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A STUDY OF THICK THERMAL INSULATION WITH DENSITY FOAM POLYSTYRENE (EPS)

BADANIA CIEPLNE GRUBYCH IZOLACJI Z POLISTYRENU SPIENIONEGO (EPS) O MAŁEJ GĘSTOŚCI

A b s t r a c t

Energy-efficient construction requires the use of thermal insulation materials of high thickness compared to traditional construction. Thus, there is a need to conduct research for thick insulation products. The paper presents the results of the measurements of thermal parameters for foam polystyrenes (EPS) with low density and of different thicknesses. The experimental work has been carried out in the Water Center Laboratory WULS-SGGW.

Keywords: *lightweight thermal insulations*, *thick thermal insulations*, *low density insulation products*, *expanded polystyrene (EPS)*, *HFM apparatus*

S t r e s z c z e n i e

Budownictwo energooszczędne wymaga stosowania izolacji cieplnych o dużych grubościach w porównaniu z budownictwem tradycyjnym. Istnieje więc potrzeba prowadzenia badań dla grubych wyrobów termoizolacyjnych. W artykule przedstawiono rezultaty pomiarów parametrów cieplnych polistyrenów spienionych EPS o małej gęstości i różnej grubości. Prace badawcze zostały wykonane w Laboratorium Centrum Wodne SGGW w Warszawie.

Słowa kluczowe: *lekkie materiały termoizolacyjne*, *grube izolacje cieplne*, *wyroby izolacyjne o małej gęstości*, *polistyren ekspandowany (EPS)*, *aparat płytowy HFM*

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1. Introduction

The need for research into thick thermal insulation in engineering practice arises from the need to check insulation products with a high thickness (i.e. more than 100–150 mm range) and low-density products, in which the effect of the thickness occurs (i.e. dependence of the measured thermal conductivity coefficient on material thickness). As there are more and more thermal design requirements, it is essential to use increasingly thick layers with traditional insulation products. The two above research cases concerning control of insulation products are of particular importance due to the thermal protection of low energy-consuming buildings e.g. passive. Providing reliable thermal values of thick insulating products' performance with their actual thickness is very important. The author of this article narrows down the subject to presenting research for low density insulation products with different thicknesses only.

For this study, we employ appropriate measuring equipment that allows for the measurement of samples with thicknesses exceeding 100 mm. Currently, among the existing plate apparatus on the market, the best apparatus to study thick samples with high accuracy (error of measurement less than 2%) have a large measuring field. Large dimensions of the measuring section enable an appropriate volume of the sample to take an active part in the research. In addition, the maximum thickness of the sample in each plate apparatus is limited to the edges of the samples-boundary conditions and related edge error heat loss. According to the guidelines contained in standards [5–7] the maximum thickness of the sample in the plate apparatus with the heat flux sensors, in symmetrical configuration with a single sample of the measuring section 300 mm, should not exceed the value of 135 mm. The permissible thickness of the sample (135 mm) is important for low density materials, for which it is recommended not to exceed the maximum permissible value of the thickness given in the standards. Generally, it is assumed that in low density material, the thickness of the sample should be greater than that for which the transfer factor ($\Im$) of material, product or system does not change by more than ±2% with continued growth.

2. Thermal insulations with low density

Most thermal insulations, including low density insulations, have a porous body with closed or open pores, filled with gas. Insulating plastics are heterogeneous in terms of the structure and may not be treated as the thermo-homogeneous medium. However, it is assumed in the standards that products with high thermal resistance are homogeneously porous. Such products can be investigated in terms of heat properties when the maximal nominal pores' size, granules or grains do not exceed one tenth of the specimen thickness [6, 7].

For the above reasons, the actual transport of heat inside the insulating products is very complex and may take place by conduction both in the solid and gas phase radiation, convection and mutual interactions. This phenomenon is often called the measured, the equivalent, the apparent or the sample effective heat conduction and the parameter describing this phenomenon is called the measured thermal conductivity coefficient (λ). The process of heat flow in thermal insulations is not fully recognized due to a lack of sufficiently accurate, quantitative description of heat transfer mechanisms. Insulations, where the heat exchange takes place by conduction and radiation, are products with medium and high thermal resistance and low bulk density ($\rho < 40$ kg/m^3). Heat transfer by radiation in isolations characterized by density ($\rho < 20$ kg/m^3) is quantitatively significant. In recent times, it has been noted that thermal radiation could be responsible for a significant part of heat transport in very light foam and fibred insulations, even at temperatures of functioning insulation which is little above room temperature [3].

The characteristic feature of thermal insulation products is an increase of thermal conductivity with a decrease in the density of the product. From the point of view of the thermal insulation of building partitions, the observed dependence of the measured thermal conductivity as a function of bulk density is unfavourable. In order to preserve a specific level of the insulation of building partitions which have been analysed, there is a need to apply a thicker layer of lightweight insulation as opposed to heavier insulation [1, 4]. In the case of polystyrene (EPS), an inversely proportional dependence of conductivity and density occurs throughout the range of density of the EPS. i.e. 10 – 45 kg/m^3. We can observe the stabilization of the measured thermal conductivity at density $\rho \geq 40$ kg/m^3 [1, 2, 4].

The aim of the experimental research performed on thermal insulations is to obtain information on the size of thermal parameters and a correlation between measured values. In studies of the perfectly conductive heat solids, i.e. thermally isotropic and homogeneous in the direction of the heat flow by the product, we can usually consider the average thermal conductivity coefficient (λ) of samples. In the complex conditions of heat flow and the research of real materials with complex construction, we apply the concept of the transfer factor ($\Im$), which is not always the intrinsic feature of the material. In products in which the heat flow results not only from conduction, the transfer factor may be dependent on the test conditions. This parameter may be greatly determined by the thickness of the sample, the temperature difference for the same mean temperature test, emissivity of the apparatus etc. In light thermal insulations (i.e. low density products) specifying the thermal transmissivity (λ_t) is more relevant because this parameter deals with cases when the heat flow is only a combination of conduction and radiation. With regard to the heat flow the thermal transmissivity is the parameter which the most precisely describes very light insulations, because it does not depend on the thickness of the sample. On the basis of an analysis of simultaneous heat conduction and radiation in low density insulations, it has been shown that the apparent thermal conductivity coefficient (λ) of the insulation type varies with the layer thickness. This effect was experimentally observed in foam insulations (polystyrene and polyurethane, phenols), fibred insulations (wools) and light weight aerated concrete [1–4]. The apparent thermal conductivity of insulations increases gradually with increasing the thickness of insulation. Starting from a thickness limit (d_m), this conductivity reaches asymptotic values corresponding to the total sum of thermal conductivity and thermal radiation [3]. The thickness effect is caused by the partial transparency of thin samples of material with low density for thermal radiation. Only with sufficient thickness, does light-weight material have a sufficiently large density for thermal radiation to be absorbed and diffused within the sample. As a result of the heat radiation absorption and the dissipation, the fixing of the values for the measured thermal conductivity coefficient succeeds. Along with a further increase in the sample thickness, there are no changes in the value of the measured thermal conductivity coefficient. On the basis of the literature [1] we can assume that with the increase in density of polystyrene the thermal conductivity coefficient should be defined for material thickness being reduced gradually. The asymptotic values of the apparent thermal conductivity coefficient can correspond to the thermal transmissivity, defined in the standards [5–7]. If the thickness effect does not occur, then the transfer factor takes the value equal to the thermal transmissivity of the material [6]. According to the standard [8], the thickness effect is negligible for EPS products with a thickness of at least 50 mm and a declared thermal conductivity coefficient of $\lambda_D \leq 0.038$ W/mK.

The evaluation of the significance of the thickness effect is possible on the basis of the experimental procedure, by means of calculation [6] or by using charts and tables [6]. The last two methods have limitations and boil down to the formulated cases assigned to selected types of products. This work concerns the experimental way of determining the thickness effect in the analysed EPS samples.

The thermal characteristics of the samples can also be described by thermal resistance (R). When research clearly shows that the thermal resistance of samples does not depend on the temperature variations in the given test average temperature, then it may be additive. The average thermal conductivity coefficient and transfer factor do not depend on the test conditions and characterise the product. However, the thermal resistance in apparent low density insulations at any mean temperature may be a function of the temperature difference determined by the sample thickness. This behaviour in this case is not due to convection because it does not participate in heat flow. Therefore, in the light type insulations, the smallest thickness of the sample (d_m) is needed – furthermore, it can be possible to define the thermal properties of the product. Then, the transfer factor is different in relation to the thermal transmissivity by less than 2% [6]. In any case, whether the effect of thickness is significant or not, it is necessary to specify the representative value, i.e. the thermal transmissivity or thermal resistance for products with low density.

The total thermal resistance of a thick product with low bulk density is determined on the basis of the thinner plasters cut from the product. There are two ways to deal with thin samples. It should be assessed experimentally which way is appropriate for the tested product. The first way involves dividing the product into a few plasters which are equal in thickness and measuring the thermal resistance of only one layer that represents the product. The total thermal resistance of the product is calculated, assuming that the other plasters have the same thermal resistance. The second option is based on separate examination of the thermal resistance of each plaster which is cut from the thick product. The total thermal resistance is calculated as the sum of the thermal resistance of the plasters. If the thickness effect is significant, then the total thermal resistance of the thick product cannot be calculated in some cases as the sum of the thermal resistance of the layers which are cut from the product [5, 6]. Then, there are possible two situations in the course of an experiment – when the sample thickness exceeds or does not exceed the measuring capabilities of the apparatus (the distance between the heating and the cooling plates). When the sample thickness exceeds the measuring capabilities of the apparatus, the transfer factor and thermal resistance are calculated from the existing formulas for low density insulating products presented in the standards. In this situation, the research is conducted for one layer and the transfer factor is determined using the interpolated equations for the full thickness of the sample, then on the basis of the transfer factor, we can calculate the total thermal resistance of the target thickness of a product. If the sample thickness does not exceed the measurement capabilities of the apparatus, the thermal parameters of the product for the thickest sample (put in the apparatus) can be determined experimentally. Hence, there is not any further need to experimentally determine the thermal conductivity coefficient for thinner samples. Thermal resistance is calculated on the basis of the determined thermal conductivity coefficient and thickness of the products concerned.

The thermal resistance, the transfer factor and the thermal transmissivity may be a result of a measurement on one sample in the test conditions for the isolation of fitting the homogeneity conditions (thermal, structural). The heat flow characteristics measured for many samples of the same material may vary due to the variety of material composition or the diversity of samples. These properties can change with the mean temperature test, can change over time or be dependent upon previous thermal history.

3. The characteristics of the analysed low density polystyrenes (EPS)

The research was conducted for three different types (A, B, C) of commercial expanded polystyrenes (EPS) with low density, produced by Polish firms. All tested types of warming plates are designed to perform the external thermal insulation of walls, including the thermal insulation of facades.

The tests have been subjected to plates A – white expanded polystyrene EPS 70, average bulk density 16.9 kg/m^3, with the declared thermal conductivity coefficient 0.040 W/mK, flexural strength above 115 kPa. Plates were cut from one polystyrene block, directly on the production line. Eleven different thicknesses of samples ranging from 20 mm to 160 mm were prepared. The product was subjected to systematic control of thermal performance for a period of 20 months from the date of manufacturing. Instability of the thermal parameters was observed at an early product in the early years of its seasoning.

The second analysed product was plates B – with the so-called expanded polystyrene in the black dot, characterized by the declared value of the thermal conductivity coefficient 0.040 W/mK at the temperature 10°C and flexural strength at least 100 kPa. The average bulk density of the tested insulation in dots was 14.2 kg/m^3. Nine samples of the thickness ranging from 20 mm to 180 mm have been tested.

The experiment also included plates C – with the so-called silver-gray expanded polystyrene. The declared thermal conductivity coefficient at 10°C is equal to 0.032 W/mK, the level of flexural strength being at least 75 kPa. The average density of polystyrene with improved insulation by graphite was 14.6 kg/m^3. Seven samples have been tested in the thickness range 20 mm to 130 mm.

During the entire period of the experiment, all the samples of the three types of products were conditioned in standard laboratory conditions, i.e. in equilibrium with temperature (23 ± 2) °C and the relative air humidity (50 ± 10) % RH.

4. The results of experimental research

In order to determine the performance of the analysed polystyrenes, the importance of the effect of the product thickness has been verified. The phenomenon was proved to be important in two cases: EPS (A) and (B). In the case of EPS (A) the minimum thickness of the product at which the effect of the thickness did not matter (d_m) was 108 mm and in the case of EPS (B) it was 60 mm (see Figure 2 and 3). Theoretically, it has been calculated that the absence of the thickness effect occurs at 218 mm (A) and 120 mm (B). In the case of EPS (C), the thickness effect did not take place in the whole population of the samples. This is also confirmed by the results presented in the literature [1].

Studies carried out for EPS (A) showed that this product in terms of thermal insulation, do not comply with the declared values for this type of expanded polystyrene. Thermal resistance (*R*) calculated on the basis of the thermal conductivity coefficient and thermal transmissivity for almost all the samples turned out to be less than that given by the manufacturer. Also, the conversion of the measured thermal conductivity coefficient due to the effect of the thickness, carried out in accordance with the standard [8] (in samples with smaller thicknesses), exceeded the declared value for this parameter. Values of measurements in which conversion is taken into consideration further in the article are called the converted thermal conductivity coefficient and are shown on Fig. 2. Consequently, in thicker samples, above the thickness limit (d_m) of the specimen, where it is possible to define the thermal properties of the product, the declared value of the thermal conductivity coefficient was exceeded. The measurements of the bulk density of the research material (A) showed its heterogeneity comparing to other polystyrenes, as illustrated on Fig. 1.

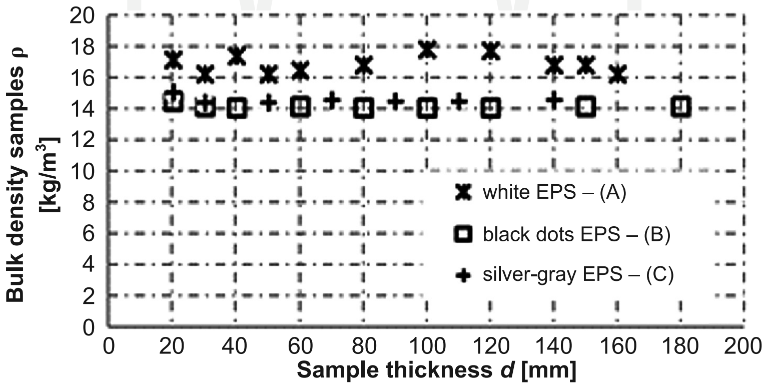

Fig. 1. The distribution of medium bulk density as a function of the change in the samples' thickness for lightweight EPS

The influence of heterogeneity in terms of bulk density is revealed in studies of thermal conductivity by the irregular arrangement of thermal conductivity coefficient points as a function of the thickness. The dependence of the measured thermal conductivity coefficient (λ) as a function of the samples thickness cutting from one block is shown on Fig. 2. The nature of the changes in the calculated transfer factor, which approximates thermal transmissivity, was also presented. The difference between the measured values of the thermal conductivity coefficient for extreme thickness is significant and is equal to 7.4%. The maximum difference between the measured thermal conductivity coefficient and the transfer factor is small and equal to 3.2%.

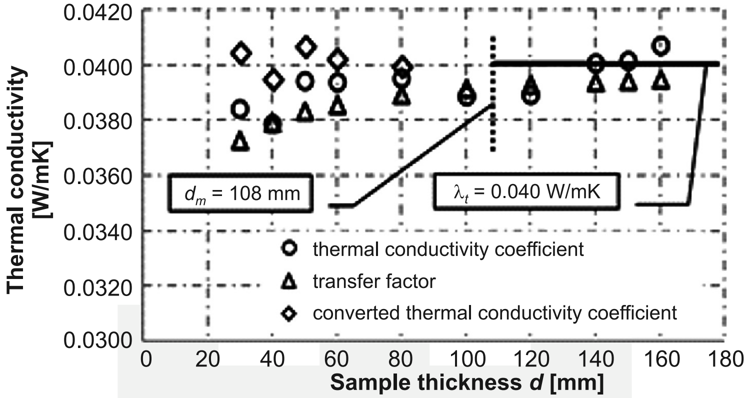

Fig. 2. The effect of the samples' thickness and density for the result of the λ measurement at the temperature of 10°C for product (A)

In the case of EPS (B) – black dots, the obtained dependency of the measured thermal conductivity coefficient as a function of the samples thickness shows no abnormalities arising from the heterogeneity of the samples (Fig. 3). The difference between the measured values of the thermal conductivity coefficient for extreme thickness is equal to 5.5%, which is significant. The biggest difference between the measured thermal conductivity coefficient and the transfer factor was 1.6%.

Mechanism of heat flow in the EPS plates (C) – the silver-gray colour compared to (A) and (B) is different. Addition of graphite causes absorption of radiant heat and contributes

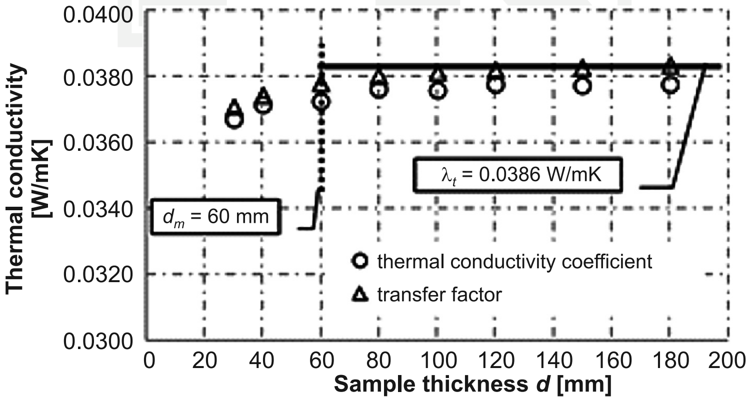

Fig. 3. The influence of the samples' thickness on the measured thermal conductivity coefficient at an average temperature of 10°C for product (B)

to the peculiar nature of the transfer factor course. The values of this parameter are being reduced with the thickness of samples tending asymptotically to thermal transmissivity (Fig. 4). The difference of the measured thermal conductivity coefficient for extreme thickness is very small – equal to 0.6%, reflecting the absence of the effect of thickness. The thermal conductivity of plates (C) is more than 20% lower compared to plates (B) with similar bulk density.

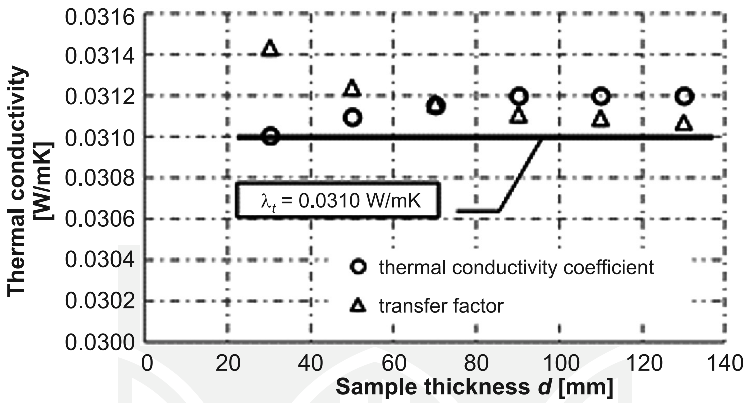

Fig. 4. The dependence of thermal parameters as a function of the samples' thickness for product (C)

5. Conclusions

Thick insulating products (EPS) with low density usually revealed the lack of thickness effect because they are non-transparent to thermal radiation. In any case, especially in new products, it is important to determine their thickness limit (d_m) experimentally. About this thickness limit thermal parameters are the intrinsic material feature. Lower density products in comparison with higher density products may show lower values of the thickness limit. In modern plate apparatus, it is possible to perform samples' tests with thicknesses exceeding the maximum acceptable thickness recommended in the standards. Studies carried out with plates apparatus FOX 600 show that the results obtained from measurements at sample thicknesses above 135 mm are reliable for EPS analysed products with low density (light).

Product control in terms of determining the thermal properties in insulations should be carried out on a number of samples of the same material and not on just one sample – then proper evaluation of the consistency of the product concerned becomes possible. Products from expanded polystyrene should have a constant bulk density. The author's suggestion is the following: a preliminary conformity assessment of the tested insulation plates with the type of product should contain control of thermal parameters and constant bulk density of the product. The visible jumps in the value of this parameter on Fig. 1 for product (A) indicate the high heterogeneity of density that can cause the dispersion of the values for the measured thermal conductivity coefficient. It could also be one of the reasons for the lack of preservation of the declared values of thermal parameters. In view of the above, easy control becomes possible at any production site to ensure the quality of the products (by checking the bulk density) without purchasing expensive apparatus by manufacturers.

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