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IMPACT OF HEAT REFLECTIVE COATINGS ON HEAT FLOWS THROUGH THE VENTILATED ROOF WITH STEEL COATINGS

**Karolis Banionis[1], Edmundas Monstvilas[2], Vytautas Stankevičius[3],
Raimondas Bliūdžius[4], Kęstutis Miškinis[5]**
*Institute of Architecture and Construction of Kaunas University of Technology,
Tunelio str. 60, LT-44405 Kaunas, Lithuania
E-mails: [1]karolis.banionis@ktu.lt (corresponding author);
[2]asi_monstvilas@yahoo.com; [3]v.stankevicius@ktu.lt; [4]silfiz@asi.lt; [5]kestutis.miskinis@ktu.lt*

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Abstract. In many EU countries, the normative requirements for thermal characteristics of roofs are associated only with rating the heat losses through the roofs during the heating period. The problem of overheated premises under the lightweight ventilated roofs, covered with steel sheets, arises in the summer time. During this period of the year, because of the intensive solar radiation and high air temperature, the steel roof coatings heat up during the day and cause additional heat inflows to the premises. One of the most effective means to reduce the additional radiative heat flow from the interior surfaces of the roof coating into the attic is to install radiant barriers with low emissivity coefficient into the roof construction. The experimental research has shown that having heat reflective coatings with low emissivity coefficient ($\varepsilon = 0.09$) installed on the exterior surface of the thermal insulation layer of the ventilated roofs with steel coatings, the heat flow from the roof coating through the roof construction into the interior premises can be reduced on the daily average of 23–25% in the summer time.

Keywords: radiant barriers, heat reflective coatings, heat flow rate, ventilated roofs, steel roof coatings.

1. Introduction

The designed heat flows through the roofs are normally calculated according to the temperatures of the exterior air and interior premises (LT EN ISO 6946:2008). The heat flows in the lightweight ventilated roofs, covered with steel sheets, is determined by the temperature difference between the premises and ventilated air gap, but not between the exterior air and premises. The temperatures of the ventilated air gap and its boundary surfaces are greatly influenced by the temperature of the steel roof coating which rapidly reacts to the impacts of the exterior air temperature and solar radiation since it has a low thermal receptivity. The steel roof coating heats up under the effect of short-wave solar radiation (Miranville *et al.* 2003; Cheikh, Bouchair 2004; Šeduikytė, Paukštys 2008; Stephenson 2009; Banionis *et al.* 2011) and due to the convective heat transfers, it also heats the exterior air, passing into the ventilated air gap. Thus, the temperature of the air becomes much higher than the temperature of the exterior air. Additionally, the breather membrane and the exterior surface of the thermal insulation layer also heat up due to the convective and radiative heat transfers. For these reasons, the heat flow through the roof into the interior premises may become much greater in the summer time. In hot climate regions, heavy roof coatings (ceramic or concrete tiles) with ventilated air gaps installed underneath are widely used in order to reduce heat inflows into the premises through the roof constructions; however, in the continental or colder climate regions, steel roof coatings are very popular. Due to their small thickness and weight, the steel roof coatings are often used where the installation of other roof coatings would be complicated or even impossible.

Under the effect of solar radiation, these coatings heat up and for this reason, undesirable heat inflows into the attic emerge. In order to reduce the heating of roof coatings, caused by solar radiation, bright colors (yellow, white, etc.) should be used instead of dark ones, but the former are rarely suitable in terms of architecture and they also make dust and dirt more noticeable. Therefore, one of the most effective means to reduce the additional radiative heat flow from the interior surfaces of the roof coating into the attic is to install radiant barriers with low emissivity coefficient (Suehrcke *et al.* 2008; Medina 2000; Joudi *et al.* 2011) into the roof construction. These heat reflective coatings would not only reduce the heat inflows into the premises during the hot period of the year, but also the heat losses through the roof constructions during the cold period of the year (Al-Homoud 2005).

Although a great number of calculations, modeling and experimental research with reflective coatings have been carried out, their thermal characteristics in the lightweight ventilated roofs with steel coatings have not been sufficiently studied yet. There is a lack of information about the possible influence of the reflective coating, installed in the ventilated air gap, on the temperatures of steel roof coating, ventilated air gap and exterior surface of the thermal insulation layer as well as heat flows through the mentioned types of roof constructions.

2. Methods and materials

The long-wave radiation emissivity of the exterior and interior surfaces of the steel roof coatings, mounted on the cells, was measured using the emissiometer "MODEL AE-AD1". The emissiometer was also applied for measuring the long-wave radiation emissivity of other building materials, used for the cell roof constructions. The measured values of thermal technical indicators of the cell roof construction layers and building materials, used for mounting the layers, are presented in Table 1.

The thermal conductivity coefficient values of the building materials, used for the cells, were determined by experiments, following LST EN 12667 (Michels *et al.* 2008; LST EN 12667:2002; Stankevičius, Kairys 2005) and using a device which meets the requirements of ISO 8301: 1991 (Šadauskienė *et al.* 2009).

The temperatures of the exterior surface of the thermal insulation layer of the roof $\theta_{ins.se}$ and interior surface of the roof construction θ_{si}, and thermal transmittance of the roof construction between the exterior surface of the thermal insulation layer and interior surface of the roof construction U_{roof} should be used for the calculation of heat flow rate through the roof construction q_{roof}.

The heat flow rate from the exterior surface of the thermal insulation layer to the interior surface of the roof construction and vice versa may be calculated using the following equation (EN ISO 13791:2004):

$$q_{roof} = U_{roof} \cdot (\theta_{ins.se} - \theta_{si}), \qquad (1)$$

where: q_{roof} is heat flow, W/m^2; U_{roof} is thermal transmittance coefficient, W/(m^2·K); $\theta_{ins.se}$ is temperature of the exterior surface of the thermal insulation layer, °C; θ_{si} is temperature of the interior surface of the roof construction, °C.

While planning the course of the experimentation, it was determined that the temperature of the ventilated steel roof coatings may be affected not only by the climatic impact, but also by the radiative heat exchange between the coating and the external surface of the thermal insulation layer of the roof. Aiming at the reduction of heat inflows into the premises through the mentioned types of roofs during the hot season of the year, the external layers of the thermal insulation of the roof could be equipped with heat reflective coatings with small emissivity, heat receptive layers made of building materials, layers with heat reflective coatings or more than one ventilated air gap, separated by a heat reflective coating, in the ventilated roof construction.

3. Experimental

In order to estimate the changes of heat flow from the ventilated air gaps of the lightweight ventilated roofs with steel coatings to the attic and vice versa, two experimental cells of identical construction and equal thermal characteristics, S1 and S2 were prepared (Fig. 1). The experiments were performed under real climatic conditions, that the climatic effect was different for every experiment. If a single experimental cell had been used for the research, the comparison of the results, obtained at different times, would have been complicated. For this reason, two experimental cells of identical construction were assembled. The construction of cell S1 was not altered during the whole experimental period, whereas the construction of cell S2 was preserved the same during the first experimental stage (Fig. 2) and changed during the others:

- Exp. 2 – 0.25 mm thick heat reflective coating was mounted above the breather membrane in cell S2;

Table 1. Values of thermal technical indicators of the cell roof construction layers and building materials, used for mounting the layers

Cell roof construction layer or building material, used for mounting the layer	Thickness, mm	Thermal conductivity coefficient, W/(m·K)	Solar radiation absorption coefficient ^{3}	Long-wave radiation emissivity coefficient
Steel roof coating	0.55	50		
a) exterior surface			0.7	0.88
b) interior surface			0.4	0.77
Ventilated air gap	50	–	–	–
Breather membrane tightly pressed to one of the surfaces of the building material	0.6	0.02*	0.5	0.69
Breather membrane between two layers of the building material	0.6	0.04*	0.5	0.69
Cement-sawdust board ^{1}	14	0.213	0.7	0.74
Heat reflective coating ^{2}	0.25	–	0.2	0.09
Mineral wool	200	0.034	–	–
Polythene film	0.2	0.04*	–	–
Chipboard	10	0.13	–	–

Note: ^{1} – used during 3 and 4 experimental research; ^{2} – used during 2, 3 and 5 experimental research; ^{3} – Prado and Ferreira (2005), Suehrcke *et al.* (2008); * – thermal resistance of thin layers, m²·K/W (STR 2.05.01:2005; EN ISO 6946:2008).

- Exp. 3 – 14 mm thick cement-sawdust board with a heat reflective coating, affixed to its exterior surface, was mounted above the breather membrane in cell S2;
- Exp. 4 – 14 mm thick cement-sawdust board was mounted above the breather membrane in cell S2;
- Exp. 5 – two ventilated air gaps, separated by a heat reflective coating with two heat reflective surfaces, were mounted above the breather membrane in cell S2.

Fig. 1. Experimental cells S1 and S2

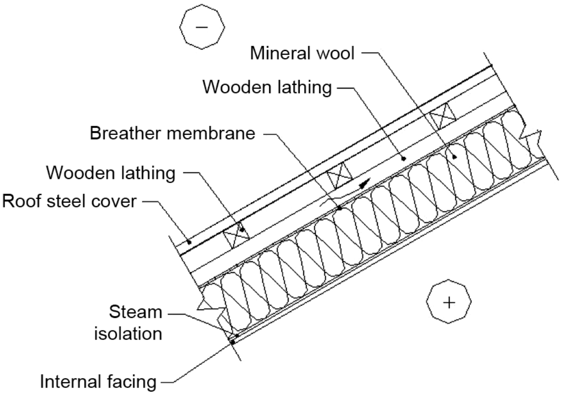

Fig. 2. Lightweight steel roof construction of experimental cell S1

Thermal transmittance coefficients of cell walls was $U_{wall} = 0.18$ W/(m^2·K), cells floor $U_{floor} = 0.18$ W/(m^2·K) and cells roof $U_{roof} = 0.16$ W/(m^2·K). Profiled dark brown color steel leafs were used as a waterproofing roof coating and a 0.6 mm thick membrane, non-conductive for air, functioned as a vapour-conductive wind proofing insulation (hereinafter "breather membrane"). The roof construction was insulated using 200 mm of mineral wool board, while 10 mm thick chipboard was used for its internal layer. In order to maximally reduce the exterior air infiltration into the inside of the cells, the junctions of the premises and their separate layers were made airtight in both cells. Thermal insulation layers of walls and floor were made from 200 mm of expanded polystyrene foam panels. The orientation of roof surfaces of both cells was identical: south direction and dimensions where 1.90 × 1.50 × 0.05 m (length × width × air gap height). Since the analysis of the solar radiation influence on the surfaces of different orientation has shown that in a twenty-four hour period, it affects the horizontal surfaces the most, a near-horizontal lean angle of the cells roofs was selected, i.e. only 2° towards horizontal projection.

In cell roof constructions, the thermocouples were installed on the internal surface of the roof, in the middle of the ventilated air gap of the roof, on the external surface of the breather membrane, on the junction of the chipboard and polyethylene film, and on the internal surface of the chipboard. Additionally, on the internal surface of the roof of each cell, two heat flow rate sensors for measuring heat flow rate through the roof construction were mounted. Fig. 2 presents the principle scheme of the cell roof constructions.

Heat exchange processes, taking place in the roof constructions, are influenced by various climatic parameters. These parameters were registered using a weather station "Davis Vantage Pro2 6162C", set up near the cells; it measured and recorded the following climatic parameters:

- intensity of diffuse solar radiation heat flow rate, W/m²;
- intensity of total solar radiation heat flow rate, W/m²;
- intensity of long-wave radiation from sky to surface, W/m²;
- intensity of balanced long-wave radiation between sky and surface, W/m²;
- external air temperature, ºC;
- relative humidity of the external air, %;
- atmospheric pressure, hPa;
- wind speed, m/s;
- wind direction, º;
- rain rate, mm.

The first experimental research was performed on the last day of June, whereas the other experiments were carried out in July when the average monthly air temperature is the highest. The experiments were performed in Kaunas, Lithuania where in July, the average daily amplitude of the exterior air temperature is 10.2 °C, and the maximum daily amplitude of the exterior air temperature is 18.7 °C.

4. Results and discussion

The measurement results, obtained during the experimental research, show that when the exterior surface of the thermal insulation layer is separated from the ventilated air gap by a breather membrane, the temperature of the exterior surface of the thermal insulation layer rises significantly and may exceed the exterior air temperature up to 35 ºC due to the great influence of the radiative heat exchange between the boundary surfaces of the ventilated air gap (Fig. 3a). The changes, introduced to the roof construction of cell S2, did not make a great impact on the temperatures of the roof coating and ventilated air gap, but its influence on the external surface of the thermal insulation layer was considerable.

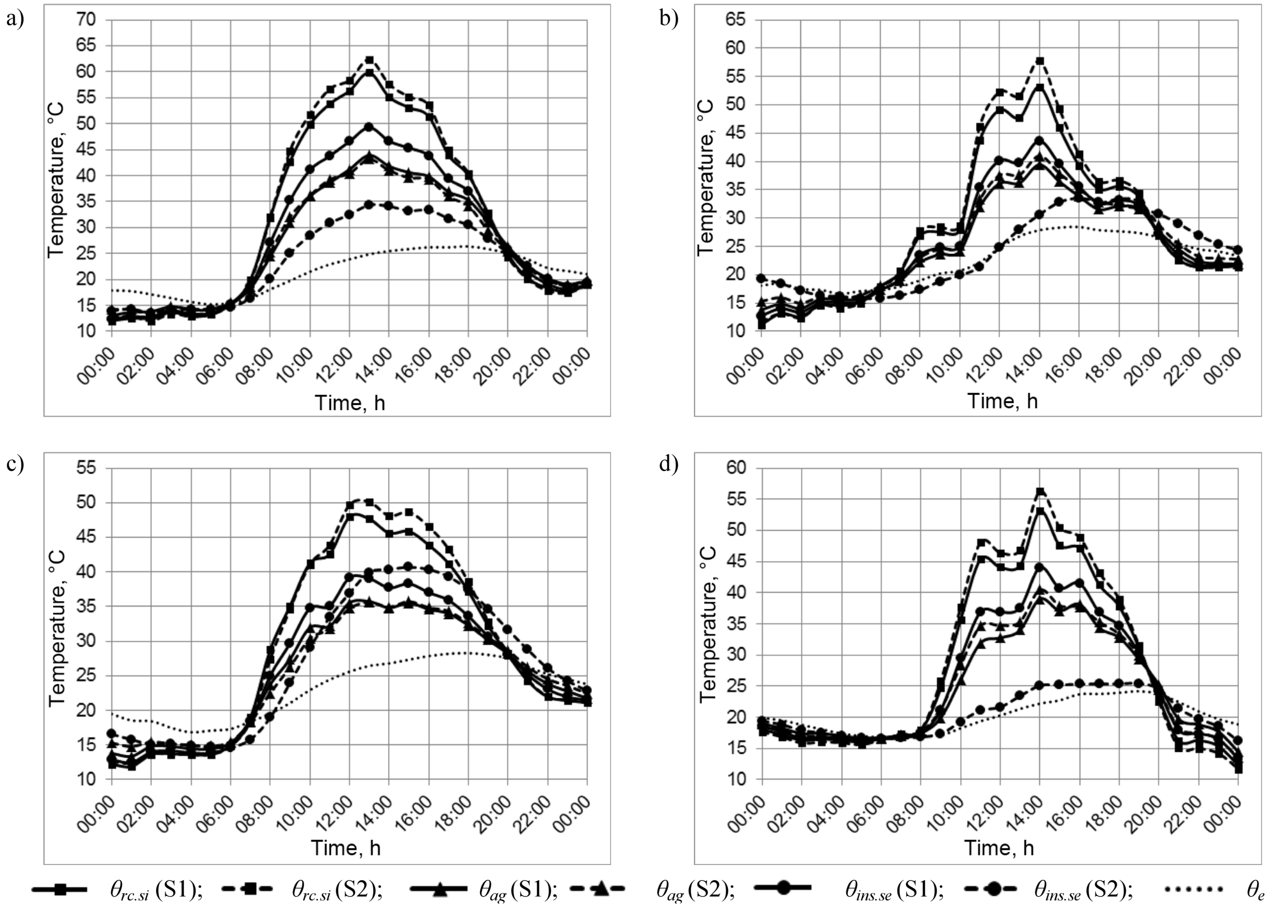

Fig. 3. Temperature variation of the roof coating $\theta_{rc.si}$, ventilated air gap of the roof θ_{ag}, external surface of the thermal insulation layer $\theta_{ins.se}$ and exterior air θ_e during different experiments: a) Exp. 2; b) Exp. 3; c) Exp. 4; d) Exp. 5

The measurement results, presented in Table 2, show that during different experimental stages, the average daily temperature of the exterior surface of the thermal insulation layer was higher than the average daily exterior air temperature (from 0.3 to 7.3 °C), and during the day (daylight hours), the average temperature of the exterior surface of the thermal insulation layer was also higher than the exterior air temperature (from 1.0 °C to 11.5 °C). During the night time hours, the average temperature of the exterior surface of the thermal insulation layer was lower than the average exterior air temperature (from −0.4 °C to 3.4 °C). The negative value suggests that during the night, the average temperature of the exterior surface of the thermal insulation layer was higher than the average exterior air temperature during the third experiment, differently from all the other experiments.

Constructional changes, introduced into the roof of cell S2 during the experimental research No. 2, 3, 4 and 5, significantly influenced the temperature of the exterior surface of the thermal insulation layer, which made an impact on the heat flow rate through the roof construction. During the experiment No. 2, after mounting a heat reflective coating on the breather membrane, the average daily heat flow rate through the roof construction diminished by 23.2%. In contrast, having a heat receptive layer, made of cement-sawdust board and covered with a heat reflecting coating, installed during the experiment No. 3, the daily heat flow rate dropped on the average of only 3.9%. Moreover, during the experimental research No.4, the daily heat flow rate through the roof construction of cell S2 was lower on the average of only 1.7%, whereas during the experiment No. 5, the average daily heat flow rate diminished by 22% after installing two ventilated air gaps, separated by a heat reflective coating (Fig. 4).

The analysis of the values, obtained during daylight hours and presented in Fig. 5, suggests that the heat flow rate through the roof construction of cell S2 diminished during the experiment No. 2 and No. 5 by 24.4% and 29.4% respectively. Meanwhile, during the experiment

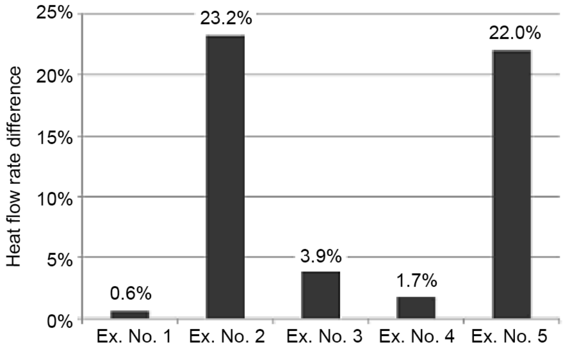

Fig. 4. Average heat flow rate differences through the cell roof constructions during twenty-four hours

Table 2. Average temperatures of the exterior air and exterior surfaces of the thermal insulation layers of the roof during the day, night and twenty-four hours, measured during the experimental research

Parameters	Cell No. 1 (“S1“)			Cell No. 2 (“S2“)		
	24 hours	Daylight hours	Night time hours	24 hours	Daylight hours	Night time hours
Exp. No. 1						
Exterior air temperature, °C	22.5	23.4	20.0	22.5	23.4	20.0
Temperature of external surface of the roof thermal insulation; °C	27.1	30.8	17.5	26.9	30.5	17.6
Exp. No. 2						
Exterior air temperature, °C	21.5	22.5	18.8	21.5	22.5	18.8
Temperature of external surface of the roof thermal insulation; °C	28.8	34.0	15.6	23.7	26.6	16.2
Exp. No. 3						
Exterior air temperature, °C	22.8	24.0	20.1	22.8	24.0	20.1
Temperature of external surface of the roof thermal insulation; °C	26.2	30.1	17.4	24.0	25.5	20.5
Exp. No. 4						
Exterior air temperature, °C	23.3	24.4	20.5	23.3	24.4	20.5
Temperature of external surface of the roof thermal insulation; °C	26.5	30.7	17.1	27.2	30.9	18.9
Exp. No. 5						
Exterior air temperature, °C	20.2	20.8	19.0	20.2	20.8	19.0
Temperature of external surface of the roof thermal insulation; °C	25.6	30.2	16.4	20.5	21.8	17.9

No. 3, the average value of heat flow rate decreased by 8.1%. The results indicate that heat reflective coatings substantially reduce the heat flows from the roof coating into the breather membrane and later through the roof construction into the interior premises. However, if the heat reflective coating is mounted on the heat receptive building materials, in this case on the cement-sawdust board, the reduction of heat flow rate during daylight hours is three times lesser than in the construction with only heat reflective coatings.

Differently from all the other experimental research, the average heat flow rate through the roof construction of cell S2 during daylight hours increased by 2% during the experiment No. 4.

At night time, the average heat flow rate through the roof construction of cell S2 diminished by 16.3%, 16.5% and 2.2% during the experiments No. 2, 4 and 5 respectively. During the experiment No. 3, in comparison to the other experiments, the rate was higher even by 5.9% than the rate of cell S1 (Fig. 6).

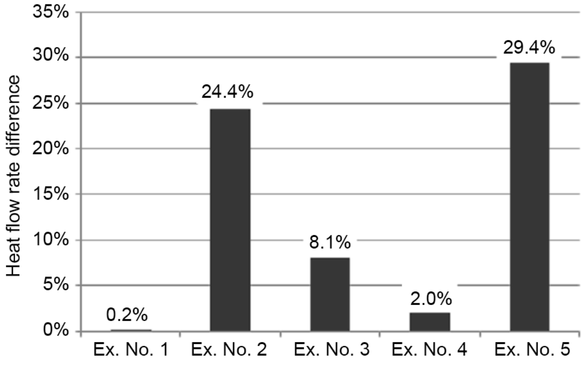

Fig. 5. Average heat flow rate differences through the cell roof constructions during daylight hours

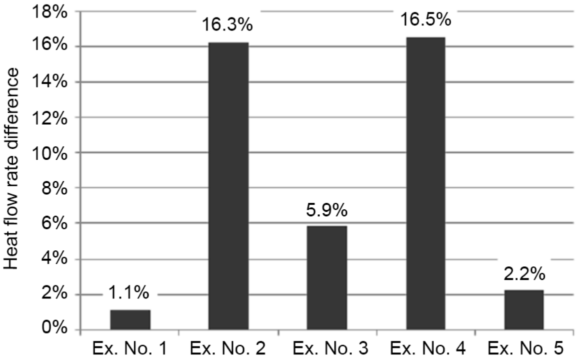

Fig. 6. Average heat flow rate differences through the cell roof constructions during night time hours

Judging from the measurement experience, the indications of heat flow meters are not reliable when the heat exchange processes in the envelopes are non-stationary. In such case, different temperature gradients form in the layers of the envelopes and their values constantly change. The measured heat flow values depend on which layer of the envelope the heat flow sensor is placed. For this reason, the European Standards do not regulate the measurement of heat flows through the envelopes and their thermal resistance under realistic conditions of envelope exploitation. Thus, the data on heat flow measurements cannot function as a reference point for the assessment of the accuracy of calculation methodologies, presented in this paper. However, these data may be applied for the analysis of the experimental peculiarities of thermal characteristics variation of the cell roofs, depending on the type of roof construction. As has been stated, the roof construction of cell S1 was not altered during all experiments, while the construction of cell S2 was

Table 3. Measured and calculated average daily heat flow rate through the cell roof constructions

Experimental stage	Average daily heat flow rate, measured in cells S1 and S2, W/m²		Absolute difference between the heat flow rate, measured in cells S1 and S2, W/m²	SP$_1$, %	Calculated average daily heat flow rate in cells S1 and S2, W/m²		Absolute difference between the calculated heat flow rate in cells S1 and S2, W/m²	SP$_2$, %
	S1	S2	S1	S2	S1	S2	S1	S2
Experiment No. 1	3.50	3.48	−0.02	−0.6	2.79	2.75	−0.04	−1.4
Experiment No. 2	3.36	2.58	−0.78	−23.2	2.99	2.20	−0.79	−26.4
Experiment No. 3	3.11	2.99	−0.12	−3.9	2.61	2.27	−0.34	−13.0
Experiment No. 4	3.51	3.45	−0.06	−1.7	2.63	2.76	−0.13	−4.7
Experiment No. 5	3.14	2.45	−0.69	−22.0	2.54	1.76	−0.78	−27.6

Note: SP$_1$ – relative difference between the heat flow rate, measured in cells S2 and S1; SP$_2$ – relative difference between the calculated heat flow rate in cells S2 and S1.

changed during different experimental stages. The variation of thermal characteristics of the roofs, depending on the peculiarities of cell roof construction, was relatively evaluated by comparing the heat flow measurement data of cell S2 with those of cell S1. The same analysis was carried out using the data on the calculation of the heat flows through the roofs of the cells; the comparison data are presented in Table 3.

The data, given in Table 3, implies that the absolute and relative variation of heat flow rate of cell S2, calculated using the measurement and calculation data of heat flow rate through the roof constructions of the cells, gathered during all experiments, are very close to those of cell S1. The relative differences between the measured heat flow rates of cells S2 and S1 are given in Fig. 7.

The results, presented in Fig. 7, suggest that greater mismatches of the calculation and measurement results were determined during the experiment No. 3 when the relative differences constituted 3.9% and 13.0%.

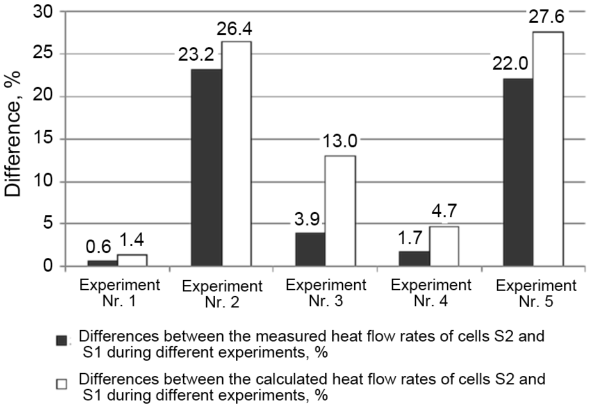

Fig. 7. Relative differences between the measured and calculated heat flow rates of cells S2 and S1 during different experiments

5. Conclusions

1. The experimental research determined that a heat reflective coating (ε = 0.09), installed above the thermal insulation layer in the steel roofs with one ventilated air gap, reduces the average daily heat flow rate through the roof into the premises by 23–25% during the summer time, in comparison to the heat flow rate through the usual ventilated roof constructions.

2. A heat reflective coating, installed above the thermal insulation layer in the steel roofs with one ventilated air gap, reduces the average heat flow rate through the roof into the premises by about 24% during daylight hours in summer, whereas a heat reflective coating, mounted between two ventilated air gaps of the roof, diminishes the heat flow rate by almost one-third. That is, introducing heat reflective covers into the ventilated roof constructions set the basis for a considerable reduction of the undesirable heat flows into the premises during the hot period of the year.

3. A layer of heavy building material (in this case, a 14 mm thick cement-sawdust board) with a heat reflective coating, mounted on the exterior surface of the thermal insulation layer in the steel roofs with one ventilated air gap, reduces the average daily heat flow rate through the roof into the premises only by 4%, while at night time, this rate increases by about 6%, comparing to the usual roof construction.

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Karolis BANIONIS. Doctor, Researcher at the Laboratory of Thermal Building Physics of the institute of Architecture and Construction, KTU. Research interests: heat transfer and thermal insulation, thermal impacts of solar radiation, determination of air permeability of buildings.

Edmundas MONSTVILAS. Doctor, Senior Researcher at the Laboratory of Thermal Building Physics of the institute of Architecture and Construction, KTU. Research interests: heat transfer and thermal insulation, technical properties of thermal insulation products.

Vytautas STANKEVIČIUS. Doctor Habil., Full Professor, Chief Researcher at the Laboratory of Thermal Building Physics of the institute of Architecture and Construction, KTU. Research interests: heat transfer, technical properties of thermal insulation products.

Raimondas BLIŪDŽIUS. Doctor, Full Professor, head of Laboratory of Thermal Building Physics at the Institute of Architecture and Construction, KTU. Research interests: thermal processes in building, thermal properties of building materials and elements.

Kęstutis MIŠKINIS. Doctor, Researcher at the Laboratory of Thermal Building Physics of the institute of Architecture and Construction, KTU. Research interests: heat transfer and thermal insulation, acoustics.