The Influence of Air Leakage on the Condensation Behaviour of Lightweight Roofs

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Introduction

This paper deals with the research on interstitial condensation in lightweight roofs, caused by air leakages. Discussed are the theoretical background, the admittance measurements and the experimental work on roofs.

Theoretical modelling[1]

Normally, the condensation behaviour of construction elements such as walls, roofs and floors is predicted by Glaser's method. One of the hypotheses of this method concerns the driving force of vapour transfer – *diffusion only.* Laboratory research over a long period and observations in situ show that, for heavy constructions and constructions without cavities (as long as the initial moisture condition is properly taken into account), the moisture content remains below the critical value. If attention is paid to a good choice of climatological conditions, i.e. calculating with a condensation-sol-air outside temperature, the calculated prediction compares favourably with actual measurements. Nevertheless, research in problem buildings with lightweight, flat or sloped roofs shows either a nil or poor correlation between the Glaser prediction of observed interstitial condensation in the roof and reality. Important differences are:

- condensation in roof sections where, according to Glaser's method, this is not possible
- much more condensation than calculated
- with sloped roofs, a remarkable correlation between 'slope with interstitial condensation' and wind direction
- condensation appears to be a quick-reacting phenomenon, while diffusion is a very slow process.

The reason for these contradictions seems to be the leakage of warm inside air through the roof to the outside, the driving forces being wind pressure and temperature differences. The calculation model therefore needs a broader basis, taking into account moisture transfer not only by diffusion but also by air flow. So a three-step stationary *convection + diffusion* model was developed (KONVEK[1]):

Step 1

Calculation of the air flow through a construction element using as the material or layer property, the airflow *admittance* and the difference in wind pressure (no thermal stack) as the boundary condition. The calculations are based on the mass-conservation law and the flow equation:

$$\phi_{m,a} = A \times \Delta p_a \times A$$

where A = airflow-admittance of a material, layer, leak or cavity – A being $f(\Delta p_a)$ (s/m)

Δp_a = the pressure difference (Pa).

A difference technique is used, resulting in a system of linear equations with variable coefficients.

Step 2

Calculation of the temperature distribution and heat fluxes using the following equation for each point of the difference grid:

$$\Sigma\phi_i + \Sigma(\phi_{m,a,i} \times h_i) = 0$$

where ϕ_i = the heat flow by conduction (W)

$\phi_{m,a,i} \times h_i$ = the enthalpy-flow, coupled to the air flow

Step 3

Calculating the vapour pressure distribution, vapour fluxes and condensation/drying rate, using the following equations for each point of the difference grid:

$$\Sigma\phi_{m,i} + \Sigma(\phi_{m,a,i} \times \frac{x_i}{1 + x_i}) + \phi_m^{c,d} = 0$$

$$x_i \leq x_s$$

$$x_i = 0{,}622 \frac{p_i}{p_a - p_i}$$

where x_i = vapour concentration (kg/kg)

$\phi_m^{c,d}$ = condensation or drying rate

p = vapour pressure

Steps 2 and 3 also lead to a system of linear equations, now with constant coefficients. The same is true for Step 3 with the vapour concentration or the condensation drying rate as variables, depending on $x_i \leq x_s$. An iteration between Steps 2 and 3 becomes necessary, depending on high, or nil, condensation.

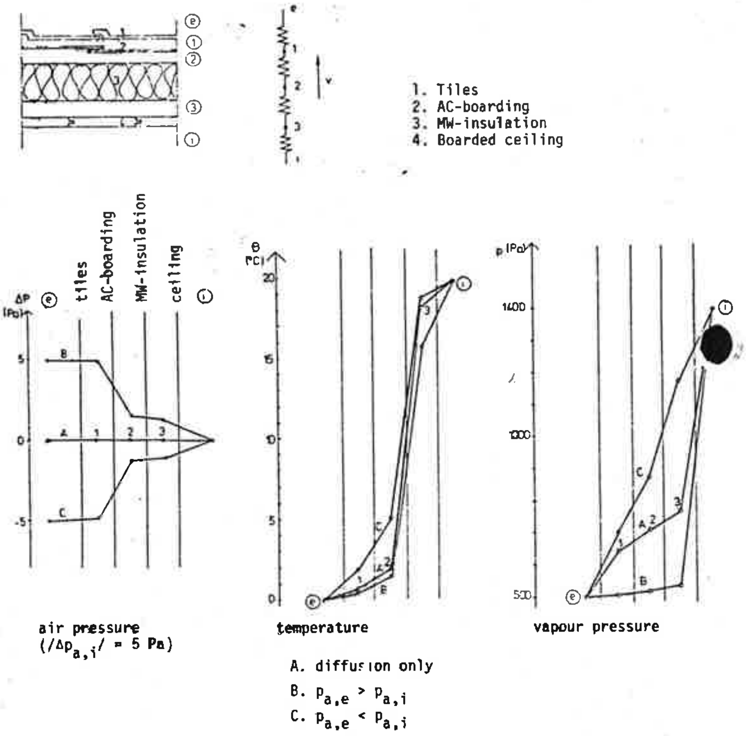


Figure 1

With the new *convection + diffusion* model, different sloped roof sections were considered (1-dimensional calculations) (see figure 1). The results show that

- with air leakage, the temperature and vapour pressure distribution in a construction element change drastically
- condensation also takes place on surfaces other than those found with Glaser's method

- for low pressure differences ($p_{a,i} > p_{a,e}$), the condensation rate grows rapidly with rising pressure difference to reach a maximum for a given difference and reduces to zero for still higher pressure differences
- as soon as air leakage plays a part, the impact of diffusion practically disappears.

Air Leakage Measurements[2,3]

An important material or layer property, used in the *convection-diffusion* model, is the air flow admittance *A*. Hydraulics show that $A(\Delta p_a)$ fits fairly well with a function:

$$\Delta p_a \leq \Delta p_{a,cr} \qquad A = C^t = A_o$$

$$\Delta p_a > \Delta p_{a,cr} \qquad A = a\,(\Delta p_a)^b$$

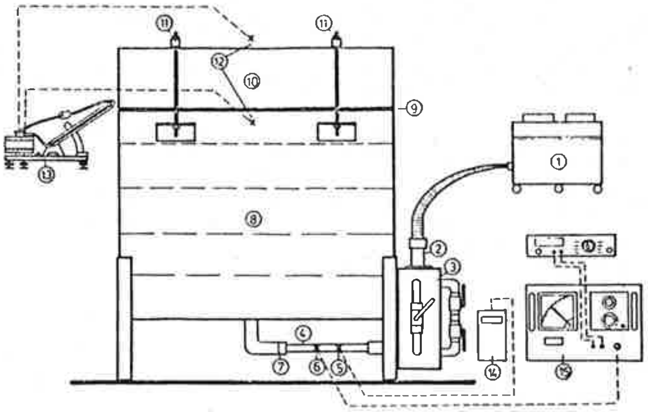
In the context of a research program on sloped roofs, $A(\Delta p)$ has been measured for different roofing materials, ceiling systems and roof-sections, with a one-chamber underpressure box 0,72 m^3 in volume and with a measuring surface of 0,87 m^2 (see figure 2). The box is coupled to an industrial extractor by a ducted supply with a flow rate measuring device. The air flow is regulated by a system of valves. The pressure difference over, and the air flow through, the element under test are measured. The results are given in Table 1. An important conclusion to be drawn from these results is that a tiled roof acts as a very air-open system.

Table 1. Air flow admittance for roofing materials, ceiling systems and different roof-sections

	a (s/m)	b	$p_{a,cr}$ (Pa)	A_o (s/m)
Roofing Material				
Ceramic tiles (single closing)	0,011	–0,045	0,2	0,012
Ceramic tiles (double closing)	0,013	–0,51	0,2	0,029
Concrete tiles	0,0064	–0,46	0,04	0,028
Slates	0,0042	–0,21	0,32	0,0053
Metal tiles	0,0016	–0,41	1,1	0,0016
AC-slates	0,0014	–0,303	1,24	0,0013
Corrugated AC plate	0,00073	–0,362	4	0,00044
Ceiling				
Board ceiling	0,00038	–0,26	2,9	0,00028
Gypsum board	$3{,}1.10^{-5}$	–0,19	59,2	$1{,}4.10^{-5}$
Roof Sections				
Tiles-insulation-vapour barrier-board ceiling				
Vapour barrier 'Airtight'	$1{,}45.10^{-5}$	0		
'Air-open'	$1{,}62.10^{-4}$	–0,292		

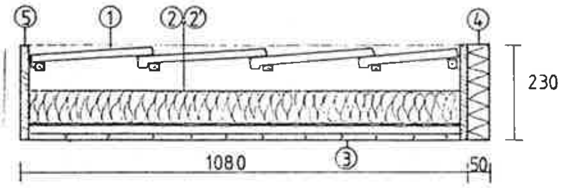
Experiments on roofs[3]

To prove the validity of the air leakage model, two hot box – cold box experiments on sloped roof sections were set up (see figure 3).



Key:
1. Industrial extractor.
3. Valves.
5,6. Air velocity meters.
8. Underpressure box.
10. Sample.
13. Pressure difference meter.
15. Measuring devices.

Figure 2. Under-pressure box



Key
1. Tiles.
2,2'. Insulation layer with vapour barrier, correctly or incorrectly installed.
3. Boarded ceiling.

Figure 3. Sloped roof sections

Roofs (from underside to upperside)

- a boarded ceiling
- air cavity
- insulation layer, d = 60 mm, with vapour barrier (in the *first roof* the vapour barrier is correctly installed, in the *second roof* it is not)
- air cavity
- ceramic tiles.

Studied parameters

- airtightness of the insulation layer with vapour barrier (see above)
- airtightness of the ceiling (during the measuring period, after 10 weeks, a 20 mm diameter leakage hole was drilled in both ceilings)
- pressure difference over the roof (during the measuring period, after 16 weeks, the pressure difference was brought from 1 Pa to 7 Pa ($p_{a,i} > p_{a,e}$).

Boundary conditions:

	θ °C	p Pa	Δp_a Pa
Warm (inside)	20,2	1570	1 to 7
Cold (outside)	1,2	570	1 to 7

Measuring results:

Roof	Week	Δp_a	Condensation		
			Y/N	Surface?	Rate kg/(m^{2}d) x 10^{-3}
1. (Airtight vapour barrier)	1–10	1,5	N		
	11–16 (+ leak in ceiling)	1	N		
	17–19 (+ leak in ceiling)	7	N		
2. (Airleaks in vapour barrier)	1–10	1,5	N		
	11–16 (+ leak in ceiling)	1	Y	Underside tiles	33
	17–19 (+ leak in ceiling)	7	Y	Underside tiles	120

These experimental results were in good accordance with the *diffusion + convection* calculations, taking into account an 'inside' airflow through the roof and an 'outside' airflow under the tiles (tiles = 'air open').

Conclusions

From practical experience and theoretical and experimental research, it seems clear that in many cases for lightweight, flat and sloped roof structures interstitial condensation is, to a large extent, coupled with air leakage (warm inside air with a higher vapour concentration passing through the roof). Therefore, the most important design rule should not be 'use a vapour barrier' but 'construct an airtight ceiling system'. In many cases where this is impossible, an airtight barrier at the warm side of the insulation is needed. So, it is better to talk about a *vapour + air* barrier:

Vapour-tight = using a suitable material

Airtight = no leaks

The research also shows that the influence of ventilation on energy consumption is only one aspect of the whole air leakage problem. Nevertheless, information is needed concerning:

- the wind pressure distribution inside and outside a building, with low wind velocities
- the influence on that distribution of changes in airtightness in the building envelope.

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