Effect of radiative cooling on heat transfer through building partitions

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Abstract. The article analyses the impact of radiative cooling on heat loss in buildings. Radiative cooling means a temperature decrease of external surfaces of building partitions below the ambient temperature. The phenomenon occurs in certain conditions – cloudless sky at night, on horizontal and inclined building surfaces. Based on the dependencies recommended in literature and standards, a mathematical model describing heat transfer in the conditions of radiative cooling has been adopted. The analysis was based on two models of building partitions, i.e. roof-ceiling and insulating glass unit (IGU). For a roof-ceiling, the study analyses the impact on heat loss in the conditions of radiative cooling of such factors as thermal insulation thickness, wind speed, surface emissivity, etc. Heat losses occurring in the conditions of a cloudless and overcast sky have been compared. For IGUs, the study analyses the impact of radiative cooling on heat transfer by convection and radiation in the sealed gas-filled gap. The results of own experimental testing of temperature drop on the surface of IGUs in operating conditions are also presented. It was found that radiative cooling of building partitions in certain weather conditions has a significant effect on heat losses, which should be included in calculations, particularly in the case of horizontal and inclined partitions.

1. Introduction

Radiative cooling is a commonly known phenomenon. It is manifested by a temperature drop on horizontal and inclined surfaces below the temperature of ambient air. This phenomenon occurs throughout the year, but is particularly visible in periods of low temperature, when we experience ground frost, morning mist over meadows or frost on rooftops, cars and other surfaces. Radiative cooling influences heat transfer between building partitions and the external environment. Additional heat losses through building partitions occur in the conditions of radiative cooling. These losses are not included in the classic computational model. The purpose of current analysis is to estimate the values of additional heat losses due to radiative cooling of building partitions on the example of roof-ceiling and insulating glass unit. We also present results of experimental testing of radiative temperature drop on a surface of a greenhouse roof.

2. Characteristics of radiative cooling

The underlying cause of radiative cooling is the so called “atmospheric window”. The Earth’s atmosphere is almost completely transparent for electromagnetic waves with lengths of 8÷13 μm and with cloudless sky the infrared radiation with these wavelengths can be transmitted through atmosphere and almost entirely lost [1-4]. Furthermore it is well known that the spectral distribution of
Electromagnetic radiation emitted by a set object depends mostly on its surface temperature, which is described with Planck’s distribution [4]. Figure 1 presents a graphic representation of Planck’s distribution for typical temperatures of building surfaces. This graph demonstrates that partitions with such temperature emit large proportion of radiation within the atmospheric window. Without possibility of absorbing heat radiation from other sources the surface temperature of such partition drops to a value at which a balance of radiative heat transfer between a building and the atmosphere is achieved.

![Figure 1. Planck’s distribution of emitters with exemplary temperature.](image)

Radiative cooling influences heat loss through building partitions at night, with cloudless weather, for horizontal and inclined partitions. On a sunny day these partitions heat up, the cloud cover minimizes the transmissibility of atmosphere, vertical partitions exchange a large part of their radiation with environment (ground surface, neighbouring buildings), which practically eliminates radiative cooling.

What is directly linked with the existence of atmospheric window is the so-called “cold sky” effect – the radiation temperature of atmosphere $t_r$ is much lower – up to over 20K in winter conditions – than the temperature of external air [5, 6]. Ascertaining the value of this temperature is of crucial importance for determining heat loss in radiative cooling conditions.

Literature also lists another aspect of the analysed phenomenon, namely the possibility of using radiative cooling as source of cold air in building air conditioning systems [7-9], which can beneficially affect the energy balance of the building.

The complex model for radiative heat transfer between a building and its external environment is presented in a monograph by Śliwowski [1]. The determination of radiative temperature of atmosphere in Polish conditions was conducted by Nowak [2], based on experimental testing. The calculation methodology adopted in the present paper is largely based on these works.

Unfortunately the issue of radiative heat loss is most often omitted in the practically applied calculation procedures concerning heat demand of buildings – with averaged external air temperature for respective periods, e.g. months, used to calculate heat loss.

3. Models of heat transfer through building partitions

For the purpose of calculation of heat losses through building partitions a steady state of heat transfer was assumed. It means a constant temperature in the cross-section of partition and a constant density of heat flow throughout a long period of time. Two computational models were considered: classic and one that includes radiative cooling of horizontal and inclined partitions.
3.1. Classic heat transfer model

We used the classic model of heat transfer through building partition for calculation of heat loss without radiative cooling. We assumed that the horizontal or inclined partition is made of homogenous layers of preset thickness and thermal insulation. We also assumed, as in majority of practical calculations, that the external surface of partition exchanges heat with the atmospheric air surrounding it by radiation and convection (Figure 2).

![Figure 2. Temperature profile in horizontal partition – classic model and the model with radiative cooling.](image)

The unit heat losses through a partition were represented by density of heat flow \( q \) (W/m\(^2\)) from

\[
q = U \cdot (t_i - t_e)
\]  

where:

- \( U \) – is the thermal transmittance, W/(m\(^2\)K),
- \( t_i, t_e \) – are the internal and external air temperature, °C.

The thermal transmittance of the partition was calculated from

\[
U = \frac{1}{\sum R + R_{sc}}
\]  

where:

- \( \sum R \) – is the total thermal resistance of building materials layers, m\(^2\)K/W,
- \( R_{si} \) – is the internal surface resistance, m\(^2\)K/W,
- \( R_{se} \) – is the external surface resistance, m\(^2\)K/W.

We assumed \( R_{si} = 0.1 \) m\(^2\)K/W according to the standard [10], for calculating \( R_{sc} \) convection and radiation were

\[
R_{sc} = \frac{1}{h_{ce} + h_{re}}
\]  

where:

- \( h_{ce} \) – is convective surface coefficient, m\(^2\)K/W,
- \( h_{re} \) – is radiative surface coefficient, m\(^2\)K/W.

Surface coefficients were calculated from the following equations [10]

\[
h_{ce} = 4 + 4 \cdot v
\]  

\[
h_{re} = 4 \cdot \sigma \cdot \varepsilon \cdot T_m^3
\]
where:
v – is the wind speed at surface, m/s,
\( \sigma \) – is the Boltzmann constant, \( 6.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4) \),
e – is the emissivity of external surface,
\( T_m \) – is the average temperature of external surface \( \theta_e \) and the surrounding air \( t_e \), K.

The equation (4) is empirical – units are not coherent.

The temperature of external surface \( \theta_e \), °C, was calculated from

\[
\theta_e = t_e + U \cdot R_{ei} \cdot (t_i - t_e)
\]  

(6)

As the \( \theta_e \), \( \hbox{h}_{ei} \), and \( U \) values are interdependent the calculations were numerical.

3.2. Heat transfer model including radiative cooling

The radiative cooling was included in the computational model by assuming that the external partition surface exchanges heat by convection with the surrounding air and by radiation with the atmosphere, that is the “cold sky” (Figure 2).

It follows that to calculate the \( T_m \) value in equation (5) we have to apply not the temperature of external air but the radiation (calorimetric) temperature of atmosphere \( t_i \) and the temperature of radiatively cooled surface \( \theta_{er} \). The temperature \( t_i \) is a measure of thermal radiation intensity of the atmosphere, basing on the assumption that “cold sky” is a perfect black body. The temperature \( \theta_{er} \) was calculated from the equation describing the heat transfer between external building partition and the sky \([1, 2, 11]\)

\[
\hbox{h}_c \cdot (\theta_{er} - t_e) + h_t \cdot (\theta_{er} - t_e) = U_r \cdot (t_i - \theta_{er})
\]  

(7)

And after transformation

\[
\theta_{er} = \frac{U_r \cdot t_i + h_c \cdot t_e + h_t \cdot t_r}{U_z + h_c + h_t}
\]  

(8)

The \( U_r \) value is the replacement thermal transmittance calculated without including the \( R_{ei} \) value

\[
U_r = \frac{1}{R_{ei} + \sum R}
\]  

(9)

The density of heat flow \( q_r \), W/m² in conditions of radiative cooling is

\[
q_r = U_r \cdot (t_i - \theta_{er})
\]  

(10)

Symbols used in equations (7-10) and the remaining relations are as in chapter 3.1. Similarly to that case we also have several interdependent values, which necessitates the numerical calculation. We used the empirical equation quoted from Nowak \([2]\) for averaged climate conditions

\[
t_r = -19.04 + 1.33 \cdot t_e
\]  

(11)

where:
\( t_r \) – is the averaged radiation temperature of atmosphere for cloudless sky, °C.

In conditions of total cloud cover the difference between the air temperature and atmosphere temperature is insignificant and has no significant influence on heat loss \([2]\).
4. Analysis of radiative heat loss for roof-ceiling

Radiative heat loss through an opaque partition were analysed on the example of a horizontal roof-ceiling. We compared the influence of different factors on heat loss through this partition which was described by its density of heat flow for both the classic model and in conditions of radiative cooling.

4.1. Computational assumptions

For the model roof-ceiling we adopted a system of layers with thermal conductivity of $\lambda$ and thickness of $g$:  
- bituminous material, $\lambda = 0.2$ W/(mK), $g = 2$ cm,  
- thermal insulation material, $\lambda = 0.04$ W/(mK), $g = 20$ cm,  
- concrete, $\lambda = 1.7$ W/(mK), $g = 15$ cm,  
- plaster, $\lambda = 0.82$ W/(mK), $g = 2$ cm.

The following computational conditions were also assumed:  
- internal temperature $t_i = 20^\circ$C,  
- external temperature $t_e = -20^\circ$C, corresponding to $t_r = -45.64^\circ$C in cloudless sky conditions according to equation (11),  
- wind speed $v = 4$ m/s,  
- emissivity of external surface $\varepsilon = 0.9$.

The influence of the respective factors on heat loss was investigated by changing the following parameters in model roof-ceiling: thickness of thermal insulation, wind speed, emissivity of surface and external temperature.

4.2. Calculation results

Results of calculations are presented in tables 1-4. For both of the investigated models of heat transfer we quoted foremostly the temperature on external surface $\theta_e$, $\theta_r$, density of heat flow $q$, $q_r$, and the percentage increase of heat losses $Z$ calculated from the following equation 

$$Z = \frac{q_r - q}{q} \cdot 100\%$$  

(12)

**Table 1.** Influence of thermal insulation thickness on heat loss in roof-ceiling.

| Insulation thickness (cm) | Classic model | Radiative cooling |
|-------------------------|---------------|-------------------|
|                         | $U$ (W/m²K) | $\theta_e$ (°C) | $q$ (W/m²) | $U_r$ (W/m²K) | $\theta_r$ (°C) | $q_r$ (W/m²) | $Z$ (%) |
| 15                      | 0.245        | -19.58           | 9.80       | 0.248        | -22.67           | 10.57       | 7.81    |
| 20                      | 0.188        | -19.68           | 7.50       | 0.189        | -22.78           | 8.09        | 7.81    |
| 25                      | 0.152        | -19.74           | 6.08       | 0.153        | -22.85           | 6.55        | 7.81    |
| 30                      | 0.128        | -19.78           | 5.11       | 0.128        | -22.89           | 5.51        | 7.81    |

**Table 2.** Influence of wind speed on heat loss in roof-ceiling.

| Wind speed (m/s) | $h_c$ (W/m²K) | Classic model | Radiative cooling |
|-----------------|---------------|---------------|-------------------|
|                 | $\theta_e$ (°C) | $q$ (W/m²) | $\theta_r$ (°C) | $q_r$ (W/m²) | $Z$ (%) |
| 0               | 4.00          | -18.99        | 7.37              | -28.90       | 9.25    | 25.40  |
| 2               | 12.00         | -19.51        | 7.47              | -24.23       | 8.36    | 11.94  |
| 4               | 20.00         | -19.68        | 7.50              | -22.78       | 8.09    | 7.81   |
| 6               | 28.00         | -19.76        | 7.52              | -22.07       | 7.96    | 5.81   |
Table 3. Influence of surface emissivity on heat loss in roof-ceiling.

| Surface emissivity | Classic model | Radiative cooling | Z (%) |
|--------------------|---------------|-------------------|-------|
|                    | $h_c$ (W/m²K) | $\vartheta_e$ (°C) | $q$ (W/m²) | $h_r$ (W/m²K) | $\vartheta_e$ (°C) | $q_r$ (W/m²) |
| 0.9                | 3.318         | -19.68            | 7.50    | 2.785         | -22.78            | 8.09    | 7.81 |
| 0.8                | 2.949         | -19.67            | 7.50    | 2.480         | -22.47            | 8.03    | 7.05 |
| 0.7                | 2.581         | -19.67            | 7.50    | 2.171         | -22.15            | 7.97    | 6.27 |
| 0.6                | 2.212         | -19.66            | 7.50    | 1.856         | -21.81            | 7.91    | 5.43 |
| 0.5                | 1.843         | -19.66            | 7.50    | 1.560         | -21.49            | 7.85    | 4.62 |

Table 4. Influence of external temperature $t_e$ on heat loss in roof-ceiling.

| $t_e$ (°C) | $t_r$ (°C) | Classic model | Radiative cooling | Z (%) |
|------------|------------|---------------|-------------------|-------|
|            |            | $\vartheta_e$ (°C) | $q$ (W/m²) | $\vartheta_e$ (°C) | $q_r$ (W/m²) |
| -20        | -45.64     | -19.68        | 7.50   | -22.78        | 8.09    | 7.81 |
| -10        | -32.34     | -9.76         | 5.63   | -12.82        | 6.21    | 10.28 |
| 0          | -19.04     | 0.16          | 3.75   | -2.78         | 4.31    | 14.78 |
| 10         | -5.74      | 10.08         | 1.88   | 7.37          | 2.39    | 27.29 |

4.3. Discussion of results

The analysis proved that higher heat loss through roof-ceiling in conditions of radiative cooling are foremostly the result of large temperature drop on the external surface of the partition and the lowered effective thermal transmittance.

We have established that with increased thermal insulation of the partition the heat losses drop proportionally for both of the considered computational models so that the Z ratio is constant in the analysed range. Lowering the emissivity causes the surface of the partition to exchange less energy with “cold sky”, which in turn results in several percent lower heat losses in conditions of radiative cooling. What has the most significant impact on increasing heat loss is the wind speed. In the classic model faster wind cools down the surface, and in radiative cooling the largest heat losses are recorded in windless conditions, which is represented by an increase of Z ratio. The Z ratio also grows in case of an increase of external air temperature, a result of almost linear dependency of heat loss on the $t_e$ temperature with constant $t_i$ temperature (Figure 3).

![Figure 3](image)

*Figure 3. Density of heat flow vs. external temperature and wind speed.*
5. Analysis of radiative heat loss for insulating glass units

The radiative heat loss through glazing were analysed on the example of insulating glass units in horizontal and inclined position with unmodified and low-emission glass.

5.1. Calculative assumptions

An insulating glass unit (IGU) is made of two glass panes divided by a sealed gas-filled gap. The manufacturers declare thermal transmittance of insulating glass units assuming their vertical position in the structure, pursuant to applicable standards [12]. Use of such values for calculation of heat losses may lead to underestimation of those losses in case of horizontal or inclined position of an IGU in structure (Figure 4). Such position increases the convection in the gap between glass panes, lowering the thermal insulation of that gap. The thermal transmittance of an IGU also depends on the difference of temperatures between areas surrounding the gap. A larger difference between these temperatures, caused e.g. by radiative cooling, additionally boosts convection and increases heat transfer by radiation between the surfaces.

![Temperature differentiation – extra convection and radiation](image)

**Figure 4.** Causes of heat losses through a horizontally located IGU.

The $U$ value of an IGU which depends foremostly on heat resistance of the gas gap, was calculated according to the detailed method presented in the standard [12]. Remaining calculations were conducted according to methods listed in chapter 3. We analysed IGUs located horizontally and inclined, at an angle of 30° to the horizontal. The following computational conditions were adopted:

- IGU with two glass panes 4 mm, $\lambda = 1.0$ W/(mK),
- 16 mm gap filled with argon,
- two variants of thermal insulation of glazing: an IGU without modifying coating (all glass panes with emissivity of $\varepsilon = 0.837$), an IGU with one low-emission coating $\varepsilon = 0.04$ (Fig. 4).
- external air temperature $t_\text{e} = 0^\circ\text{C}$, corresponding to $t_r = -19.04^\circ\text{C}$.

5.2. Calculation results

Results of calculations are presented in tables 5 and 6. Apart from the $Z$ ratio that was calculated as in chapter 4.2 we also determined the $Z_n$ representing the percentage rise in heat flow in relation to the respective type of IGU in vertical position. The IGUs in vertical location (standard conditions) have the following parameters:

- IGU with unmodified glass, $U = 2.11$ W/(m²K), $q = 42.22$ W/m² for $v = 0$ m/s; and $U = 2.54$ W/(m²K), $q = 50.78$ W/m² for $v = 4$ m/s
- IGU with low-emission glass, $U = 1.00$ W/(m²K), $q = 19.96$ W/m² for $v = 0$ m/s; and $U = 1.11$ W/(m²K), $q = 22.27$ W/m² for $v = 4$ m/s.
Table 5. Heat losses through IGUs inclined at an angle of 30° to the horizontal.

| Wind speed (m/s) | Classic model | Radiative cooling |  |
|------------------|---------------|-------------------|--|
|                  |               |                   | Z (%)         |
|                  | \(U\) (W/m²K) | \(\delta_h\) (°C) | \(q\) (W/m²) | \(Z_n\) (%) | \(U_r\) (W/m²K) | \(\delta_r\) (°C) | \(q_r\) (W/m²) | \(Z_n\) (%) |
| IGU with unmodified glass |               |                   |             |             |               |                   |             |             |           |
| 0                | 2.39          | 6.00              | 47.71       | 12.99       | 3.41          | 0.18              | 67.64        | 60.18       | 41.76      |
| 4                | 2.98          | 2.50              | 59.69       | 17.52       | 3.41          | 0.08              | 68.01        | 33.92       | 13.96      |
| IGU with low-emission glass |           |                   |             |             |               |                   |             |             |           |
| 0                | 1.38          | 3.51              | 27.87       | 39.60       | 1.81          | -2.95             | 41.43        | 110.06      | 50.47      |
| 4                | 1.62          | 1.35              | 32.23       | 45.19       | 1.78          | -1.20             | 37.75        | 69.57       | 16.77      |

Table 6. Heat losses through IGUs positioned horizontally.

| Wind speed (m/s) | Classic model | Radiative cooling |  |
|------------------|---------------|-------------------|--|
|                  |               |                   | Z (%)         |
|                  | \(U\) (W/m²K) | \(\delta_h\) (°C) | \(q\) (W/m²) | \(Z_n\) (%) | \(U_r\) (W/m²K) | \(\delta_r\) (°C) | \(q_r\) (W/m²) | \(Z_n\) (%) |
| IGU with unmodified glass |               |                   |             |             |               |                   |             |             |           |
| 0                | 2.42          | 6.06              | 48.46       | 14.75       | 3.49          | 0.32              | 68.72        | 62.75       | 41.83      |
| 4                | 3.04          | 2.55              | 60.87       | 19.87       | 3.49          | 0.13              | 69.33        | 36.63       | 13.97      |
| IGU with low-emission glass |            |                   |             |             |               |                   |             |             |           |
| 0                | 1.48          | 3.72              | 29.59       | 48.24       | 1.94          | -2.81             | 44.29        | 121.87      | 49.67      |
| 4                | 1.73          | 1.45              | 34.60       | 55.40       | 1.91          | -1.09             | 40.32        | 81.06       | 16.51      |

5.3. Discussion of result

The analysis proved that the value of heat loss through IGUs depends foremostly on the position of this element in the structure. A horizontal or inclined position causes the heat losses to be significantly higher in relation to IGUs of standard parameters in a horizontal position. A particularly significant rise in the density of heat flow occurs in case of low-emission IGUs with a low \(U\) value. In this case a feedback occurs – high thermal resistance of the gap results in higher temperature differences on the surrounding surfaces, therefore the value of \(Z_n\) ratio increases.

Another detrimental factor is the radiative cooling that causes a further increase of heat losses, especially without movement of air. At the same time the action of these factors can lead to over 60% increase in the density of heat flow for unmodified IGUs and over 120% increase in case of IGUs with low-emission glass.

6. Testing of temperature on external surfaces of IGUs

In order to verify the computational model we conducted temperature measurements on surfaces of IGUs which had parameters similar to those previously analysed in calculations.

6.1. Conduct and results of testing

Model IGUs sized 60×160 cm were installed on a roof plane of an operated greenhouse. The roof plane was inclined at an angle of 31.5° to the horizontal. Tables 7 and 8 present the values of measurements performed in conditions similar to computational ones – with total cloud cover and cloudless sky. The measurements were performed in spring, at night, with greenhouse heating on. The measured temperatures were compared to the values expected on the basis of calculations.
Table 7. Measured and expected temperatures of external IGU surface – cloudless night.

| No. | Temperature (°C) | Temperature $\Delta t$ (°C) | Temperature $\Delta t$ (°C) |
|-----|------------------|-----------------------------|-----------------------------|
|     | $t_e$ | $t_i$ | measured | expected | difference | measured | expected | difference |
| 1.  | 6.5   | 22.1 | -10.4    | 6.2     | 5.2       | 1.0      | 6.3      | 6.1       | 0.2       |
| 2.  | 2.0   | 15.7 | -16.4    | 1.4     | 0.4       | 1.0      | 2.5      | 1.2       | 1.3       |
| 3.  | 1.8   | 17.8 | -16.6    | 0.5     | 0.4       | 0.1      | 2.2      | 1.3       | 0.9       |
| 4.  | 1.2   | 18.6 | -17.4    | 0.0     | -0.1      | 0.1      | 1.7      | 0.9       | 0.8       |
| 5.  | 0.2   | 18.0 | -18.8    | 0.0     | -1.1      | 1.1      | 1.3      | -1.0      | 1.4       |
| 6.  | 4.5   | 14.9 | -13.1    | 3.2     | 2.7       | 0.5      | 3.7      | 3.4       | 0.3       |
| 7.  | 9.2   | 21.0 | -6.8     | 8.5     | 7.6       | 0.9      | 9.0      | 8.3       | 0.7       |
| 8.  | 8.7   | 21.8 | -7.5     | 7.3     | 7.2       | 0.1      | 9.0      | 8.0       | 1.0       |
| 9.  | 4.4   | 18.6 | -13.2    | 3.1     | 2.9       | 0.2      | 3.7      | 3.7       | 0.0       |
| 10. | 7.9   | 18.0 | -8.5     | 6.4     | 6.1       | 0.3      | 7.6      | 6.8       | 0.8       |
| 11. | 8.4   | 21.0 | -7.9     | 6.4     | 6.8       | -0.4     | 7.5      | 7.6       | -0.1      |
| 12. | 2.0   | 17.6 | -16.4    | 1.0     | 0.6       | 0.4      | 2.6      | 1.5       | 1.1       |
| 13. | 9.0   | 19.0 | -7.1     | 7.5     | 7.2       | 0.3      | 8.4      | 7.9       | 0.5       |
| 14. | 10.3  | 21.8 | -5.3     | 8.9     | 8.7       | 0.2      | 10.0     | 9.4       | 0.6       |
| 15. | 4.8   | 20.7 | -12.7    | 3.1     | 3.5       | -0.4     | 4.4      | 4.3       | 0.1       |

Standard deviation: 0.470

Table 8. Measured and expected temperatures of external IGU surface – cloudy weather.

| No. | Temperature (°C) | Temperature $\Delta t$ (°C) | Temperature $\Delta t$ (°C) |
|-----|------------------|-----------------------------|-----------------------------|
|     | $t_e$ | $t_i$ | measured | expected | difference | measured | expected | difference |
| 1.  | 8.8   | 18.2 | 9.4      | 9.4      | 0.0        | 9.7      | 10.0     | -0.3       |
| 2.  | 6.2   | 18.1 | 7.2      | 7.0      | 0.2        | 8.2      | 7.7      | 0.5        |
| 3.  | 4.2   | 17.9 | 5.2      | 5.0      | 0.2        | 6.2      | 5.9      | 0.3        |
| 4.  | 7.6   | 19.0 | 8.1      | 8.3      | -0.2       | 9.3      | 9.0      | 0.3        |
| 5.  | 6.9   | 17.2 | 7.5      | 7.5      | 0.0        | 8.8      | 8.1      | 0.7        |
| 6.  | 7.5   | 22.6 | 8.0      | 8.5      | -0.5       | 9.0      | 9.4      | -0.4       |
| 7.  | 8.1   | 24.1 | 8.5      | 9.1      | -0.6       | 10.2     | 10.1     | 0.1        |
| 8.  | 7.1   | 20.4 | 8.3      | 7.9      | 0.4        | 9.1      | 8.8      | 0.3        |
| 9.  | 10.1  | 22.0 | 10.7     | 10.8     | -0.1       | 11.5     | 11.6     | -0.1       |
| 10. | 10.8  | 22.9 | 11.9     | 11.5     | 0.4        | 12.7     | 12.3     | 0.4        |

Standard deviation: 0.343

6.2. Discussion of results
Measurement results indicate the practical applicability of adopted computational models, which is proven by standard deviations that do not exceed 0.5°C. What is notable is that in case of radiation cooling the temperature on IGU surface was in almost all cases slightly higher than expected. The probable cause for that is firstly the location of the greenhouse in an area surrounded by higher buildings, secondly the local dusting of air (the testing was conducted during the heating season). Both of these factors affect possible weakening of the radiative cooling effects.

7. Conclusions
In practical applications heat losses through building partitions are most frequently estimated with use of classic model of heat transfer, where the temperature of external air $t_e$ is considered adequate for the calculation of radiative heat transfer between partition surface and its surrounding. That approximation
is sufficient in case of horizontal and inclined partitions in case of cloudy sky, but in cloudless conditions the model that includes radiative cooling is adequate, which was proven by actual tests described in the current paper.

Additional heat losses occur in conditions of radiative cooling as the result of lowered effective thermal resistance of the building partition and foremostly from the radiative lowering of the building surface temperature. This phenomenon is magnified at night in conditions of cloudless and windless weather. For a roof-ceiling, during lowered outside temperatures the radiative cooling in windless conditions increases temporary heat loss by over 25%. In case of higher air temperatures this percentage of increase is even higher.

In case of insulating glass units another detrimental phenomenon occurs – with horizontal or inclined IGUs and a higher difference of temperatures which results from radiative cooling, the heat transfer in the internal gas gap intensifies. This leads to significant increase of actual thermal transmittance, when compared to declared (standard) values. This effect is particularly strong in case of IGUs with a low $U$ value (e.g. IGUs with low-emission coating). Temporary heat losses through IGUs analysed in the article can be in unfavourable conditions by over 120% greater in relation to glass unit with declared parameters for the standard conditions.

It is evident that the particularly detrimental radiative conditions (cloudless sky and no movement of air) only occur for a limited number of days throughout the heating season. Nevertheless in case of horizontal or inclined roof-ceiling and large area glazing the inclusion of radiative cooling in computational procedure will definitely lead to higher accuracy of the calculated values and their correspondence with actual values. This can be done, e.g. by introduction of a corrective, negative adjustment to the calculated external air temperature, which was already postulated in the past [1, 2] or by adopting the $U$ values that are adequate to their position in the structure.

References
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