Vol. 10, No 1/2021, 119-126

DOI: 10.17512/bozpe.2021.1.12

Construction of optimized energy potential
Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Condensation of water vapor on the external surfaces of building envelopes

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Abstract: The improvement in thermal insulation of building envelopes minimizes the problem of water vapor condensation on their internal surfaces. However, the probability of water vapor condensation on the external surfaces increases. This may take place under radiative cooling conditions when the temperature on these surfaces drops below the air temperature. The aim of this article is to analyze the influence of different factors on the possibility of external condensation. Relevant computational examples and practical insights based on real-life observations are shown. It was found that the basic factors contributing to the condensation of water vapor on the external surfaces are the horizontal or oblique placing of the envelopes, no wind, cloud-less sky and low thermal transmittance of the envelopes. The described phenomenon can be mitigated by covering the surfaces with a low-emission coating.

Keywords: building physics, moisture of building envelopes, radiative heat transfer, radiative cooling

Please, quote this article as follows:

Respondek Z., Condensation of water vapor on the external surfaces of building envelopes, BoZPE, Vol. 10, No 1/2021, 119-126, DOI: 10.17512/bozpe.2021.1.12

Introduction

In recent years, a serious problem has been the moisture of the internal surfaces of building envelopes, which may lead to fungus formation, especially in poorly insulated places (Tóth & Vojtuš, 2014). In residential buildings, where the thermal insulation systems used are good quality, this problem occurs only in the case of insufficient ventilation or installation errors during insulation.

However, as the thermal insulation efficiency of building envelopes increases, the temperature on their external surfaces decreases. Thus, the probability of water vapor condensation on these surfaces increases.

For a mathematical description of this phenomenon, the classical model of calculating the temperature distribution in a multi-layer building envelope is insufficient.

The standard external surface resistance is assumed to be R_{se} = 0.04 (m^2·K)/W, therefore the design temperature on the external surface of an envelope is always higher than the temperature of the surrounding air, i.e. higher than the dew point temperature. Condensation of water vapor is possible when the temperature on the external surface drops below the air temperature, and this is only possible under the conditions of radiative cooling. It is a well-known phenomenon (Śliwowski ed., 1992) and used as a source of cooling in air-conditioning systems (Eicker & Dalibard, 2011; Vall et all., 2020).

The cause of radiative cooling is the so-called atmospheric window, i.e. the range of electromagnetic waves 8-14 μm for which the Earth's atmosphere is almost completely transparent (Zhang et all., 2018). In the absence of cloud cover, the surfaces (ground, building envelopes) exchange heat by radiation with the so-called "cold sky", which leads to additional heat losses (Adelard et all., 1998). In the case of complete cloud cover, this phenomenon does not occur. Radiative cooling is most intense on horizontal envelopes. Vertical ones also exchange heat with the ground, other buildings, etc., which results in less cooling.

The aim of the article is to analyze the influence of different factors (wind, insulation of building envelopes, their placing, emissivity of their surfaces) on the possibility of water vapor condensation on the external surfaces of building envelopes. The computational examples and practical examples of the effects of this phenomenon on the basis of practical observations were presented.

1. Methodology of research

The analysis of the possibility of temperature drop on the external surface of a building envelope, ϑ_e, °C (or Θ_e, K) below the dew point temperature t_d, °C, was carried out assuming a steady state of heat transfer through the envelope, under radiative cooling conditions. Under such conditions, the external surface exchanges heat by radiation with the "cold sky" and by convection with the surrounding air. The temperature ϑ_e was determined from the formula (Śliwowski, ed., 1992)

$$\vartheta_e = \frac{U_p \cdot t_i + h_{ce} \cdot t_e + h_{re} \cdot t_r}{U_p + h_{ce} + h_{re}} \tag{1}$$

with

$$h_{ce} = 4 + 4 \cdot v \tag{2}$$

$$h_{re} = 4 \cdot \sigma \cdot \varepsilon \cdot T_m^3 \tag{3}$$

where:

U_p – partial thermal transmittance, calculated without including the R_{se}, W/(m^2·K);

t_i, t_e – internal and external air temperature, °C;

t_{r} – calorimetric temperature of atmosphere, °C;
h_{ce}, h_{re} – convective and radiative surface coefficient, (m^2·K)/W;
v – wind speed, m/s;
σ – the Boltzmann constant $6.67\cdot10^{-8}$ W/(m^2·K^4);
ε – emissivity of the external surface, –;
T_{m} – average temperature of the external surface Θ_{e}, K, and the atmosphere T_{r}, K.

Since the quantities ϑ_{e} and h_{re} are interdependent, the calculations were performed numerically.

Nowak recommends taking the temperature of atmosphere t_{r}, °C, according to his own empirical formula for the climate conditions of Poland (Nowak, 1999)

$$t_{\mathrm{r}} = 1.33 \cdot t_{\mathrm{e}} - 19.04 \quad (4)$$

This is the temperature for a cloudless sky. For total cloud cover, it can be assumed that $t_{\mathrm{r}} = t_{\mathrm{e}}$ (no radiative cooling), for partial cloud cover, t_{r} takes intermediate values.

Equations (1) and (3) are correct when an envelope exchanges heat by radiation only with the "cold sky", i.e. for horizontal envelopes (roofs, roof-ceilings), if these envelopes are not surrounded by higher buildings or vegetation, etc. As already mentioned, steeply sloping and vertical envelopes also exchange heat with the ground, other buildings, etc. (Kruczek, 2009). Then, in Equations (1) and (3), instead of the atmosphere temperature, the averaged ambient temperature t_{amb}, °C, (or T_{amb}, K) should be used. The formula was used here (Clarke, 1985; Nowak, 1999)

$$T_{\mathrm{amb}} = (\alpha \cdot T_{\mathrm{r}}^4 + \beta \cdot T_{\mathrm{gr}}^4 + \gamma \cdot T_{\mathrm{bu}}^4)^{1/4} \quad (5)$$

where:
T_{gr}, T_{bu} – average temperature of the ground and surfaces of buildings K,
α, β, γ – dimensionless coefficients depending on the type of building development.

In the calculations in Section 2, $T_{\mathrm{gr}} = T_{\mathrm{e}} - 3$ K, $T_{\mathrm{bu}} = T_{\mathrm{e}}$ and the coefficients recommended by Clarke for medium-intensive urban development were assumed: $\alpha = 0.41$, $\beta = 0.41$, $\gamma = 0.18$.

For full, opaque envelopes, the estimation of the U_{p} value is not a big problem. The situation is different in the case of transparent envelopes with tight gas-filled gaps, i.e. insulating glass units (IGUs). We are dealing here with a complex heat transfer, and the thermal resistance of gas gaps depends on many factors, including strongly on the slope. There are several interdependent quantities in the calculations of the temperature distribution, therefore these calculations were performed numerically, using standard (PN-EN 673: 2011) values of parameters characterizing heat transfer and the data on materials.

Calculations of the dew point temperature t_{d}, °C, were performed according to the generally known procedure, assuming the dependence of the partial pressure of saturated water vapor, p_s, hPa, on the temperature t_e determined by the Magnus formula (Madany, 1996).

2. Results

Figure 1 shows the limit temperature drop calculated using the Magnus formula, defined as $\Delta t_{d-e} = t_d(\varphi,\ t_e) - t_e$. This parameter shows by how many degrees the temperature on the envelope surface must be lower than the t_e temperature, at the specified air humidity φ, %, in order to achieve the dew point temperature t_d, below which there are conditions for water vapor condensation on the surface.

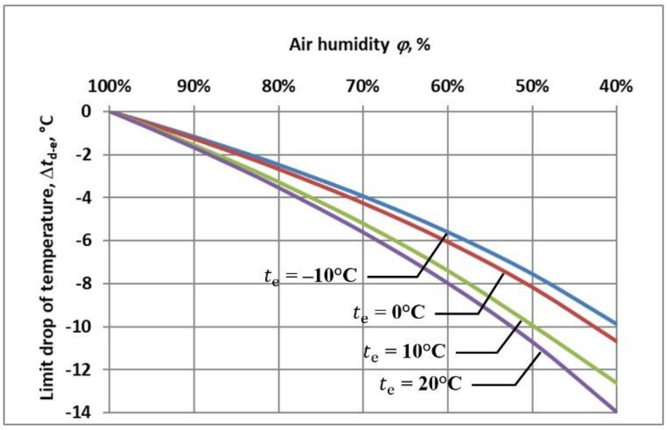

Fig. 1. Temperature drop necessary to reach the dew point on the surface, description in the text (*own research*)

Table 1. The influence of different factors on the radiative temperature change Δt_{er}, °C, on the surfaces of building envelopes at v = 0 m/s, t_i = 10°C (*own research*)

U_p W/(m²·K)	t_e = 0°C, t_r = –19.04°C, t_{amb} = –8.64°C				t_e = 10°C, t_r = –5.74°C, t_{amb} = 2.57°C			
	ε = 0.85		ε = 0.2		ε = 0.85		ε = 0.2	
	horizontal	vertical	horizontal	vertical	horizontal	vertical	horizontal	vertical
1.5	–4.11	–0.25	2.23	3.48	–4.91	–1.65	0.02	1.17
1.0	–5.50	–1.40	0.70	2.09	–5.77	–2.28	–0.81	0.44
0.5	–7.06	–2.67	–1.13	0.44	–6.67	–2.98	–1.79	–0.43
0.3	–7.74	–3.23	–1.94	–0.31	–7.09	–3.29	–2.24	–0.82
0.2	–8.10	–3.52	–2.37	–0.71	–7.30	–3.44	–2.47	–1.03
0.1	–8.47	–3.82	–2.81	–1.12	–7.51	–3.61	–2.72	–1.24

Table 1 shows the influence of various factors (envelope insulation, air temperature, envelope placing, surface emissivity) on the temperature change $\Delta t_{er} = \vartheta_e - t_e$

in the conditions of radiation cooling. A negative value of Δt_{er} means that water vapor condensation on the envelope surface is possible. The calculations were made for two variants of the surface emissivity $\varepsilon = 0.85$ (the approximate value for most commonly used building materials) and $\varepsilon = 0.85$ (e.g. aluminum or surfaces covered with a low-emission coating). The internal temperature is assumed to be $t_i = 20°C$. Windless weather was also assumed, because on the basis of preliminary calculations it was found that in such conditions radiative cooling is the highest.

Based on the data from Table 1, Figure 2 shows (for $\varepsilon = 0.85$) the limit of air humidity φ_{lim}, %, beyond which water vapor condensation on the envelope surface is possible.

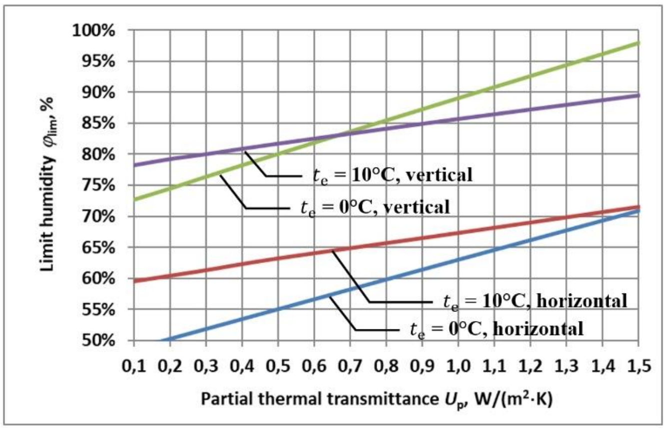

Fig. 2. Dependence of air humidity, at which water vapor condensation on the envelope surface is possible, on its insulation, for $\varepsilon = 0.85$ (*own research*)

Table 2. Thermal parameters and radiative temperature drop Δt_{er}, °C, for typical insulating glass units, calculations for $t_e = 0°C$ (*own research*)

Parameter	double-glazed IGU one low-E coating		triple-glazed IGU two low-E coatings	
	horizontal	vertical	horizontal	vertical
U_{st}, W/(m²·K)	1.730	1.113	0.884	0.564
U_{st0}, W/(m²·K)	1.480	0.998	0.811	0.534
U_p, W/(m²·K)	1.941	1.195	0.975	0.576
Δt_{er}, °C	–2.81	–0.88	–5.36	–2.42
φ_{lim}, %	79.1%	93.0%	63.7%	81.8%

Table 2 shows the results of the calculations for Δt_{er} and φ_{lim} in typical IGUs, i.e. double- and triple-glazed units with internal low-emission coatings ($\varepsilon = 0.04$ was assumed), the thickness of the glass panes 4 mm, the thickness of the argon-filled gaps 16 mm, the emissivity of the external surface $\varepsilon = 0.837$. The individual values of the thermal transmittance mean:

U_{st} – standard value calculated at a wind speed of 4 m/s, without taking into account radiative cooling; for the vertical position it is the nominal value most often given, e.g. in company guidelines;

U_{st0} – as above, in the absence of wind;

U_p – partial thermal transmittance (Eq. (1)), under radiative cooling conditions, in windless weather.

3. Discussion

The possibility of water vapor condensation on the external surfaces of building envelopes is closely related to the radiative cooling of these surfaces. Of course, the values of temperature drops and critical air humidity were estimated for certain calculation conditions, unfavorable in the context of the described phenomenon, i.e. clear sky and no wind. The wind mitigates the radiative temperature drops as more heat is exchanged by the envelope by convection with the air at the temperature t_e. Nevertheless, some general trends follow from the results of the calculations presented in the Section 2:

- calculations confirmed that the high thermal insulation of the envelopes increases the probability of condensation; it is a certain unfavorable phenomenon related to the improvement of the energy parameters of buildings;
- temperature drops on vertical and diagonal envelopes are significant, at least twice as high as on vertical ones;
- low emissivity of the surfaces significantly reduces the described phenomenon;
- in the case of roof-ceilings and well-insulated walls, a drop in the temperature t_e increases the probability of condensation, e.g. at t_e = 0°C, on a roof-ceiling with U_p = 0.1 W/(m^2·K), condensation may occur at air humidity below 50%.

The intensity of the phenomenon is also influenced by factors not included in the presented calculations but confirmed by practical observations:

- Uneven temperature distribution in a room (at the top – warmer, at the bottom – colder) causes condensation to be more visible in the bottom part of rooms (Fig. 3a).
- Due to the differentiation of the thermal insulation of an envelope, it can sometimes be observed that the condensation avoids poorly insulated places (Fig. 3a, b).
- Moisture or frosting of building surfaces intensifies most often in the morning and remains in shaded places even for the first few hours of the day; this is due to the fact that during the day, building envelopes and the surrounding ground accumulate heat, which in the first hours of the night soothes the surface temperature drops.
- External condensation is favored by a drop in room temperature, e.g. with controlled or without a drop in heating efficiency.

Condensation of water vapor may be one of the reasons (precipitation is of course the main factor here) of permanent facade contamination, algae growth and accelerated corrosion of building materials. Figure 4 shows an example of permanently dirty walls with acrylic plaster. Interestingly, there is no dirt in the places of thermal bridges (pins that fix the insulation, gaps between the panels) – these places are warmer and always dry faster.

Fig. 3. Typical forms of external condensation of water vapor on envelopes: a) on the glass facade; no condensation in the upper part of the room and near poorly insulated structural frames, b) on the roof slope; no condensation in places of poorly insulated rafters (*own photos*)

Fig. 4. Permanently soiled facades with acrylic plaster. Unsoiled surfaces in the area of: a) mounting pins, b) gaps between the panes (*own photos*)

Conclusions

Condensation of water vapor on the external surfaces of building envelopes is a natural phenomenon, as is ground frost or morning dew on the grass. It occurs in conditions of radiative cooling, when, for example, at an air temperature of 0°C, the radiative temperature of the atmosphere is about –19°C and the ambient temperature for vertical envelopes is below –8°C. With a cloudless sky and no wind, the temperature on the horizontal surfaces can drop by more than 8°C, and at the horizontal by about 4°C below the temperature of the external air, which creates the possibility of water vapor condensation after exceeding a certain limit value of air humidity. Radiative cooling does not occur when it is completely cloudy, and the wind reduces it. Radiative cooling is also less intensive if the surface has low emissivity, e.g. by using low-emissivity paints. These paints also have a beneficial effect on the thermal parameters of building envelopes (Fantucci & Serra, 2019; *Ograniczenie*, 2017).

Water vapor condensation is favored by the horizontal placing of an envelope and its good thermal insulation. In certain conditions even at air humidity below 50%, condensation is possible on surfaces of roofs and roof-ceilings. It is also often possible to observe dampness on the well-insulated part of the facade and, at the same time, lack of moisture in less insulated places and in places of thermal bridges.

Condensation intensifies in the morning, when the temperature of the environment surrounding the building is the lowest, and the moisture or frosting sometimes lasts several hours during the day in shaded areas (e.g. northern and eastern facades).

Long-lasting condensate on building surfaces can be one of the causes of their permanent contamination or corrosion.

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