) or by increasing the inside part diffusion resistance Z_1. The better insulated a roof, the more important both tools. Because the flow velocity depends of the non controlable temperature and pressure differences over in- and outlets, all design aids and standards focus on cavity width, in and outlet area and vapour retarders in the inside part. To be at the save side in dimensioning, the outside part - in a sloped roof the tiles, slates or these + the underroof - is supposed air and vapourtight.

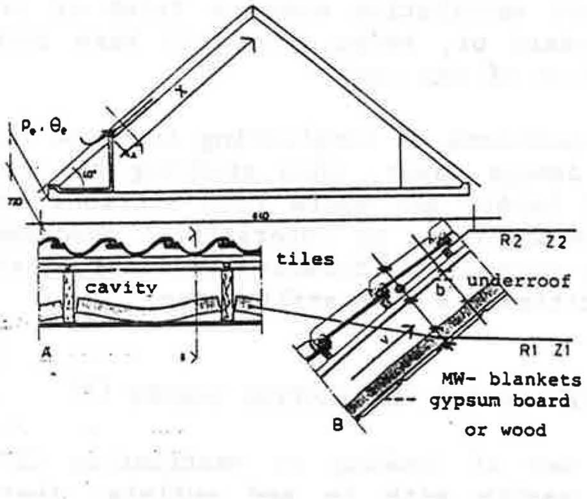


FIGURE 1. The ventilation model ((eq 1) to (eq 4))

3. WEAK POINTS IN THE MODEL

The model overlooks some very important facts:

- wind and temperature differences introduce pressure gradients in the roof an between the roof air spaces and the in - and outside environment;
- roof coverings, more , most roof layers aren't vapour and air tight;
- pressure differences and air openess cause convective flows in and through the roof section, increasing the heat losses and influencing in a very negative, orientation dependant, quick reacting way the hygric behaviour;
- undercooling lowers the temperature of covering and underroof so, that active ventilation may cause condensation instead of excluding it;
- suction of the materials used may be dominant in moisture behaviour.

These discrepancies between model and reality were convincingly proved by analysing a major damage case of insulated sloped roofs in a social estate in the neighbourhood of Leuven, Belgium (1), well or no condensation depending more of orientation than of room use, dripping moisture only after clear sky cold nights, a lower conduction loss, but higher temperatures in the roofs than expected (convective inflow lifts the temperature profile).

3. ARE SPECIAL VENTILATION FEATURES IN COVERINGS NEEDED?

This first question has been answered by studying the diffusion thickness and air permeance of different covering choices (tiles, slates, corrugated plates) and analysing the ventilation pattern (2)(3).

3.1. Diffusion Thickness and Air permeance

3.1.1 Measuring Methods

The diffusion resistance factor μ or -thickness μd of the roof covering materials (tiles, slates, ...) was measured with the wet cup- dry cup method.

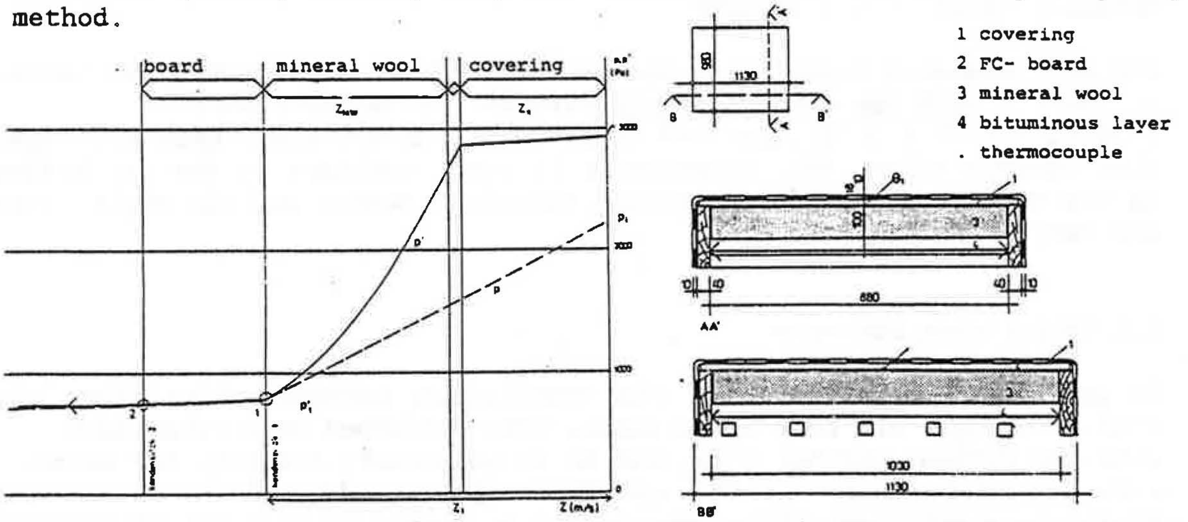


FIGURE 2. Test roof, used to measure the equivalent diffusion thickness of different sloped roof covering deck solutions

The equivalent diffusion thickness of the deck was derived from long lasting interstitial condensation tests on flat roofs in a Hot Box-Cold Box apparatus with the deck as internal lining:

Roof Section (Area: 0.906 m^2/ from down to top- figure 2):

roof covering;
air cavity;
thermal insulation: Mineral Wool, $d = 10cm$, $\mu d = 0.15m$;
a capillar fibro-cement board, $d = 18mm$;
bituminous layer, $d = 10mm$, $\mu d > 100m$

Interstitial condensation is generated in the fibrocement board (figure 2), the amounts being determined by weekly weighting, during 8 to 10 weeks, the roofs. If the temperature and vapour pressure in the Hot and Cold Box are known, then, from the measured condensation rate, the diffusion resistances of the ceiling= covering can be calculated. For the tests performed, we had: HOT BOX : $\theta = 24.1 \pm 0.2$ °C, RH= 70 ± 5 %/ COLD BOX: $\theta = 2.4 \pm 0.2$ °C

The air permeance K_a was measured by fixing a frame with the covering, against an under-pressure box, measuring area 0.896 m^2, coupled to a dust aspirator by way of a flow gauge. After determining, as function of the air pressure difference , the air flow through the covering, K_a can be deduced from the resulting 'flow-pressure'-diagram.
For all covering systems, a relation $\mathbf{K_a = a\Delta p^{-b}}$ is found, t.m., a permeance, decreasing with higher pressure difference.

3.1.2 Results

See table 1
The table shows that roof covering decks with an important length L of locks/overlaps, have an equivalent diffusion thickness significantly lower then the elements, and a high air permeance, in spite of the elements being airtight. For example:

Ceramic tiles : L = 8.3 à 9.2m/m^2
Concrete tiles : L = 6.2m/m^2
Metallic tiles : L = 3.5m/m^2

The air permeance being high, becomes very clear in comparing the values of table 1 with the <specific> air permeance of masonry work: $1.0E\text{-}4\Delta p^{-0.36}$ à $3.7E\text{-}5\Delta p^{-0.20}$ s/m, t.m.160 à 430 times more air tight than ceramic tiles. The consequence is that, contrary to the assumption in the ventilation model, supposing coverings vapour and air tight, they are very vapour and air open.

3.2 Ventilation Patterns

To get some understanding of the ventilation patterns under these air open coverings, air flow measurements were performed on a tiled deck with and without venting tile, and on an underroof- covering air space, with an underpressure at the air inlet. The results of the first step showed no significant difference in air permeance between ± 1 m^2 of

Table 1. Diffusion thickness μd, equivalent diffusion thickness $[\mu d]_{eq}$ and air permeance K_a of roof coverings.

COVERING	μd material RH	μd material -	$[\mu d]_{eq}$ deck (RH= 75%)	K_a deck s/m	
	%-	m	m	a	b
ceramic tiles, single lock	75 86	1.5 0.8 σ=0.13	0.16	1.6E-2	-0.49
ceramic tiles, double lock	86	0.85 σ=0.09	0.26	(1) 1.3E-2 (2) 1.2E-2	-0.50 -0.32
concrete tiles (sneldek)	70	3.9 σ=0.35	0.46	7.8E-3	-0.46
fibro-cement slates	52 70 86	0.9 (0.6 à 1.1) 0.35 σ=0.07 0.34 σ=0.12	0.85 à 1.4	1.7E-3	-0.21
natural slates		> 10	2.1	5.4E-3	-0.34
corrugated (1) fibro-cement (2) plates	70 75	0.64 1.5	0.84	9.1E-4	-0.37
metallic tiles		∞	1.8	2.1E-3	-0.43

tiling with and without venting tile: $1.5E\text{-}3\Delta p^{-0.5}$ vs $1.3E\text{-}3\Delta p^{-0.5}$.
The second step learned that, with ceramic tiles (highest permeance), inlet under- or overpressure only generates local flow between the vent and the adjacent tiles, that with concrete tiles partially a flow in the cavity, partially local flow developes and that with fibro-cement slates a clear cavity flow exists: figure 3.
These measurements were completed with calculations, using the KONVEK-

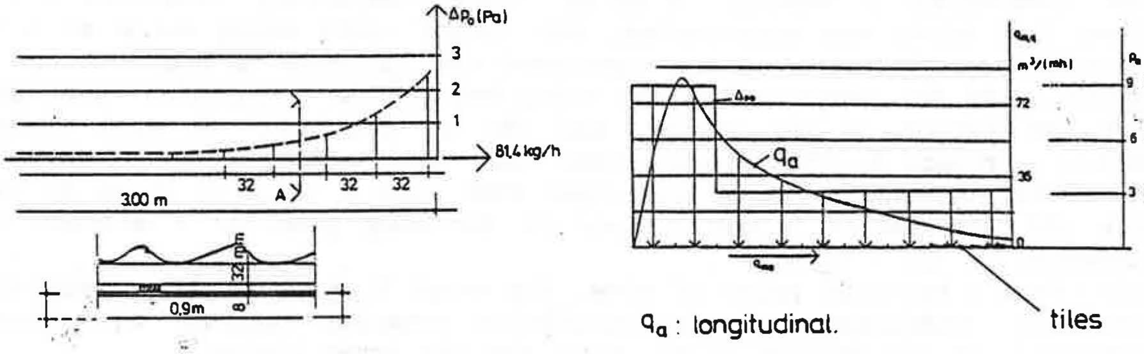


FIGURE 3. Pressure line (measured) and air flow (calculated) under a tiled deck

air flow model (3). The results confirmed the measurements : with ceramic tiles no vent tiles needed to get outside air ventilation, the flow pattern being very local (figure 3). Also concrete tiles, metallic tiles and slates reveiled air open enough to give venting.

4. IS VENTILATION NEEDED?

Remains the question, if the unavoidable ventilation between covering and underroof and the induced ventilation between underroof and thermal insulation is really necessary, more, could harm? The answer is coupled to two realities:

- the air permeance and possible rotative stack flow in vented sloped roof sections;
- undercooling.

4.1 The air permeance of layers and roof sections

See table 2 (For the measuring method: 3.1.1)
The air permeabilities look high enough to give, when pressure and temperature differences exist -and these are pronounced in a vented roof-, important convective air flows through sections, composed of the layers of the table. This results in extra heat losses and, if inside air passes through, excessive interstitial condensation.

Both has been proven by a series of long lasting Hot Box- Cold Box tests on 2 roof sections, composed of (from outside to inside): tiles, air cavity, mineral wool blanket d= 5.4 cm with vapour barrier, air cavity, timber slabs ceiling, the one with , the other without the vapour barrier air tight fitted. Boundary conditions and measuring results: table 3. These results confirm the excessive heat loss and interstitial condensation, when no air tightness is achieved. The spontaneous Cold Box air ventilation under the tiles, with local air velocities up to 0.28 m, didn't prevent the problem(2).

4.2 Rotative stack flow (4)

To get some estimation of the importance of rotative stack flow around the insulation, a 'cavity/ 50 mm EPS-insulation/cavity' rotatable 1.5 m long flat plate was constructed, the cavity leafs being build as heat flow meters. The measurements concerned the increase in heat loss as a function of the slope, the joint width between the insulation layer and top and bottom of the cavity, and the cavitie width at both sides. Results: figure 4. This figure shows that, with cavity widths of only 35 mm at the one and 16 mm at the other side, and a joint of 14 mm at the top and the bottom - not so bad in building practice - already an increase of 380 % is noted!!
Also from a hygrical point of view, the stack flow may be very ennuyous, reducing, independant of the insulation material applied, the vapour thickness of the section to the value for the inner lining.
Or, this stack effect must be avoided by all means. The pity now is that exactly the demand for a vented cavity between underroof and insulating

Table 2. The diffusion thickeness and air permeance of sloped roof layers

LAYER/SECTION	$[\mu d]_{eq}$ RH %-	$[\mu d]_{eq}$ - m	K_a s/m a	K_a s/m b
gypsum board, the joints plastered	30 77 90	0.1 0.05 0.04	3.1E-5	-0.19
gypsum board, open joints			3.3E-4	-0.27
gypsum board, open joints perforated (electr.)			6.3E-4	-0.27
timber slabs ceiling	55	0.85	4.2E-4	-0.32
timber slabs ceiling, perforated (electr.)			7.6E-4	-0.37
MW-blankets, perfectly closed overlays	70 à 86	0.3 à 5	6.5E-5	-0.29
MW-blankets, current practice			3.2E-3 à 8.9E-4	-0.15
underroof in FC-board d= 3.3mm,correctly installed	74	0.14	4.2E-4	-0.34
underroof in FC-board d= 3.3mm, current practice			1.0E-2	-0.45
micro-perforated plastic foil, glass fibre fabric reinforced, d= .1 à .2mm	86	1.7 à 8	5.0E-4	-0.35

Table 3. Measured interstitial condensation in 2 sloped roof sections, one with and the other without air barrier

SLOPED ROOF → ↓	θ_{cb} °C	Pcb Pa	θ_{hb} °C	Phb Pa	ΔPa Pa	air tight $U^{(a)}$ W/(m²K)	air tight $m_c^{(b)}$ g/d	air open U W/(m²K)	air open m_c g/d
+ with airtight vapour barrier									
no leak in the ceiling	1.5	580	20.3	1573	1.5	0.465	5	1.0	1.7
leak φ 20 mm in the ceiling	1.2	569	20.1	1554	1.0	0.46	4.9	1.1	26.0
leak φ 20 mm in the ceiling	1.5	612	20.3	1335	7.0	0.45	4.5	2.8	120.0

(a) related to the sensible heat loss
(b) condensation against the tiles, the water dripping on the MW.

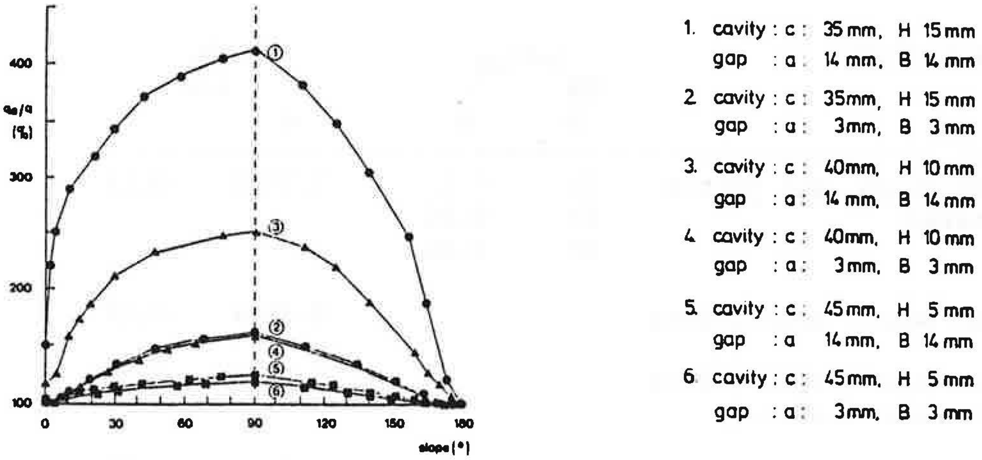


FIGURE 4. The increase in heat loss because of rotative stack flow

layer gives one of the two air spaces needed, the other being found under the insulation not in close contact with the internal lining. Gaps at the ridge and the gutter parapet are almost always present.
Still worser reveals the combination of rotative stack flow and air flow through the roof.

4.3 The Undercooling effects

Undercooling by long wave radiation of the covering has been analysed by temperature measurements, during the autumn, winter and springtime of 1983-1984, on 2 tiled decks above dwellings in use, one insulated (U= 0.32 W/(m²K)) the other not, both with underroof, the insulated deck with battens, the other not. Measuring results: see table 4.

Table 4. Undercooling effects.

ROOF	U-VALUE W/(m²K)			SURFACE TEMPERATURES undercooling °C	 no undercooling °C
Dwelling 1	0.33⁽¹⁾	SE	night	$-0.6+\theta_e$	
			day	$0.9+0.9.\theta_e$	
	0.38⁽²⁾	NE	night	$-1.4+1.2.\theta_e$	$0.3+0.98.\theta_e$
			day	$-1.3+1.2.\theta_e$	
	0.33⁽²⁾	SW	night	$-0.4+1.1.\theta_e$	$0.2+0.99.\theta_e$
			day	$1.0+\theta_e$	
Dwelling 2	2.35⁽¹⁾	SE	night	$-1.0+0.9.\theta_e$	$0.7+0.95.\theta_e$
			day	$0.4+0.9.\theta_e$	
	1.19⁽²⁾	NE	night	$-1.1+0.9.\theta_e$	
			day	$-0.8+0.9.\theta_e$	
	1.27⁽²⁾	SW	night	$-0.9+0.9.\theta_e$	
			day	$0.9+0.8.\theta_e$	

(1) calculated
(2) measured for the orientation given

The effect is undoubtly present, more pronounced on the insulated than on the uninsulated roof. In both, orientation plays a role, as important as the insulation value, with NE the worsiest.
The insulated roof becomes colder than the air, for θ_e lower than 7°C - t.m. from November to March -, the uninsulated only if θ_e drops below - 11°C - t.m. with very cold weather.
However, undercooling isn't only linked to nightly clear sky long wave radiation but also to condensation on and drying of the tiles. The whole phenomenon is condensed in a steady state formula for the surface temperature θ_s:

$$\theta_s=[A.\theta_i+(h_{ce}+4.F_s.e_L)-F_s.e_L.(100-87c)+1.3e_L.F_{ss}+0.019h_{ce}.(p_e-p'_s)]/B \qquad \text{(eq 5)}$$

with $A= 1/(1/U-1/h_e)$ and $B=1/[1/(1/U-1/h_e)+h_{ce}+4.F_{ss}.e_L]$

In (eq 5), h_{ce} is the convective outside film coefficient, e_L the longwave emissivity of the covering, c the cloudiness factor, F_s the view factor roof- sky, F_{ss} the view factor roof- surroundings, h_e the outside film coefficient, U the U-value of the roof and p'_s the covering saturation pressure.

As a consequence, the covering turns wet in autumn, stays wet during the whole winter, and dryes not earlier than springtime.How wet,is inversely proportional to the U-value: table 5.

Table 5. The mean saturation degree of the tiles from december 1983 to march 1984

ORIENTATION	INSULATED ROOF U= 0.34 W/(m²K)	NON INSULATED ROOF U=?
NE	0.94	0.87
SE	0.94	0.73
SW	0.77	0.75

5. TEST ROOF CONFIRMATION

All aspects analysed above, have been checked in a TEST ROOF PROGRAM: 4 NE oriented tiled sloped roofs with underroof and internal lining,

- the first, well insulated (18 cm MW), build following the sandwich-concept, with air- vapour barrier;
- the second vented between the covering and the underroof and the underroof and the insulation (6 cm of MW- blankets, practice mounted);
- the thirth not insulated;
- the fourth insulated between the underroof and the tiles;

were constructed at the laboratory site in 1987 and followed since.
The results approve the previous work, with convincing additional information:
- in the ventilated roof 2, a clear stack effect developed, with much higher heat losses than by pure conduction;
- with very cold weather, surface condensation was seen on the internal

lining of roof 2, near the vent openings in the gutter parapet, showing that ventilation and stack effect together may be very ennuyous;

- venting tiles had not a minor influence on the winterly saturation degree in the tiles, but the hygroscopic timber laths and bathens became wetter with then without;
- a hygroscopic underroof was found wetter, the lower the U-value, independant from well or no ventilation between it and the insulation and well or no air-vapour barrier at the inside;
- a plastic foil underroof remained perfectly dry in the sandwich roof 1 with air- vapour barrier, but gave ennuyous interstitial condensation in the ventilated roof 2, with moisture dripping on the insulation. and in the sandwich roof, when the air barrier was omitted;

6. CONCLUSIONS

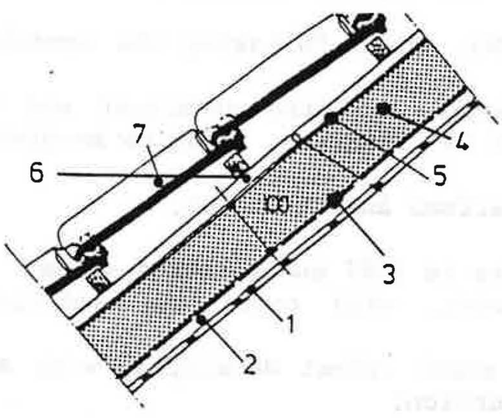
The research gave interesting conclusions and showed how insulated sloped roofs should be constructed:

- tiled and slated decks are air open enough to need no extra venting features;
- no positive effects of deck-ventilation on the moisture load of tiles underroof, laths and battens found. Reasons: undercooling, neutralising effective winterly drying + the suction behaviour laths and battens, making them wetter if, undercooled, ventilation is increased!
- a ventilation space between the underroof and the thermal insulation can be the step to get very ennuyous stack effects with extra heat losses and more interstitial condensation.
- At the lewside, a ventilation space, being in underpressure, activates inside air and vapour flow through each non airtight roof with, extra condensation, loss of thermal quality, etc;
- at the windside, outside air may flow through, causing very high ventilation rates and cooling the internal lining or, locally, the leaky zones...

These conclusions are alarming enough to leave the ventilation concept and introduce a new design philosophy for insulated sloped roofs:

THE SANDWICH SOLUTION.

From in- to outside (figure 5):



1. inside lining
2. wiring cavity
3. AIR and VAPOUR barrier
4. MW- thermal insulation, filling the whole space
5. UNDERROOF, acting as secundary rain barrier, wind barrier, dust barrier
6. laths and battens, the battens for drainage reasons
7. roof covering

FIGURE 5. The sandwich solution

3 and 4 or 3, 4 and 5 may hygrothermally be combined in 1 layer: airtight mounted, airtight insulation slabs. However, from an acoustical and form freedom point of view, this choice performs poorer.

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