EFFECT OF LONGWAVE RADIATION IN COLD ROOFS – REMARKS ON SIMULATIONS

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ABSTRACT

The cooling effect caused by long wave radiation between the roof surface and the sky is studied here. The external surfaces may cool down below the dew point of the air and the condensation may form [1]. Typically, the covering of cold roofs has a low thermal resistance and the condensation may form also on its downside. These phenomena are quantified and discussed here. It is shown that the amount of condensation could be surprising high, even by temperatures of external air about 0 ^{o}C and higher. The effects of different boundary conditions and of different quality of the air tightness are studied here. These phenomena should be implemented in the standard calculation procedures in the future.

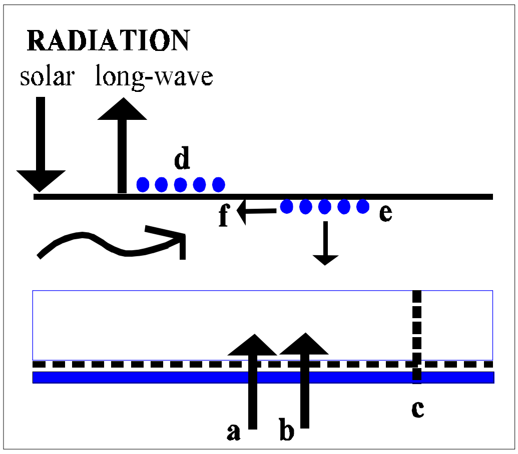

Fig.1 *Scheme of a cold roof. (a- heat flux (heat loss), b-water vapour diffusion, c-local failure (open joint etc.), d-condensation on external surface, e-condensation on downside of the roofing, f-collection of condensed water)*

INTRODUCTION

The long-wave (thermal) radiation between the sky and the external surface can have an important influence on hygro-thermal performance of building envelopes, especially of cold roofs. The radiation heat flux causes a significant decreasing of the temperature on external surfaces with resulting condensation of water vapour from the external air. Generally, the importance of these phenomena becomes higher with increasing of thermal insulation level of building envelopes. The main reason of its neglecting in “standard” calculations is the following: in the past, this effect was at least partially overlapped by heat loss flux coming from the interior through the lower part of the roof. Fig.1 introduces the situation in well insulated cold roofs.

SIMULATION

Following approach was used for the quantification of radiation heat transfer: Equation (1) gives the effective sky temperature [2], assuming that the sky may be treated as a black body:

$$T_{sky} = \sqrt[4]{0.526 + 0.649 * \sqrt{p_d * 10^{-4}}} * T_e \quad (1)$$

Radiation heat flux is calculated as:

$$q_{rad} = \varepsilon * \sigma_{rad} * \left[\left(\frac{T_{sky}}{100} \right)^4 - C * \left(\frac{T_{se}}{100} \right)^4 \right] \quad (2)$$

where C is a constant describing the presence of clouds. C varies in the range between 1.0 (clear sky) and 1.42 (fully overcast with low clouds) [2].

Typical values for clear sky (Tab.1) and for fully overcast sky in winter conditions (Fig.2, 3, 4) for well insulated roof are shown here.

Tab.1 *Typical values for the nights with clear sky*

t_e [°C]	t_{sky} [°C]	t_{se} [°C]	radiation heat flux [W.m^{-2}]
-15	-45.7	-21.7	66.6
-10	-39.5	-16.8	67.0
-5	-32.9	-11.6	66.8
0	-26.0	-6.5	64.2
5	-18.7	-1.1	61.5
10	-11.0	4.2	57.1

Using the theory of similarity and assuming a free air convection with low velocity, the process of water vapour condensation is described [4] as follows:

$$P_g = \text{constant} * (\text{Gr})^{0.333} * \left(\frac{100 * \Delta p_d}{p_b} \right)^{1.4} \quad (3)$$

Condensation coefficient P_g is given as:

$$P_g = \frac{j_d * L}{\delta_{air} * p_b} \quad (4)$$

Resulting condensation flux by relevant boundary condition is the following:

$$j_d = A * (\Delta t)^{0.333} * (\Delta p_d)^{1.4} \quad (5)$$

where A is a constant number depending on the surface orientation [4]:

horizontal, upwards A = 5.2 . 10^{-10}
horizontal, downwards A = 9.7 . 10^{-10}
vertical A = 7.5 . 10^{-10}

The heat transfer coefficient expressed on usually way includes the heat transfer due to phase change:

$$h = h_{rad} + h_{conv} + j_d * r \quad (6)$$

However, the thermal effect of phase change is very small compared to both other components.

Equation (7) describing the partial vapour pressure along the ventilated air space [3] was used to study the effects on the downside of the roofing:

$$p_{dx} = \frac{A' + [p_{de} * (\Lambda_L + \Lambda_H) - A'] * \exp\left(- \frac{(\Lambda_L + \Lambda_H) * T_x}{d * w * 217.10^{-5}} * x \right)}{\Lambda_L + \Lambda_H}$$

where $A' = \Lambda_L * p_{di} + \Lambda_H * p_{de}$ (8) (↑7)

If the temperature on downside is under the corresponding dew point the condensation forms.

In fact, the equation (7) is often used in the calculation procedure [3] even for preventing of surface condensation in ventilated air layers of building envelopes. Its amount is to quantify using equation (5). This approach is to understand as a first approximation only; there is a lack of measured and evaluated data closer to the boundary and geometry conditions in the roof spaces.

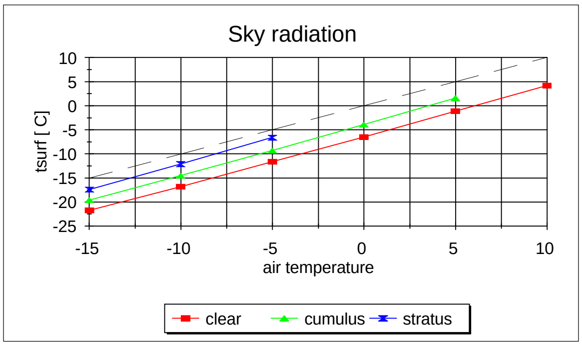

Fig.2 *Temperatures on external surface of a cold roof by different temperatures of external air (winter condition) for clear sky and for fully overcast sky (cumulus, stratus). Assuming the heat loss from the interior is negligible.*

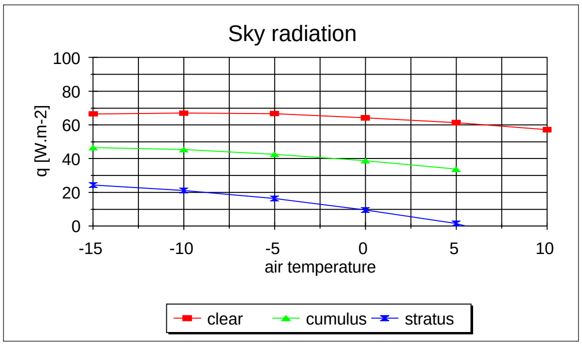

Fig.3 *Resulting heat flux on external surface for clear sky and for fully overcast sky (cumulus, stratus)*

RESULTS OF CALCULATIONS

Different situations were calculated using the procedure described above assuming the steady state thermal conditions. The lower part of the roof consists of gypsum board, 4 cm mineral wool in the space for supporting frame, vapour retarder and of 20 cm mineral wool. The U-Value of the lower part of the roof is 0.16 W.m^{-2}K^{-1}. The typical roof coverings were used in the calculations: metallic covering with negligible thermal resistance, bituminous covering on wooden boards (thermal resistance 0.11 m^{2}K.W^{-1}), respectively. Temperature and partial vapour pressure of external air correspond to values for Czech winter conditions [2]. Resulting air movement velocity inside the roof is in the range 0.25 – 0.30 m.s^{-1} for constructions studied here (depending on geometry of air space, inlets and outlets).

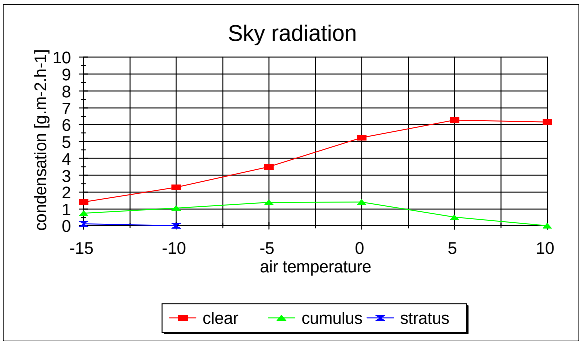

Fig.4 *External surface condensation in the condition described in Fig.3*

Different situations concerning the quality of water vapour retarder installed in the lower part of the roof were studied here: high quality retarder with negligible permeance, construction without retarder and retarder of degraded quality caused by open joints.

The results of previous study of the air convection through the open joints and leakages [5,6] were used as input data. It was assumed that the width of such opening is 1 mm on 1 m length on the area of 1 m^2. Simplified, their degradation effect for the cold roofs used in the calculations is given in Tab.2.

Tab.2 *Degradation of cold roof quality caused by open joints for different barometric pressure difference [5, 6]. The permeance of vapour retarder is to multiply by relevant degradation factor.*

Barometric pressure difference [Pa]	Increase of heat transfer coefficient [W.m^{-2}K^{-1}]	Vapour retarder degradation factor [-]
0 (no open joint)	0	1
5	0.1	1050
10	0.3	2100

The mean values of condensation along the air path are shown on following figures. The situation in winter conditions for clear sky is given in Fig.5. The maximum of condensation is in the range of external temperature from -5 °C to +5 °C. There is no increasing of condensed amounts by deeper air temperature because of its very low absolute humidity. Fig.6 is comparing the constructions with different qualities: ideal construction, construction with degraded retarder by presence of 5 Pa and 10 Pa barometric pressure difference (effect of air convection through the open joints) and the construction without any vapour retarder. Fig.7 brings the results of calculations for the winter design temperature (-15 °C) and for more frequent winter temperature 0 °C. The effect of the thermal resistance of the roof covering is shown in Fig.8. There is no significant difference between metallic and bituminous roofing on wooden board. A visible decreasing of condensation amount could be reached with upper roofing part having the thermal resistance 0,5 m^{2}K.W^{-1} and higher. The amounts of collected moisture in the strips 1 m wide and 10 m long (from the ridge to the gutter) is illustrated in Fig.9. The situation in non ventilated roof with the identical layers is compared here.

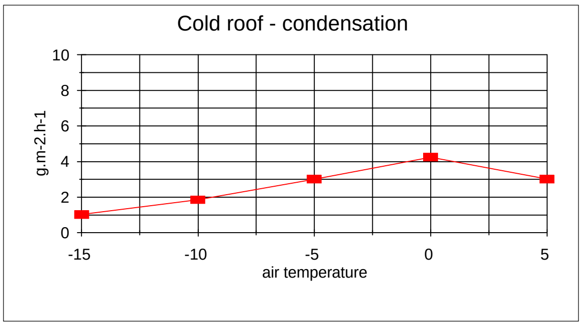

Fig.5 *Condensation in the cold roof by different external air temperature (clear sky)*

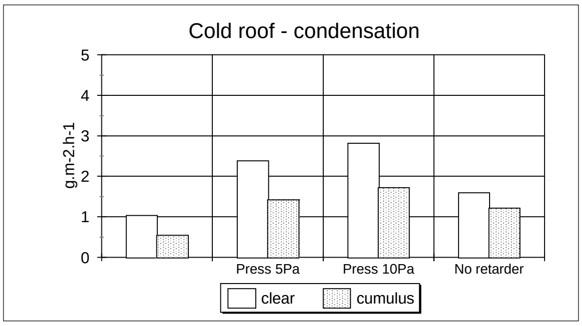

Fig.6 *Condensation in the cold roof by –15 °C for clear and fully overcast sky. Different tightness of lower part: nominal, open joint by 5 Pa and 10 Pa barometric pressure difference, without retarder*

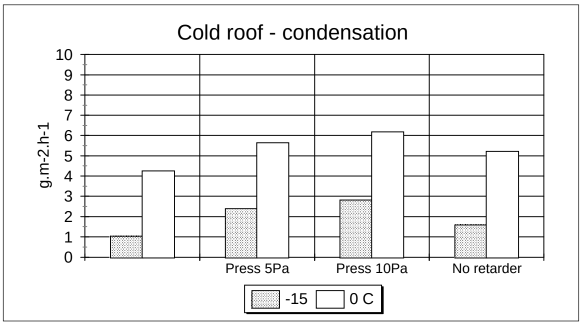

Fig.7 *Condensation in the cold roof by –15 ^{o}C and by 0 ^{o}C for different tightness of lower part (clear sky): nominal, open joint by 5 Pa and 10 Pa barometric pressure difference, without retarder*

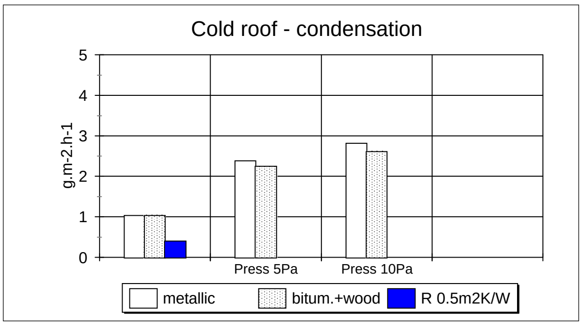

Fig.8 *Condensation in the cold roof by –15 ^{o}C and clear sky. Different thermal resistance of the covering*

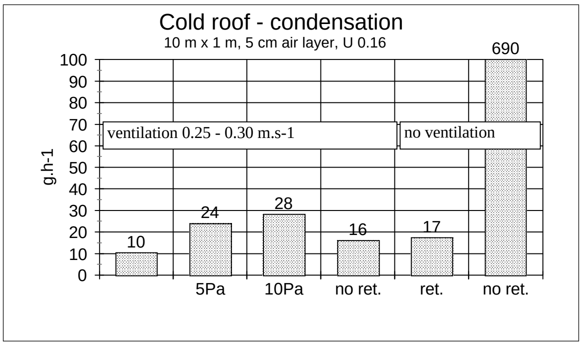

Fig.9 *Condensation in the cold roof – collected moisture in 1m x 10 m strip by –15 ^{o}C*

No relevant experimental data were found in the literature to compare the results of calculations directly. On the other hand, various simple expressions evaluated from the experiments could be found. Such estimations based on the simple similarity between surface coefficients for heat and vapour transfer (e.g. $\beta_p \approx 7.10^{-9} * h_{conv}$ [7], $\beta_x \approx h_{conv}/c_a$ [2], etc.) are in the same order comparing to complex calculations described in the paper.

CONCLUSIONS

Simulation methodology

The approach presented in this paper could extend the „standard calculations“ of evaporation/ condensation of water vapour in ventilated building envelopes, especially in the cold roofs. The condensed amounts calculated for typical boundary conditions can bring important information. Detailed calculations by means of the local reference year taking into account both, long-wave and solar radiation could be very helpful. They should bring results closer to reality. However, the using of equation (3) should be understood as a first approximation only; experimental investigation focused on low air movement in the spaces of small height should bring the corresponding corrections.

Consequences for the design of roofs

The phenomena discussed in this paper are often used as a tool in the argumentation about design of the roofs, e.g. ”cold roofs are not more free from condensation – the only right solution is a warm roof....“. The amount of condensed water caused by long-wave radiation effects could be high; it means reasonably higher than the typical amounts in warm roofs calculated without radiation effects. However, the condensed water could dry out quickly in the cold roof: often within the following period with the solar radiation. To guaranty this, the condensed water may not penetrate deep into the layer of the lower part of the roof. This is mostly easy to solve using vapour permeable protective foils above the thermal insulation layer. A special attention should be given to the metallic coverings in a light sloped position: The transferring of condensed moisture on the downside for longer distances was investigated in some cases. The local effects could be critical for durability of the construction e.g. by vertical supporting elements (corrosion, wood deterioration etc.) or in the area of gutters.

Future research

The experimental investigation of the surface condensation due by both, long-wave and solar radiation heat transfer is foreseen in the next step of the research.

ACKNOWLEDGEMENTS

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NOMENCLATURE

c_a	thermal capacity of the air [J.kg^{-1}.K^{-1}]
d	height of the air space [m]
Gr	Grasshof-coefficient
h_{conv}	convection heat transfer coefficient [W.m^{-2}K^{-1}]
h_{rad}	radiation heat transfer coefficient [W.m^{-2}K^{-1}]
j_d	surface condensation flux [kg.m^{-2}s^{-1}]
L	typical length [m]
p_b	barometric air pressure [Pa]
p_{de}	vapour pressure of the external air [Pa]
p_{di}	vapour pressure of the internal air [Pa]
p_{dx}	vapour pressure of the air in distance *x* from inlet [Pa]
r	condensation heat [J.kg^{-1}K^{-1}]
T_{sky} (t_{sky})	effective sky temperature [K, ^{o}C]
T_e (t_e)	temperature of external air [K, ^{o}C]
T_{se} (t_{se})	temperature on external surface [K, ^{o}C]
T_x	temperature of the air in distance *x* from inlet [K]
w	air velocity in the air space [m.s^{-1}]
x	distance in the air space from inlet [m]
β_p	vapour transfer coefficient related to Δp_d [kg.m^{-2}Pa^{-1}s^{-1}]
β_x	vapour transfer coefficient related to moisture content difference in the air (surface - ambient air) [kg.m^{-2}s^{-1}]
δ_{air}	vapour diffusivity of air [s]
ε	emissivity [-]
Λ_H	vapour permeance of upper part of the roof [s.m^{-1}]
Λ_L	vapour permeance of lower part of the roof [s.m^{-1}]
σ_{rad}	Stefan-Boltzman-coefficient
Δp_d	vapour pressure difference: surface - ambient air [Pa]
Δt	temperature difference: surface-ambient air [K]