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Experimental estimation of thermal emissivity for the roofing paper in blue colour

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Abstract Effective use of energy in various branches of economy is one of world trends in development of power engineering. Relevant energy consumption occurs during exploitation of buildings, so there is still potential to diminish it as far as heating, ventilation, and air conditioning are concerned. Particularly in summer season, the choice of respective roofing colour can play a decisive role for the heat flux transferred to the inside of the object. Decrease of heat flux causes a lower heat burden to the building and lower power consumption by the air conditioning systems. In winter, on the contrary, heat flux transferred to building's interior should be higher, as a result, demand of energy for heating will be lower. However, calculations of the heat flux require that energy balance must be made for the object. Unfortunately, not all producers of roofing covers inform about the values of reflectivity and thermal emissivity of their products, which is, in turn, necessary for calculations. In the present paper, research methodology elaborated by authors is proposed for determination of thermal emissivity of roofing covers. The paper presents test stand, methodology, and research results for roofing paper in blue colour (as an example) for which the thermal emissivity is an unknown parameter.

Keywords: Blue roof cover; Thermal emissivity of roof; Reflectivity of roof; Energy balance for roof

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Nomenclature

d	–	thickness, m
G	–	irradiance, W/m^2
h	–	convective heat transfer coefficient, W/m^{2}K
n	–	successive day of year
$\dot{q}$	–	density of energy flux, W/m^2
r	–	reflectivity
t	–	temperature, °C
T	–	absolute temperature, K
U	–	overall heat transfer coefficient, W/m^{2}K

Greek symbols

δ	–	solar declination, °
ε	–	thermal emissivity
λ	–	thermal conductivity, W/mK
σ	–	Stephan-Boltzmann constant, W/m^{2}K^4
Φ	–	latitude, °
ω	–	hour angle, °

Subscripts and superscripts

A	–	ambient
C	–	roof cover (roofing paper)
e	–	equivalent
H	–	sky (horizon)
R	–	interior
S	–	styrofoam
β	–	sun

1 Introduction

Currently, development of world energy engineering aims at reducing carbon dioxide emission, replacing fossil fuels by energy obtained from renewable energy sources, and raising energetic efficiency of devices and technological processes [1]. Buildings are a significant consumer of heat and power energy [2–7]. One of ways to reduce energy consumption in buildings is a possibility to choose the construction [8–12] or the colour as well as the structure of roofing cover [13–15]. Roofing is not a transparent body to solar radiation. Solar beams can be reflected or absorbed after their contact with the external surface of roofing. In roofing cover, the absorbed solar radiation is converted into the interior energy and then some part of this energy is emitted to the sky, some is transferred to ambient and remaining part is conducted to successive layers of roof. The right colour of the outer layer of roofing cover affects the energy flux transferred to the interior of a building, particularly if there is no insulation of the roof, or when the insulation is insufficient [12,15–21]. This problem is very important for countries with hot climate [16].

On the other hand, colour of roofing cover affects significantly the temperature of its outer surface [15,20]. This temperature is in principle higher than temperature in the environment of the building. Thus, in highly urbanized regions, heat islands occur, that is, regions with higher temperature as related to the neighbouring suburbs or rural areas. The phenomenon of heat islands affects meaningfully the local climate conditions [12,19,21–24]. In order to diminish this effect, various environment cooling technologies can be applied. Analysis of these technologies is given by, among others, Santamouris [25,26]. One of options is application of cool roofs, that is, roofs with lowered surface temperatures of roofing covers [27–29]. Materials characterized with high reflectivity of solar irradiance and with high thermal emissivity [18,21,30,31] are applied to construct the cool roofs. As Athanasopoulos and Siakavellas [32] give, structures based on bioinspired self-shape materials, create new possibilities of changing the thermal emissivity of roofing covers. In order to lower air temperature in urbanized regions, also the following solutions can be applied: cool pavements [19,23,26,30], green roofs [26,33–36] or green areas [26].

In summer, reduction of the heat burden of the building results in diminishing the cooling power of air-conditioning system, and so, in lower power consumption by this system [18,30]. On the other hand in winter, too high heat transfer through roofing to the environment can cause increase of the heat burden of the building and thus increase of power used for heating and air conditioning [18]. When the roof insulation is efficient, the influence of solar radiation on heat burden of building is lower. Effect of reflectivity and emissivity of materials used for roofing covers on their surface temperatures as well as on power demand for heating or air conditioning of buildings was analyzed by, among others, Chung *et al.* [37] for humid and for continental climate, and by Suehrcke *et al.* [15] for hot climate.

Papers [16–17,38] present the energy balance for roofing cover. In the energy balance equation, there appear parameters of roofing cover. They are usually given by producers as technical data. However, according to the present legislations in many countries, producers of roofing covers are not obliged to publish properties of their products (reflectivity and thermal emissivity). For that reason, simplified methodology to estimate thermal emissivity for roofing covers is proposed in [38].

The aim of the present paper is presentation of research results on thermal emissivity for roofing paper in blue color (as example) calculated by means of the above methodology. Initial elaboration of the results is to be found in [39].

2 Working stand

The working stand is a 'mini-house' with a flat roof. The stand is placed on south-west side of the roof of Department of Heat Engineering (DHE), West Pomeranian University of Technology in Szczecin, Poland (Fig. 1a). Walls of the stand are made of plywood with the thickness of 0.014 m. Geometrical dimensions of the 'mini-house', which is a cuboid, are as follows: height – 0.88 m, length – 1.14m, and width – 0.84 m. Inner sides of walls are insulated with 0.05 m thick panels of mineral wool (Fig. 1b). Roofing of the 'mini-house' is made of plywood covered with a layer of insulation. Two panels of styrofoam with thickness of 0.1 m are applied here as insulation. The styrofoam items are interlaced to avoid apertures and thus to prevent heat bridges. The outer side of styrofoam is covered by roofing paper under research.

The construction of 'mini-house' is placed on a styrofoam panel with the thickness of 0.01 m. The panel insulates the working stand from below. Temperatures and irradiance recorders have been placed in a metal box in order to secure them against weather conditions.

In order to measure temperatures in characteristic points of the test stand, five platinum resistance thermometers, Pt100 sensors have been applied. Sensors are connected with data collector of type APAR206 [40]. Temperature sensors have been placed as follows:

- in the middle of roofing cover (roofing paper) (t_C),
- in the middle of styrofoam surface, on the side of the roofing paper (t_{S1}),
- in the middle of styrofoam surface, on the side of the interior of the working stand (t_{S2}),
- centrally in the inner space at distance of 0.09 m from the styrofoam layer (t_R).

A sensor to measure the ambient temperature (t_A) has been additionally placed in a shelter behind the working stand. Pyrometer with sensor of type

a) b)

Figure 1: Working stand: a) view, b) interior. (Photo A. Walterowicz [39].)

CMP-3 to measure irradiance have been placed in the distance of 1,5 m from the working stand and connected to data collector of type LB-900 [41].

3 Methodology of research

In order to estimate the thermal emissivity of the roofing material, it is necessary to take measurements of the characteristic temperatures of individual mediums and to measure the irradiance of solar radiation. Ambient temperatures, temperatures of particular layers of the roofing, of the interior of the stand, and of irradiance were measured every three minutes. Next, runs of changes of these parameters in time were drawn.

In papers [16,17,38], author presents simplified steady-state model of heat transfer for roofing cover. This model neglects the energy accumulated in the roof structure. Balance of energy fluxes for this cover has the shape (Fig. 2)

$$(1-r)\,G_\beta = h_{C-A}\left(T_C - T_A\right) + \varepsilon\sigma\left(T_C^4 - T_H^4\right) + U_e\left(T_{S1} - T_R\right) \quad . \tag{1}$$

Values of thermal emissivity for the roofing paper under research were calculated from equation of energy balance

$$\varepsilon = \frac{(1-r)\,G_\beta - h_{C-A}\left(T_C - T_A\right) - U_e\left(T_{S1} - T_R\right)}{\sigma\left(T_C^4 - T_H^4\right)} \,. \tag{2}$$

Sky temperature in Eq. (2) was calculated by means of the simplified Swinbank's formula [42–45]

$$T_H = 0.0553 T_A^{1.5} \quad . \tag{3}$$

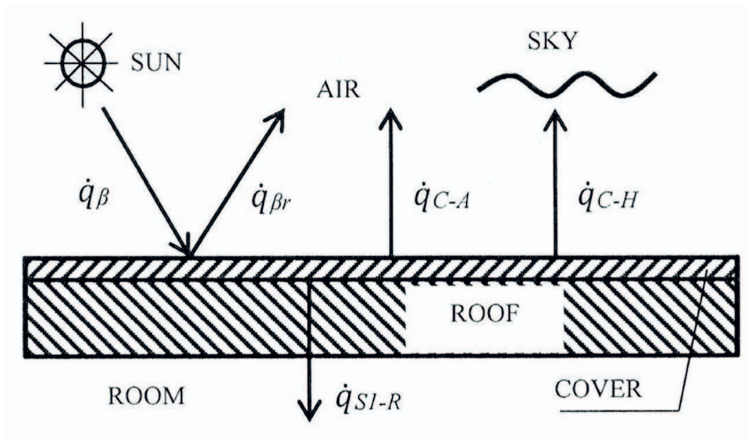

Figure 2: Energy fluxes for roof [38].

This formula is valid when the sky is cloudless. Besides, it was assumed for calculations that the values of reflectivity, convective heat transfer coefficient between atmospheric air and roofing paper, and of equivalent overall heat transfer coefficient are known. Last of the above parameters includes heat conductivity in styrofoam and heat transfer between styrofoam and air in the interior of the object. The coefficient can be determined as follows:

$$U_e = \frac{\lambda_S}{d_S} + h_{S-R} \quad . \tag{4}$$

By means of Eq. (2), thermal emissivity of roofing paper can be estimated if its reflectivity is known. In present paper, if the analysis is performed for the daytime, the reflectivity of the roofing is to be assumed. However, when the analysis is conducted for the night, when there is no solar orradiation, knowledge of this parameter will not be necessary. Besides, the irradiance from the moon and from other possible sources was neglected. At night, when solar irradiance equals zero, Eq. (2) has a simpler form:

$$\varepsilon = \frac{-h_{C-A}\left(T_C - T_A\right) - U_e\left(T_{S1} - T_R\right)}{\sigma\left(T_C^4 - T_H^4\right)} \quad ;. \tag{5}$$

In order to analyse the data separately for the daylight and for the night, it is necessary to determine the sunrise and sunset times in the site of research. Thus, the first step was to calculate the solar declinations from the relation [42]

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \qquad (6)$$

and next, hour angles of sunrise were to be determined from relation

$$\omega_{sunrise} = \arccos\left(-\tan\Phi\tan\delta\right) \quad . \qquad (7)$$

Times of sunrise and of sunset were determined from relations

$$\tau = 12.00 - \frac{|\omega_{sunrise}|}{15} \quad \text{and} \quad \tau = 12.00 - \frac{|\omega_{sunset}|}{15} \; . \qquad (8)$$

4 Results

The research was carried out between 17th and 25th of October 2017. The research were only aimed at checking the correctness of the proposed methodology for determining the thermal emissivity of the roofing material. In the present paper, research results were analyzed for the whole period of research, for the chosen days in this period, and for one characteristic night between chosen days, as well as for chosen night hours.

On the basis of carried out measurements, a run for solar irradiance changes in the period under research was drawn (Fig. 3). Next, the chart of changes of characteristic temperatures of layers of roofing and of ambient and inside air in the function of time was drawn (Fig. 4). The Figures allowed to find out if the considered days and nights were cloudless. Next these temperatures were introduced into Eqs. (2) or (5) and were used to calculate the temporary thermal emissivity values of the roofing material.

It was assumed for calculations of emissivity of roofing paper that convective heat transfer coefficient roofing paper side $h_{C-A} = 5.8$ W/m^{2}K [17]. Wind velocity was assumed 1 m/s. In case of carried out research, velocity of wind overflowing the test stand was usually very small. The building of DHE is surrounded from east, north, and west by higher buildings. Its spatial localization provides a lee for the working stand against west and north-west winds that occur most often in the premises. In turn, equivalent overall heat transfer coefficient was calculated according to Eq. (4) and $U_e = 0.18$ W/m^{2}K [17].

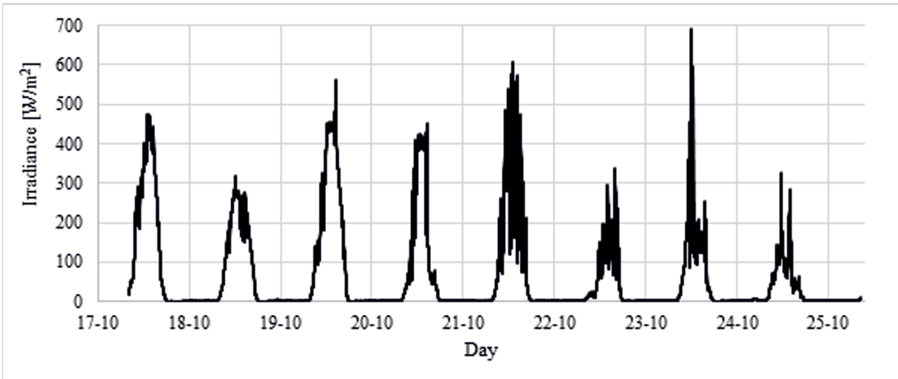

Figure 3: Irradiance in the period under research.

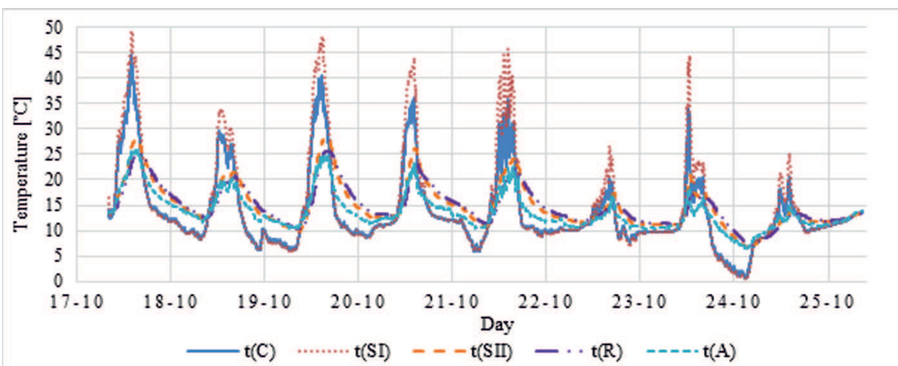

Figure 4: Changes of characteristic temperatures in the period under research.

Still, it is very difficult to estimate the reflectivity of the roofing paper under research. Value of this parameter can only be estimated on the basis of data in literature [45]. Figures 5 and 6 show values of thermal emissivity for the blue roofing paper in relation to assumed values of reflectivity equal to 0.7 and 0.8, respectively. It results from data analysis that assumed value of reflectivity for the roofing paper affects the thermal emissivity determined for the daylight. Certainly, at night, when there is no irradiance, reflectivity for roofing paper does not affect the thermal emissivity. So, as it is written in [38], the analysis of measurements data was restricted only to the night time. Still, values of thermal emissivity for blue roofing paper calculated for the night time also change in a certain range of value. The reason for changeability of this parameter can be the uncertainty of sky temperature calculated from the simplified Swinbank's formula. Swinbank's formula does not include the effect of both cloudiness and air pollution [42–43]. Thus, as it is proposed in [18], days and nights should be found in the period under research when the sky is cloudless. It can be stated on the basis of analysis of data presented in Figs. 5 and 6 that the cloudless days can be: 17 Oct., 18 Oct., and 19 Oct.. Hence, data for nights between these days should be taken into account.

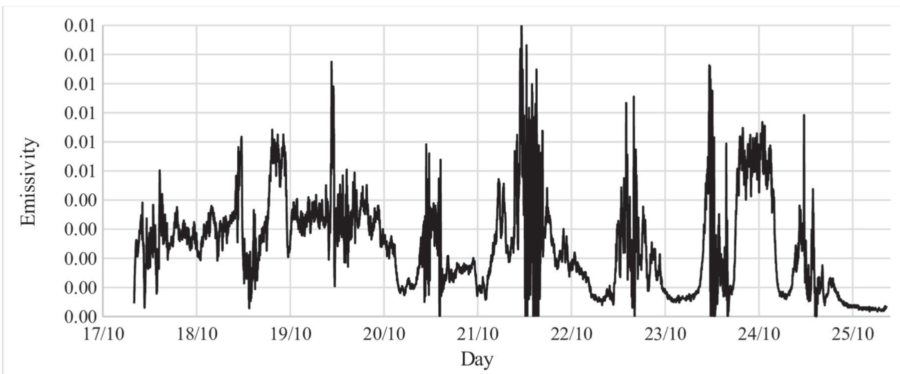

Figure 5: Temporary thermal emissivity for blue roofing paper with reflectivity 0.7.

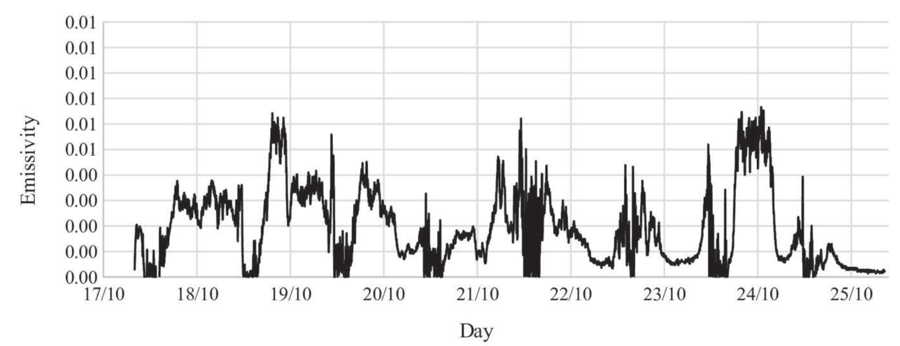

Figure 6: Temporary thermal emissivity for blue roofing paper with reflectivity 0.8.

Figures 7 and 8 present values of temperatures under research and calculated values of thermal emissivity in function of time. Certainly, on the basis of registered temperatures changes, it can be stated that there occur processes of heat transfer from the interior to the layer of roofing cover and from the ambient air to the roofing cover. It could be anticipated

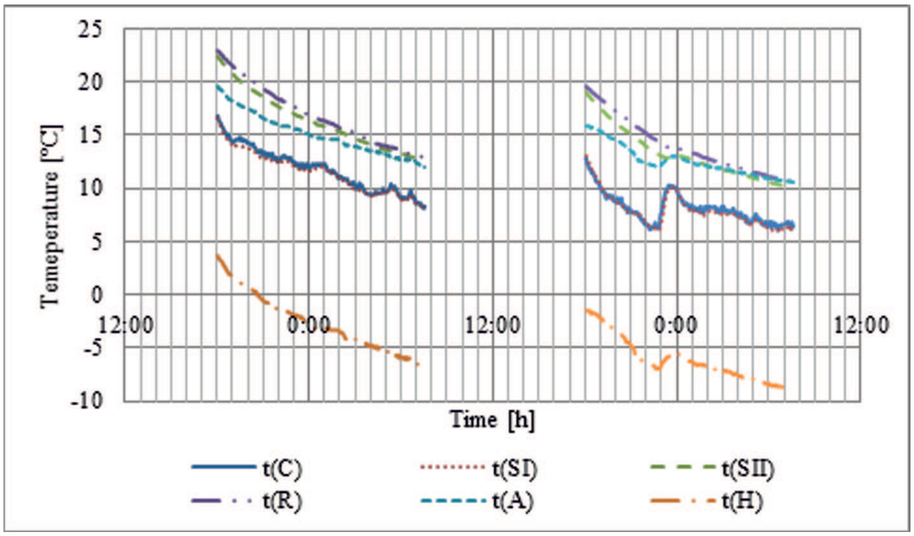

Figure 7: Distributions of characteristic temperatures at night time; nights 17/18 and 18/19 of October 2017.

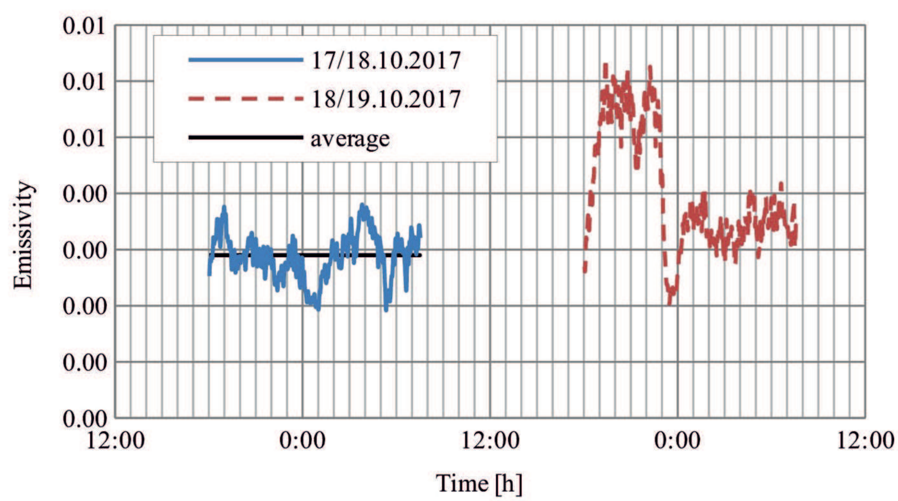

Figure 8: Temporary thermal emissivity for roofing paper; nights 17/18 and 18/19 of October 2017.

that surface temperatures of roofing paper were nearly equal on its both sides. Still, the highest gradient of temperatures was to be observed between the roofing paper and the sky. Hence, the energy flux to the sky has the highest effect on the energy balance of roofing cover. Besides, analysis of temperatures distribution at night from 18th to 19th of October 2017 (Fig. 7) allows to state that most probably rapid cloudiness occurred in the first phase of the night, which caused a high temperatures change, and in turn a wide spread of thermal emissivity values from 0.2 to 0.6. The run of changes of thermal emissivity for the roofing paper under research is much milder if it is calculated for measurements data obtained at night from 17th to 18th of October. Mean value of blue colour thermal roofing paper emissivity equals then 0.29, and boundary values of this parameter are equal 0.19 and 0.38, respectively. Thus, in order to estimate the values of thermal emissivity for roofing paper, measurements made at night time and by cloudless sky should be analysed.

5 Conclusions

The present paper proposes application of energy balance for the night time in order to calculate emissivity for the roofing cover. In this equation, only thermal emissivity of roofing paper is unknown, and its reflectivity can be neglected.

Based on performed research it can be concluded:

- proposed estimation method for thermal emissivity of roofing paper is correct when measurements are made during cloudless nights,
- thermal emissivity of blue colour roofing paper equals approx. 0.29,
- in the proposed methodology measurement of wind velocity and direction should be additionally introduced.

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