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THE EFFECT OF VERTICAL AIR GAPS TO THERMAL TRANSMITTANCE OF HORIZONTAL THERMAL INSULATING LAYER

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Abstract. In order to reduce the amounts of work at the construction site, single-ply dual density thermal insulating roofing boards are used with increasing frequency for thermal insulation of flat roofs. In this case, the joints between boards are not overlapped by the other ply over it; therefore gaps of varying width form between the sides of the boards through the entire thickness of the insulating layer, whose effect on the effective thermal conductivity of the thermal insulating layer must be evaluated. The aim of this project was to assess the reliability of standard method, used to determine the impact of such air gaps on the effective thermal conductivity of the thermal insulating layer by comparing the results of calculations and the results of measurements of thermal conductivity, also to determine the correction factors for thermal transmittance of horizontal thermal insulation layers due to the forming vertical air gaps between the single-ply mineral wool boards. After measurements of thermal resistances of 50 mm thick thermal insulation board with the air gaps which width varied from 3 mm to 20 mm, it was determined that the thermal conductivity value of the air gaps increases with the increment of the width of air gaps. After completion the experimental measurements of thermal conductivity it was determined that the height of closed and unventilated or partly ventilated air gaps has no effect on the properties of effective thermal conductivity of the thermal insulation layer when the air gap width is up to 5 mm. When wider unventilated or partly ventilated air gaps occur, the effective thermal conductivity coefficient increases proportionally as the height of the air gaps increases. Calculated according to the standard method the affix to the thermal transmittance is overly general and not always appropriate. In some cases it is 6 times higher or 4 times lower than the measured one. In this paper a method to evaluate the effects of air gaps by the use of correction factor to the thermal transmittance of the horizontal thermal insulating layer is proposed.

Keywords: air gap, dual density thermal insulating board, thermal conductivity, thermal transmittance.

1. Introduction

Dual density thermal insulating boards are produced in factory and consist from two connected different density layers. The use of these boards allow to reduce the time, cost and amount of works, when insulating flat roofs. Dual density single ply thermal insulating boards are used instead of two-ply joint overlaying thermal insulation layer (Buska and Mačiulaitis 2007). Due to deviation of dual density single-ply board measurements, vertical air gaps may form at the joints of it. The results of the performed experiments (Endriukaitytė *et al*. 2003) reveal, that when air gaps form in the walls of buildings, thermal convection takes place in them, therefore the effective thermal conductivity of the thermal insulation layer increases (Manik *et al*. 2008). Depending on the method of laying the rock wool boards on flat roofs, the formed air gaps might be long and blown through by wind. For this reason, the effect of air gaps on the effective thermal conductivity of the thermal insulation layer must be evaluated.

Results of experiments on the influence of air gaps on the thermal properties of walls are presented in sources (Chebil *et al.* 2003; Bankvall and Sikander 2008; Qin *et al*. 2009; Šeduikytė and Paukštys 2008; Šadauskienė *et al*. 2009). However, there are no data about the evaluation of the influence of vertical air gaps on the thermal transmittance of the roof, when they are formed in thermal insulation layer laid horizontally on a flat roof. The Standard EN ISO 6946:1997 gives a method of calculating the thermal resistance of air gaps forming in buildings' components, when the thickness of the thermal insulation material is not higher than 50 mm. However, the requirements to thermal resistances presented in building technical regulation STR 2.05.01:2005 are stronger; therefore a thermal insulation layer of 50 mm is not sufficient to comply with them. The thermal insulation layers of flat roofs of new and existing buildings have to be thicker. Therefore, a need arose to determine whether the standard (EN ISO 6946:1997) method of calculation is suitable for calculating the thermal resis-

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tance of air gaps, when the thickness of the thermal insulation layer is 100 mm, 150 mm or 200 mm.

As mentioned above, the aim of this project was to determine the reliability of the calculation method, presented in the standard (EN ISO 6946:1997), used for calculating the influence of air gaps on thermal resistance of horizontally laid thermal insulation layers, compare these results with the measurements of thermal conductivities and to determine the corrections to thermal transmittance value of horizontally laid thermal insulation, which is enlarged due to the formed air gaps.

2. The potential of forming vertical air gaps in the joints between horizontally laid thermal insulation boards

Dual density rock wool boards for insulation of flat roofs with the dimensions of 2000 mm × 600 mm have been selected for testing. The highest allowed deviations of the board dimensions were determined according to the EN 13162:2000:

- the allowed deviation of length is ±2% or up to ±40 mm;
- the allowed deviation of width is ±1.5% or up to ±9 mm;
- the allowed deviation from squareness according to the width and length is up to 5 mm/m.

The width and length of the boards were measured with the precision of 1 mm, according to the requirements of EN 822:1997, and the squareness with the precision of 0.5 mm, rounding to 1 mm/m, according to the requirements of EN 824:1998.

After measuring the boards used for testing, these average deviations were determined:

- deviation of length up to ±20 mm;
- deviation of width up to ±5 mm;
- deviation from squareness according to width and length 3 mm/m.

The results show that the measured average deviations of the dimensions of thermal insulation boards are lower than the highest allowed deviations indicated in the standard (EN 13162:2000). The width of vertical air gaps, forming in the thermal insulation layer between these boards was up to 5 mm. In such gaps air is capable of moving due to convection and influence of infiltration (Valančius *et al.* 2006). To prevent forming long air gaps blown through by wind, it is necessary to ensure the integrity of this layer and it is recommended to lay down the thermal insulation boards by overlapping their joints (Fig. 1).

After covering a rectangular area with dual density boards, the ratio of the joints in connections between the thermal insulation boards to the unit area of the thermal insulation layer has been determined. The area in Fig. 1 marked with the dotted line has the dimensions of 4000 x 1800 mm, i.e. 7.2 m^2. In this area, the total length of joints between the thermal insulation boards is: 4 m × 3 + 1.8 m × 2 = 15.6 m. Therefore, in one square metre of thermal insulation layer installed like this, the length of joints would be 15.6 / 7.2 = 2.167 m/m^2.

According to the highest allowed deviations for board dimensions, the highest theoretical combinations of air gaps, which can form in the thermal insulation layer, have been determined:

- at the short 600 mm long edges:
  - triangular 0÷6 mm wide air gaps, whose resultant gap width is 3 mm. It is assumed that such gaps make up to half of the total number of gaps;
  - other gaps are assumed to be 1.3 mm wide.
- at the 2000 mm long edges:
  - the biggest triangular 0÷18 mm wide air gaps, whose resultant gap width is 9 mm. It is assumed that such gaps make up to one third of the total number;
  - the biggest rectangular 18 mm wide air gaps. It is assumed that such gaps make up to one third of the gaps;
  - the remaining part is gap-free joints, which make up the remaining one third of the total.

Based on these assumptions, in the analysed 7.2 m^2 area next to the short edges 1.8 m length by 3 mm width and 1.8 m length by 1.3 mm width vertical air gaps will form; next to the long edges 4 m length by 9 mm width, 4 m length by 18 mm width gaps and 4 m length gap-free joints will form. These data, when recalculated for the thermal insulation layer area of 1 m^2, become:

- 1.3 mm wide gaps' length is 0.25 m, area 0.000325 m^2;
- 3 mm wide gaps' length is 0.25 m, area 0.00075 m^2;
- 9 mm wide gaps' length is 0.556 m, area 0.005 m^2;
- 18 mm wide gaps' length is 0.556 m, area 0.01 m^2.

According to the measured deviations of dimensions of the tested boards, practical combinations of air gaps, which can form in the thermal insulation layer, were determined:

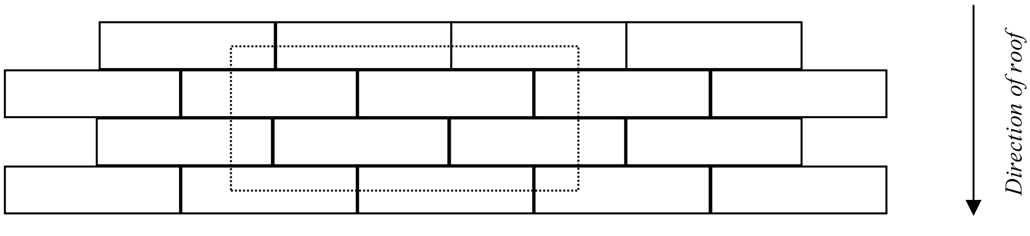

Fig. 1. Laying of 2000 × 600 mm magnitude roofing thermal insulating boards by overlapping joints

- at the short 600 mm long edges:
  - biggest triangular 0÷6 mm wide air gaps, whose resultant gap width is 3 mm. It is assumed that such gaps make up to half of the total number of gaps;
  - the other half of the joints are assumed to be gap-free;
- at the long 2000 mm long edges:
  - the biggest triangular 0÷6 mm wide air gaps, whose resultant gap width is 3 mm. It is assumed that such gaps make up to one third of the total number of gaps;
  - the biggest rectangular 5 mm wide air gaps. It is assumed that such gaps make up to one third of the total number of gaps;
  - the remaining part is gap-free joints, which makes up to the remaining one third of the total.

Based on these assumptions, in the marked (Fig. 1) 7.2 m^2 area next to the short edges 1.8 m length by 3 mm width and 1.8 m length gap-free joints will form; next to the long edges, 4 m length by 3 mm width, 4 m length by 5 mm width gaps and 4 m length gap-free joints can be formed. These data, when recalculated for the thermal insulation layer area of 1 m^2, become:

- 3 mm wide gaps' length is 0.806 m, area 0.0024167 m^2;
- 5 mm wide gaps' length is 0.556 m, area 0.0027778 m^2.

3. Calculation of thermal resistance of vertical air gaps formed in horizontal thermal insulation layer

After determining the forming possible air gaps in the joints between the thermal insulation boards, the thermal resistance of vertical air gaps in 50 mm thick thermal insulation layer was calculated, when the width of air gaps is 3 mm, 5 mm, 7 mm, 9 mm, 12 mm, 15 mm, 18 mm and 20 mm. The calculations were done according to the formula (1) presented in EN ISO 6946:1997:

$$R_g = \frac{1}{h_a + 1/2 \cdot E \cdot h_{ro}(1 + \sqrt{1 + d^2/b^2} - d/b}, \quad (1)$$

here: R_g – thermal resistance of the air gap, (m^2·K)/W; d – the height of the air gap, mm; b – the width of the air gap, mm; h_a – surface coefficient of heat transfer by conduction and convection. When the heat flows upwards, it is higher than 1.95 W/(m^2·K) and 0.025/d W/(m^2·K) (EN ISO 6946:1997); E – the radiative thermal transmittance between surfaces, calculated by the formula (2):

$$E = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}, \quad (2)$$

here: ε_1 and ε_2 – the thermal emissivities of surfaces bordering the air gap; h_{ro} – the surface coefficient of heat transfer by radiation of black body, equal to 5.1 W/(m^2·K) for a surface with the temperature of 10 °C (EN ISO 6946:1997).

When calculating, it is assumed that $h_a \approx 2.0$ (EN ISO 6946:1997) and $\varepsilon_1 = \varepsilon_2 \approx 0.8$.

The calculation results of thermal properties of vertical air gaps forming in horizontal thermal insulation layers in Table 1 show, that the value of the thermal conductivity of vertical air gaps increases, when the width of the air gap increases. However, in this case, the height of the air gaps is not taken into account (it is constant at all times, i.e. 50 mm). In order to evaluate the thermal properties of the roof construction, when the thermal insulation layer is thicker than 50 mm, the method of calculation presented in the standard is not appropriate.

4. Experimental measurements

In order to determine the influence of the height of the air gap on the thermal conductivity of the thermal insulation layer, experimental measurements were performed.

The thermal conductivities of the vertical air gaps in horizontal thermal insulation layers were measured with a thermal conductivity measurement apparatus according to ISO 8301:1991, which has the central measuring part with the area of 250 × 250 mm, the temperature gradient through a specimen approximately 20 °C, the temperature of the horizontal hot bottom plate 20 °C, the temperature of the horizontal cold top plate approximately 0 °C, the direction of the heat flow is vertical, going upwards.

The thermal conductivities of vertical air gaps are determined in this order:

- the thermal conductivity of the studied thermal insulation board is measured;
- three parallel 200 mm long air gaps are cut at 60 mm distances between them in the central part of the specimen – to measure extremely narrow air gaps (Fig. 2); two parallel 200 mm long air gaps, distanced at 200 mm or 150 mm away from each other, to measure gaps wider than 5 mm;
- the thermal conductivity coefficients of the samples with air gaps of various widths are measured.

Table 1. The results of calculations of the thermal properties of vertical air gaps, forming in horizontal thermal insulation layer, according to EN ISO 6946

The height of the vertical air gap d, mm	The width of the vertical air gap b, mm	The thermal resistance of the vertical air gap R_g, m^2·K/W	The thermal conductivity of the vertical air gap λ_g, W/(m·K)
50	3	0.26660	0.18755
50	5	0.26422	0.18924
50	7	0.26189	0.19092
50	9	0.25962	0.19259
50	12	0.25634	0.19506
50	15	0.25320	0.19748
50	18	0.25021	0.19983
50	20	0.24830	0.20137

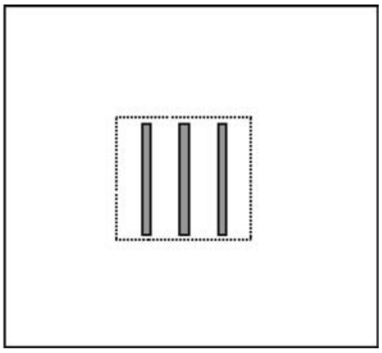

Fig. 2. The positioning of air gaps in thermal insulation specimen board, used to determine the thermal conductivities of vertical air gaps

The thermal conductivity of unventilated vertical air gap is calculated by formula (3):

$$\lambda_o = \frac{\lambda \cdot A - \lambda_m \cdot A_m}{A_o}, \quad (3)$$

here: λ – the thermal conductivity of the specimen with air gaps, W/(m·K); A – the central measuring area of the measuring apparatus, m^2; λ_m – the thermal conductivity of the material of the specimen, when measured without air gaps, W/(m·K); A_m – the area of material of the specimen, equal to A-A_o, m^2; A_o – the total area of air gaps, m^2.

The measurements in Fig. 3 show, that the values of thermal conductivity of closed unventilated air gaps, with width from 1.3 mm to 5 mm and height from 50 mm to 250 mm, are similar. When the values of the air gaps width and height become bigger, the value of the thermal conductivity increases proportionally. It shows that the influence of air gaps up to 5 mm in width and 250 mm in height on the thermal conductivity of the thermal insulation layer is insignificant. Vertical air gaps of this size do not have significant influence on the building's heat losses through the roof. However, the influence of wider vertical air gaps must be evaluated by calculating effective thermal resistance of the thermal insulation layer.

Comparing the values of thermal conductivity of 50 mm high air gaps, calculated according to the standard (EN ISO 6946:1997) with the coefficient values of the thermal conductivity of air gaps of the same size determined by the experiment (Table 2), major differences were found. The difference between the results of calculations and measurements is the lowest, when the width of the vertical air gap is 12 mm. Where the air gaps are narrower, the measured thermal conductivity values are lower than the calculated, and when they are wider than 12 mm, these measured values are higher. This shows that the calculation method presented in the standard (EN ISO 6946:1997) is not accurate.

Table 2. The comparison of calculated according to the standard (EN ISO 6946:1997) thermal conductivity values of 50 mm height vertical air gaps with the thermal conductivity of the same height, determined by experiment

The width of the vertical air gap b, mm	Calculated λ_g, W/(m·K)	Measured λ, W/(m·K)
3	0.18755	0.07033
5	0.18924	0.09959
7	0.19092	0.15615
9	0.19259	0.16725
12	0.19506	0.19477
15	0.19748	0.21774
18	0.19983	0.21378
20	0.20137	0.21649

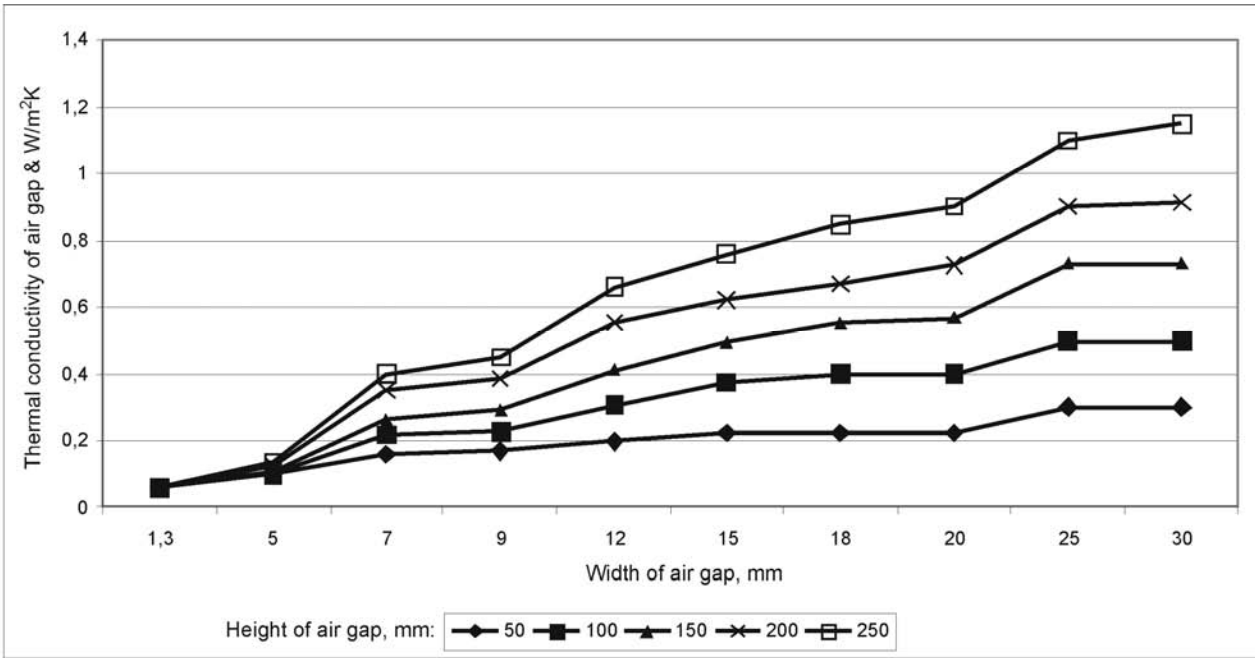

Fig. 3. The measured thermal conductivity values of vertical gaps of various widths and lengths

5. The corrections to thermal transmittance to evaluate the influence of vertical air gaps

According to standard (EN ISO 6946:1997), the correction $\Delta U'' = 0.01$ W/(m^2·K) to the thermal transmittance of the roof construction, was calculated. However, when calculating this correction it was not evaluated that the thickness of the thermal insulation layer (in which the vertical air gaps are formed) can vary from 50 mm to 250 mm, and the width and height of the forming air gaps per area unit of the thermal insulation layer will be different. Therefore the correction may be too high in one case and too small in another. In order to evaluate the effect of air gaps, forming between boards on the thermal transmittance over horizontal thermal insulation layers, the corrections to thermal transmittance of the thermal insulation layer were determined (Table 3), according to the data derived from measurements and to the forming vertical air gap combinations per area unit of the thermal insulation layer. This correction shows, how many times the overall thermal conductivity of the thermal insulation layer with vertical air gaps is higher than the thermal conductivity of a layer of the same thickness without the air gaps. The effective thermal conductivity of the thermal insulation layer with vertical air gaps is calculated by the formula (4):

$$\lambda = \frac{\sum(\lambda_{o,i} \cdot A_{o,i}) + \lambda_m \cdot A_m}{A}, \qquad (4)$$

here: λ – the effective thermal conductivity of the thermal insulation layer with vertical air gaps, W/(m·K); $\lambda_{o,i}$ – the thermal conductivity of the vertical air gap which has the width of i, W/(m·K); $A_{o,i}$ – the area of the vertical air gap which has the width of i, m^2; λ_m – the thermal conductivity of the material of the thermal insulation layer, W/(m·K); A_m – the area of the material of the thermal insulation layer excluding the gaps: $A_m = A - \Sigma A_{o,i}$, m^2; A – the total area of the thermal insulation layer (area with air gaps included: $A = A_m + \Sigma A_{o,i}$), m^2.

The areas of air gaps of all widths are calculated for 1 m^2 of the total area. Therefore, in the formula $A = 1$ m^2.

Having acquired the effective thermal conductivities of thermal insulation layers with vertical air gaps of various heights and widths, the effective thermal transmittances of horizontal thermal insulation layers and the corrections of these coefficients to evaluate the influence of the air gaps were calculated (Table 3). Using these results, the probable increase of the thermal transmittance value due to the influence of vertical air gaps forming in the joints was calculated. The calculations are provided in Table 4.

The results show that the standardised $\Delta U''=$ 0.01 W/(m^2·K) correction is too all-encompassing and not always appropriate. In some cases it is up to 6 times higher or up to 4 times lower than necessary. A single value of such correction is not sufficient for the big variety of roof thermal insulation boards.

According to the results of measuring and calculations (Table 3), an empiric equation to calculate the correction of thermal transmittance value of the thermal insulation layer with air gaps was derived. The empiric equation (5) of the correction coefficient to thermal insulation boards with combinations of air gaps of biggest widths is:

$$k_u = -0.00000112 \cdot d^2 + 0.0001312 \cdot d + 0.9998, \qquad (5)$$

here: k_u – the coefficient of correction to the thermal insulation layer due to vertical air gaps formed in the layer; d – the thickness of the thermal insulation layer, mm.

Then the effective thermal transmittance of the thermal insulation layer with combinations of air gaps of biggest widths would be calculated by equation (6):

$$U = U_m \cdot k_u, \qquad (6)$$

here: U_m – the thermal transmittance of the thermal insulation layer without air gaps, W/(m^2·K).

Table 3. The corrections to thermal transmittance of thermal insulation layers with the biggest and average combinations of vertical air gaps

The thickness of the MW layer d, mm	The λ_m, of the MW layer W/m·K	Effective λ, W/(m·K)	The coefficient of correction k_λ	The U_m, of the MW layer W/(m^2·K)	Effective U, W/m^2·K	The coefficient of correction k_U	$\Delta U=U-U_m$
The corrections for 2000 × 600 mm boards with the combinations of air gaps of biggest width in the thermal insulation layer							
50	0.036	0.03854	1.0706	0.6415	0.6815	1.0624	0.0400
100	0.036	0.04062	1.1283	0.3392	0.3800	1.1202	0.0408
150	0.036	0.04245	1.1791	0.2306	0.2700	1.1709	0.0394
200	0.036	0.04413	1.2257	0.1747	0.2127	1.2175	0.0380
The corrections for 2000 × 600 mm boards with the combinations of air gaps of average width in the thermal insulation layer							
50	0.036	0.03626	1.0072	0.6415	0.6456	1.0064	0.0041
100	0.036	0.03626	1.0072	0.3392	0.3415	1.0068	0.0023
150	0.036	0.03630	1.0083	0.2306	0.2324	1.0078	0.0018
200	0.036	0.03635	1.0098	0.1747	0.1763	1.0092	0.0016

λ – the effective thermal conductivity of mineral wool (MW) with vertical air gaps, W/(m·K);
k_λ – the coefficient of correction to mineral wool layer thermal conductivity due to forming of air gaps;
U – the effective thermal transmittance of mineral wool with vertical air gaps, W/(m^2·K);
k_U – the coefficient of correction to mineral wool layer thermal transmittance due to forming of vertical air gaps;
ΔU – the correction to roof thermal transmittance, W/(m^2·K).

Table 4. The corrections to thermal insulation layer with the biggest and average combinations of air gaps due to the influence of vertical air gaps formed in joints between the boards

The thickness of MW layer d, mm	Correction ΔU	Ratio $\Delta U''/\Delta U$
The corrections to 2000 × 600 mm boards with the combinations of biggest air gaps due to the influence of air gaps formed in joints between the boards		
50	0.0400	0.25
100	0.0408	0.245
150	0.0394	0.254
200	0.0380	0.26
The corrections to 2000 × 600 mm boards with the combinations of average air gaps due to the influence of air gaps formed in joints between the boards		
50	0.0041	2.44
100	0.0023	4.35
150	0.0018	5.56
200	0.0016	6.25

6. Conclusions

1. The values of thermal conductivity coefficients of vertical 50 mm height air gaps, calculated according to EN ISO 6946:1997, differ significantly from the measured values of thermal conductivity coefficients of vertical air gaps of the same height. It shows that the method of calculation provided in the standard is not accurate.

2. Through a theoretical research it was determined that between thermal insulation boards conforming to the common European standard EN 13162:2000, when they are used to insulate a rectangular area, may form the air gaps of up to 18 mm in width, with the total area of 160 cm^2 per total area of one square meter.

3. After completing the experimental measurements of thermal conductivity, it is determined that the height of closed unventilated air gaps has no influence on the effective thermal conductivity properties of thermal insulation layer, when the width of the air gap is less than 5 mm.

4. In case of wider than 5 mm air gaps, the thermal transmittance of the thermal insulation layer can increase up to 20%, therefore the influence of the gaps must be evaluated.

5. In order to avoid extra heat losses due to the influence of air gaps, which form when installing the thermal insulation layer using single ply boards, it is necessary to fill up the air gaps that are wider than 5 mm with pieces of a light mineral wool.

6. The manufacturers of dual density thermal insulating boards, after determining the exact deviations of dimensions of boards and the probabilities of air gaps formations, should provide the empirical formula, in the order described in this article, enabling to calculate the correction factors to thermal transmittance values of horizontal thermal insulation layers with air gaps.

7. The manufacturers should provide the further investigation of the technical possibilities to reduce the limits of the measurements of dual density rock wool boards to exclude an additional thermal transmittance due to influence of air gaps.

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PLOKŠČIŲ SANDŪROSE SUSIDARANČIŲ VERTIKALIŲJŲ ORO PLYŠIŲ POVEIKIS HORIZONTALIOJO TERMOIZOLIACINIO SLUOKSNIO ŠILUMOS LAIDUMUI

J. Šadauskienė, A. Buska, A. Burlingis, R. Bliūdžius, A. Gailius

S a n t r a u k a

Nornt sumažinti darbų apimtis statybos vietoje, stogams šiltinti vis dažniau naudojamos vienu sluoksniu klojamos dvitankės termoizoliacinės plokštės. Šiuo atveju plokščių sandūros neperdengiamos, todėl tarp plokščių kraštinių susidaro įvairaus pločio plyšių, kurių įtaka termoizoliacinio sluoksnio šilumai perduoti turi būti įvertinta. Šio darbo tikslas yra įvertinti standartinio metodo, taikomo tokių plyšių poveikiui sluoksnio šilumos laidumui, patikimumui nustatyti lyginant skaičiavimo ir šilumos laidumo matavimų rezultatus, nustatyti horizontaliojo termoizoliacinio sluoksnio šilumos perdavimo koeficiento pataisas dėl vertikaliųjų oro plyšių susidarymo.
Apskaičiavus 50 mm storio termoizoliacinio sluoksnio oro plyšių šilumines varžas, kai plyšių plotis yra nuo 3–20 mm, nustatyta, kad oro plyšių šilumos laidumo koeficiento vertė didėja didėjant oro plyšio pločiui. Atlikus eksperimentinius šilumos laidumo matavimus, nustatyta, kad susidarančių uždarų ir nevėdinamų arba iš dalies vėdinamų oro plyšių aukštis neturi įtakos termoizoliacinio sluoksnio šilumos laidumo savybėms, kai oro plyšys yra iki 5 mm pločio. Esant platesniems uždariems ir nevėdinamiems oro plyšiams, šilumos laidumo koeficientas proporcingai didėja didėjant oro plyšių aukščiui. Pagal standartinį metodą skaičiuotas šilumos perdavimo koeficiento priedas yra per daug apibendrinantis ir ne visada tinkamas. Kai kuriais atvejais jis yra 6 kartus didesnis arba 4 kartus mažesnis už išmatuotąjį. Šiame darbe pasiūlytas horizontaliojo termoizoliacinio sluoksnio šilumos perdavimo koeficiento priedo, naudojamo plyšių įtakai įvertinti, skaičiavimo metodas.

Reikšminiai žodžiai: oro plyšys, dvitankė termoizoliacinė plokštė, šilumos laidumas, šilumos perdavimo koeficientas.

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