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INFLUENCE OF IRRADIANCE AND AMBIENT TEMPERATURE ON ROOF COATING TEMPERATURE AND HEAT FLUX TRANSFERRED TO INTERIOR OF BUILDING

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Abstract: The following article presents an analysis of the influence of the irradiance and ambient temperature on the roof coating temperature. The roof coating temperature depends mainly on the optical properties of the coating material. Those properties are the reflectivity and emissivity. The roof surface temperature determines the heat flux through the roof into the interior of the building. Proper material selection for the coating of the roof can significantly decrease the surface temperature, and as a result, decrease the heat flux into the space just below the roof. During the calculations, the model of the heat exchange derived by the author for the flat roof was used. The paper includes results of heat calculations for two coating materials with different reflectivity coefficients. The calculations were made for the specific weather conditions.

Keywords: roof coating material, heat load of building, energy balance of flat roof

1. INTRODUCTION

Dynamic development of our civilization requires more and more energy. Currently, most of the energy comes from the combustion of fossil fuels. In recent decades many countries decided to switch to renewable energy sources and to produce so-called *green energy*. Another solution to the problem is energy efficiency in industry and construction. In temperate and cold climate, households require heating in the winter and air-conditioning in the summer.

The following paper presents an analysis of possible reduction of the heat load for building in the summer by proper roof coating material selection. The coating material selection influences the heat flux through the roof into the neighboring rooms. Such investment allows improving the energy efficiency of ventilation and air-conditioning systems. Higher energy efficiency reduces electricity consumption during the summer peak.

Building's roofs coated with materials with proper optical properties are called the cool roofs. Selection of material with high reflectivity and emissivity coefficients effectively reduces the roof coating temperature. Lower external roof surface temperature results in lower heat flux through the roof into the neighboring rooms. On the website of an international organization called *the Cool Roofs* [1], it is possible to find information about materials used as a roof coating and their optical properties.

The problem of selecting a roof coating requires compliance with both constructional and architectural (e.g. color) constraints [2]. However, the constructor, architect or energy auditor cannot precisely estimate how the specific material will perform under a different irradiance and ambient temperature.

The aim of this paper is to determine the influence of the irradiance and ambient temperature on the roof coating temperature and the heat flux into the building. The analysis will cover various irradiance and ambient temperature. The calculations will be made for two materials with different reflectivity coefficient.

2. ENERGY BALANCE OF FLAT ROOF

In order to determine the roof coating temperature, the author derived a model of heat transfer through the flat, horizontal roof. This model will be presented in this chapter.

An investigated building has a flat, horizontal roof. Details concerning construction and material of the roof are not relevant, the resultant heat resistance of this partition, however, is necessary for the calculations. Only variable concerning the roof is the coating material. An additional assumption that the coating material does not affect the resultant heat resistance was made.

The energy balance was derived for the roof. The roof is treated as a quasi-steady thermodynamic system. The balance takes into account only the heat transfer in the longitudinal direction, omitting heat transfer in the transverse direction.

The solar radiation falling on the surface of the roof is partially reflected and partially absorbed by the roof. Then the heat penetrates into the room(s) neighboring with the roof. The analysis does not take into account the heat transfer through radiation between the ceiling and the walls. Additionally, the room temperature just below the ceiling is assumed to be known a priori.
The energy balance was made for a surface of 1 m^2.

Figure 1 shows the heat fluxes exchanged through radiation and convection between specific mediums and the roof.

The solar irradiance falling on a flat surface of the horizontal roof depends mainly on the latitude, season of the year and time of the day. This parameter is denoted as $G_{S\beta}$. The flux of solar energy falling on the outer surface of the roof (coating) is partially reflected and partially absorbed.

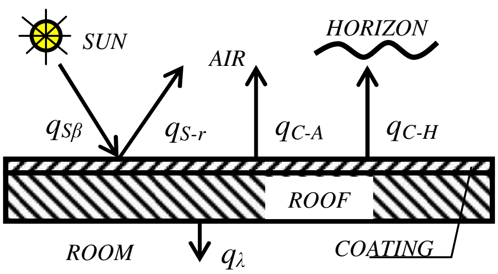

Fig. 1. Heat fluxes for the flat horizontal roof

Therefore, the energy balance equation for the solar radiation has the following form:

$$G_{S\beta} = G_{Sr} + G_{Sa}. \tag{1}$$

The flux of the solar energy reflected by the coating of the roof depends on the reflectivity coefficient of the material. This flux can be expressed as follows:

$$G_{Sr} = r_C G_{S\beta}. \tag{2}$$

The flux of the solar energy reflected by the coating of the roof, however, is described by the following formula:

$$G_{Sa} = a_C G_{S\beta} = (1 - r_C) G_{S\beta} . \tag{3}$$

Therefore, for a given moment in time, the balance of the heat fluxes for the outer surface of the roof has the following form:

$$G_{Sa} = q_{C-A} + q_{C-H} + q_\lambda . \tag{4}$$

The terms appearing on the right-hand-side of the equation (4) represent: heat flux exchanged through convection between roof outer surface and surrounding air, heat flux radiated by the roof outer surface into the horizon and heat flux conducted by the roof that penetrated inside the building, respectively.

The convective heat flux exchanged between the roof outer surface and atmospheric air can be determined using the following formula:

$$q_{C-A} = h_{C-A}(T_C - T_A). \tag{5}$$

The heat flux radiated by the roof outer surface into the horizon can be calculated according to the following relation:

$$q_{C-H} = \varepsilon_C \sigma (T_C^4 - T_H^4). \tag{6}$$

The resultant temperature of the horizon is defined by the Swinbank's formula [4]:

$$T_H = 0{,}0553 \cdot T_A^{1{,}5}. \tag{7}$$

The heat flux conducted by the roof that penetrates into the air inside the building can be expressed as follows:

$$q_\lambda = U_e(T_C - T_R). \tag{8}$$

The resultant heat transfer coefficient depends on the heat resistances of each roof layer and the convective heat transfer coefficient between the plasterwork and the air inside the building. Therefore:

$$U_e = \frac{1}{R_e} . \tag{9}$$

The heat resistance of a multi-layer partition and the heat resistance for the convective heat transfer into the air inside the building can be determined using the following formula:

$$R_e = \sum_{i=1}^{N} R_i + R_R. \tag{10}$$

The heat resistance of a single layer partition is calculated according to the following formula:

$$R_i = \frac{\delta_i}{\lambda_i} . \tag{11}$$

The heat resistance for the convective heat transfer from the ceiling into the air inside the building, however, follows the relation:

$$R_R = \frac{1}{h_R}. \quad (12)$$

After substituting the equations (3), (5), (6) and (8) into the equation (4), the energy balance equation for a flat, horizontal roof was derived:

$$(1 - r_C)G_{S\beta} = h_{C-A}(T_C - T_A) + \varepsilon_C\sigma(T_C^4 - T_H^4) + +U_e(T_C - T_R). \quad (13)$$

Using the formula (13) it is possible to determine the roof coating temperature:

$$T_C^4 + C_1 \cdot T_C + C_2 = 0, \quad (14)$$

where:

$$C_1 = \frac{h_{C-A} + U_e}{\varepsilon_C \cdot \sigma}, \quad (15)$$

$$C_2 = -\frac{(1-r_C)\cdot G_{S\beta} + h_{C-A}\cdot T_A + U_e \cdot T_R + \varepsilon_C \cdot \sigma \cdot T_H^4}{\varepsilon_C \cdot \sigma}. \quad (16)$$

Subsequently, after determining that temperature, and using the formula (8), it is possible to calculate the heat flux from the roof outer surface into the building. Then using the equations (5) and (6) it is possible to calculate the heat flux exchanged between the roof outer surface and the atmospheric air, and the heat flux radiated into the horizon.

The heat fluxes obtained using the equations (5), (6) and (8) can be normalized to the solar irradiance, therefore:

$$u_{C-A} = \frac{q_{C-A}}{q_{Sa}}, \quad (17)$$

$$u_{C-H} = \frac{q_{C-H}}{q_{Sa}}, \quad (18)$$

$$u_\lambda = \frac{q_\lambda}{q_{Sa}}. \quad (19)$$

The reduction of the heat transfer penetrating through the roof achieved with the change of the coating material can be measured by introducing a new parameter called the heat load reduction coefficient:

$$z_\lambda = \frac{q_{\lambda,0,2} - q_{\lambda,0,85}}{q_{\lambda,0,2}}. \quad (20)$$

This coefficient can be expressed in percentages.

3. CALCULATIONS

The heat calculations concern the building with a flat, horizontal roof. This method, however, is valid for buildings with a little-inclined roof as well. Roofs can have a different construction, different materials and usually are built as multilayered. Those materials have different thermal properties, especially the heat conduction coefficient. Therefore, it is hard to precisely evaluate the heat resistance of the partition. First of all, the roof must have a support. Outside the main support, usually, there are: insulation foil, insulation material, engineered lumber board (e.g. OSB) acting as a support for the coated cover. Inside the building, there are: dry-wall and plasterwork. Sometimes between the support and the dry-wall there is an additional air-gap.

Among those materials, the most important for the heat resistance is the insulation material. The heat resistance depends on the material and the thickness of its layer. Therefore, if the constructional details are known, the heat resistance is easy to calculate. However, if those details are not known, the heat resistance can only be roughly estimated or assumed using the legal acts binding when the building was put into service. In the reference, it was estimated that the resultant heat resistance for the roof varies in a range between 5 and 15 $(m^2K)/W$.

Therefore, according to the formula (9), the resultant heat transfer coefficient will vary in a range between 0.07 and 0.20 $W/(m^2K)$. The upper value corresponds to the constructional regulation (binding until the end of 2016). Since the beginning of 2017, the binding regulations require the U_e parameter to be lower than 0.18 $W/(m^2K)$ for a partition over a room with temperature $t_R \geq 18°C$. For the calculations presented in this paper, the value of $U_e = 0.20$ $W/(m^2K)$ was assumed. Moreover, the change of the coating material does not affect this parameter. Such assumption is reasonable because the thickness of the coating usually does not exceed 0.005m.

In this paper, two roof coating materials with extremely different optical properties were investigated. Roofs constructed according to old technology were usually coated with the bitumen. The reflectivity coefficient r_C for this material range from 0.1 up to 0.2. Roofs constructed according to new technology have the reflectivity coefficient starting from 0.5 up to 0.89 [1,2,5]. For the following calculations, two values of the reflectivity coefficient were assumed: 0.2 and 0.85. Therefore, the absorption coefficients a_C are 0.8 and 0.15, respectively.

The thermal emissivity coefficient of the coating material ε_C is assumed constant and equals 0.8. In practice, for the gray bodies, the emissivity coefficient ε_C is equal to the absorption coefficient a_C. Moreover, a value of this parameter depends on the roof coating temperature as well.

The calculations also require determining the heat transfer coefficient h_{C-A} from the roof coating into the atmospheric air. A value of this parameter depends on i.a. the velocity of atmospheric air flowing around the roof. The higher velocity, the better heat exchange between those mediums. The air velocity is assumed constant and equals 1 m/s in this paper. The heat transfer coefficient also depends on the spatial orientation of the roof and the temperatures of both mediums. Precise estimation of the heat transfer coefficient h_{C-A} between the roof coating and the environment is very hard, therefore it is assumed constant and equals 5,8 W/m^2K [6].

The temperature of space just below the roof can vary in relatively wide range. In this paper, it is assumed constant and equals T_R = 295.15 (22°C). This temperature corresponds to the typical value for air conditioning calculations for the summer time. This temperature is often referred as the thermal comfort temperature.

The calculations will be conducted for a wide range of the solar irradiance $G_{S\beta}$ and selected ambient air temperatures. In this paper, it is assumed that the solar irradiance varies in the range between 200 and 1000 W/m^2, and the ambient temperatures equal 35°C, 30°C and 25°C. Those environmental parameters are typical for Poland. Substituting the ambient temperature values into equation (7), the following horizon temperatures were obtained: 298.59K, 291.36K and 284.18K.

With this data and equations (15) and (16), it is now possible to calculate the C_1 and C_2 constants.

Subsequently, using the equation (14), the roof coating temperature was determined. The roof coating temperatures as functions of the solar irradiance and ambient temperature are shown in Fig. 2 and 3, separately for each material. Basing on the data presented in Fig. 2, it can be stated that during a sunny day with no clouds in the sky ($G_{S\beta}$ =1000W/m^2, t_A =35°C), the roof coating temperature for the material with reflectivity coefficient 0.2 can reach up to 90°C. When the sky is cloudy, the solar irradiance is lower (around 200 W/m^2) and the ambient temperature is also lower (around 25°C), then the roof coating temperature (bitumen) does not exceed 35°C. When the roof is coated with material with high reflectivity coefficient $r_C = 0.85$, however, during a sunny day with no clouds in the sky, the roof coating temperature is much lower and does not exceed 45°C. On a cloudy day, the roof coating temperature is close to the temperature inside the building.

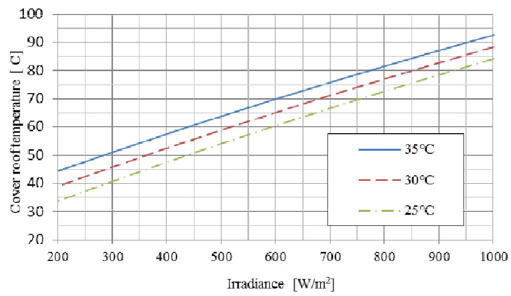

Fig. 2. Roof coating temperature as a function of solar irradiance for three different ambient temperature, reflectivity coefficient of material r_C = 0.20

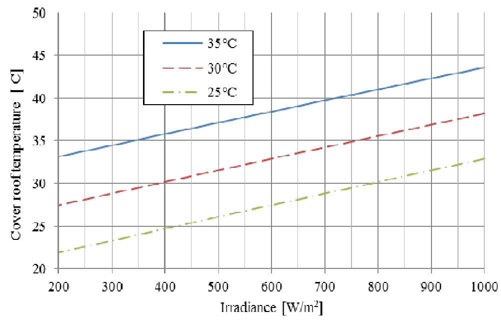

Fig. 3. Roof coating temperature as a function of solar irradiance for three different ambient temperature, reflectivity coefficient of material r_C = 0,85

The heat fluxes through the roof into the building for two different coatings and specific weather conditions are shown in Fig. 4 and 5. Of course for the higher reflectivity on a cloudy day (ambient temperature around 25°C), the heat flux into the building is close to zero.

Fig. 6 shows the heat load reduction coefficient calculated according to the formula (20) for the change of the coating material. The analysis of the results shows clearly that for high solar irradiance, the reduction of the heat entering the building through the roof varies from 70 up to 85% (the lower ambient temperature, the higher reduction).

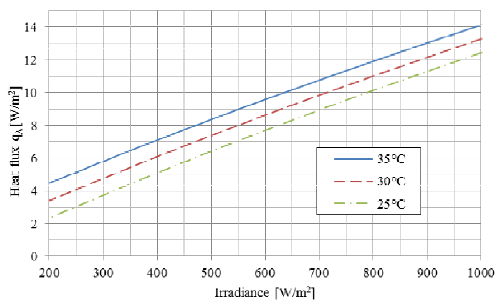

Fig. 4. Heat flux through the roof into the building as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material r_C = 0,20

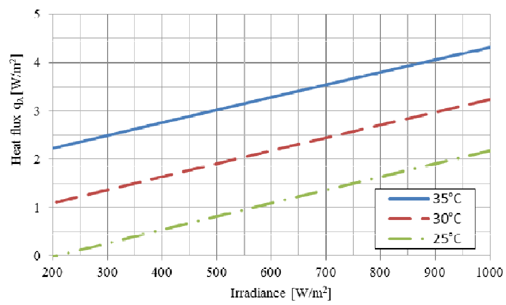

Fig. 5. Heat flux through the roof into the building as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material r_C = 0,85

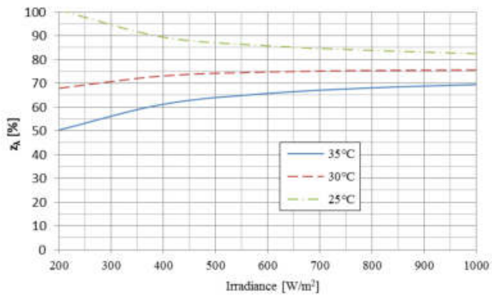

Fig. 6. Heat load reduction coefficient as a function of solar irradiance

For low solar irradiance and the ambient temperature 35°C, the heat load reduction coefficient is around 50%. However, if the ambient temperature equals 25°C, the z_λ coefficient equals 100%.

Looking at the heat flux entering the building and comparing it to the solar irradiance, it can be stated that for the bitumen it is around 3% (low solar irradiance and high ambient temperature). But it is almost 2.5 times higher for the high reflectivity material (Fig. 8). For high ambient temperatures (35°C and 30°C) this yield drops while the solar irradiance increases. However, for lower ambient temperature (25°C) this yield grows. Fig. 9 and 10 shows how the yields of heat transfers exchanged between the roof coating and the horizon (upper lines), and between the roof coating and the ambient air (lower lines) depends on the solar irradiance and the ambient temperature.

The yield of heat flux exchanged between the roof coating and the atmospheric air grows with the solar irradiance. The yield of heat flux exchanged between the roof coating and the horizon acts contrary.

For the building's roof coated with high reflectivity material and low solar irradiance it can be stated that the heat flow direction reverses, i.e. the heat is transferred from the air to the roof.

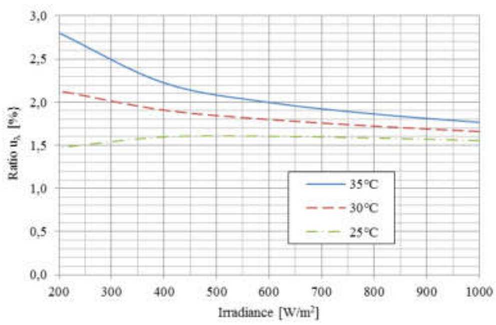

Fig. 7. Ratio of heat flux entering the building through the roof and solar irradiance as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material $r_C = 0{,}20$

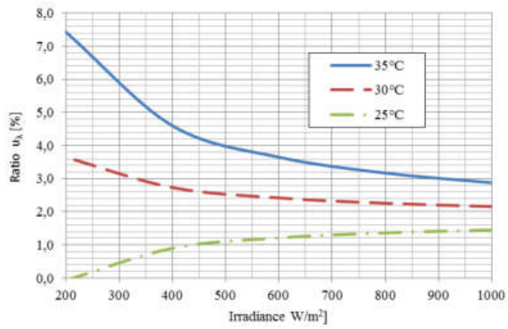

Fig. 8. Ratio of heat flux entering the building through the roof and solar irradiance as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material $r_C = 0{,}85$

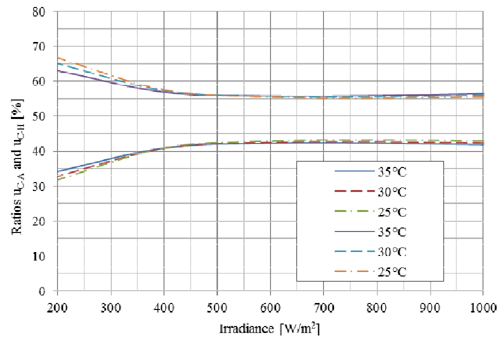

Fig. 9. Ratios of heat flux exchanged with air and radiated into horizon to solar irradiance as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material $r_C = 0{,}20$

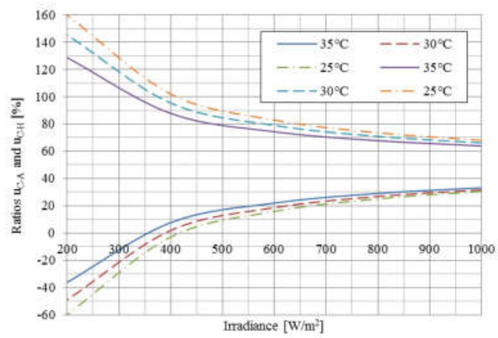

Fig. 10. Ratios of heat flux exchanged with air and radiated into horizon to solar irradiance as a function of solar irradiance for three different ambient temperatures, reflectivity coefficient of material $r_C = 0{,}85$

4. CONCLUSIONS

Basing on the calculations presented in this paper, the following conclusions can be stated:

- roof coating with high reflectivity coefficient provides relatively low temperatures of roof surface,
- heat load reduction coefficient on a sunny day can reach around 70-90%,

- heat load reduction coefficient on a cloudy day varies in wider range (50-100%) and strongly depends on ambient temperature,
- yield of heat flux entering the building through the roof is only around a few percent.
- on a cloudy summer day, heat flux changes direction, i.e. heat is transferred from air to the roof.

Nomenclature

Symbols

a – coefficient of absorption,
h – convection heat transfer coefficient, W/(m^{2}K),
r – reflectivity,
R – heat resistance, (m^{2}K)/W,
T – temperature, K,
u – ratio,
U – overall heat transfer coefficient, W/(m^{2}K),
δ – coating thickness, m
ε – emissivity,
σ – Stephan-Boltzman constant for black body, $\sigma = 5{,}76 \cdot 10^{-8}$ W/(m^{2}K^4),
λ – conduction, W/(mK).

Indices

A – air
C – roof coating
e – equivalent
H – horizon
R – room

References

1. http://coolroofs.org/products/results (dostęp 30.04.2017)
2. Monczyński B., Ksit B.. (2017). Komu w Polsce są potrzebne chłodne dachy. *Inżynier Budownictwa*, 147, nr 2, 2017, s.96-100 (in Polish)
3. Zapałowicz Z. (2017). Wpływ właściwości optycznych pokrycia dachowego na gęstość strumienia ciepła przenikającego do wnętrza budynku. *Instal* (praca w redakcji czasopisma) (in Polish)
4. Pluta Z. (2000). *Podstawy teoretyczne fototermicznej konwersji energii słonecznej*. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa (in Polish)
5. http://www.dachyplaskie.info.pl/technika-i-technologie/zimny-dach/ (dostęp 30.04.2017)
6. Chwieduk D. (2011) *Energetyka słoneczna budynku*. Arkady, Warszawa (in Polish)

Biographical note

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