

Defining the thermal conductivity of thermally heterogeneous hollow wall bricks used as elements for increasing the comfort of buildings

Krzysztof PAWŁOWSKI^{*1} and Maciej NIEDOSTATKIEWICZ²

¹Bydgoszcz University of Science and Technology, Bydgoszcz, Poland

²Gdansk University of Technology, Gdańsk, Poland

Abstract

The article presents numerical calculation analysis in the scope of determining thermal conductivity coefficient λ_{eq} [W/(m·K)] of thermally heterogeneous hollow bricks of thermally heterogeneous structure (a combination of structural material with thermal insulation material). Numerical calculations were conducted by means of professional software TRISCO-KOBRU 86, serving thermal circulation analysis in a 2D field in stationary approach. The analyzed hollow wall bricks may be used, for instance, as a structural layer of layered outer walls of a building. In the article also the results of the U_c thermal conductivity coefficient calculations for double-layer walls with the use of the analyzed hollow wall bricks are presented in regard to thermal requirements.

Keywords: thermal conductivity, hollow wall bricks, building usage comfort.

1 Introduction

Legal requirements regarding energy saving and thermal protection of buildings [2, 17] (minimizing the non-renewable energy demand coefficient EP [kWh/(m²·year)] for a whole building as well as thermal conductivity indices U [W/(m²·K)] for individual partitions of a building) demand introduction of modern material and structural solutions for the shell of the building, high-efficiency installation systems as well as renewable energy sources (RES). It must be highlighted that operations within this scope concern buildings at the design stage, buildings under construction, and buildings in use both in Poland and in other developed countries [4, 11, 21].

An integral factor in shaping the material layers of inner partitions is knowledge of their thermal conductivity indices λ [W/(m·K)]. For reasons given above it is necessary to implement numerical methods (professional software for stationary thermal circulation) which allow definition of the thermal conductivity of shell elements of a building, where those elements may be of thermally homogeneous or heterogeneous structure. Valid definition of the properties of thermal partition layers allows accurate determination of thermal loss through conductivity. The basic stage of thermal design of elements of a building's shell is to use numerical methods based on the temperature distribution in the building materials.

In many cases thermal circulation analysis amounts to determining thermal conductivity through a flat building partition in a one-dimensional field (1D), without considering thermal circulation in two-dimensional (2D) or three-dimensional (3D) fields.

2 Methods of determining thermal conductivity of elements of the shell of a building

Calculating thermal loss in a building is the most significant stage of thermal designing. The basic technical parameter of a material, which is taken into consideration in thermal calculations, is the thermal conductivity coefficient λ [W/(m·K)]. This is the amount of heat conducted, per unit of time and through 1 m² of surface, with a surface

^{*}Corresponding author: E-mail address: krzypaw@utp.edu.pl (Krzysztof PAWŁOWSKI)

temperature difference on both sides of the partition equal to 1K. Standardization has introduced two concepts related to the thermal conductivity coefficient of materials (or thermal resistance of materials):

- The declared value (λ_D), serving production quality control, and matching laboratory conditions; and
- The calculated value (λ_{ob}), serving design purposes, and matching material usage conditions in a building.

Climatic conditions, both inside and outside a building, influence the thermal conductivity volume of materials. Consideration of the impact of specific climatic conditions on an element of a building allows for precise estimation of actual thermal losses. Determining the calculation value relies on incorporating temperature and humidity differences between the conditions for which the declared value of thermal conductivity has been specified and the conditions under which the material actually works. In the case of construction usage application humidity plays a vital role. For technical insulation materials temperature changes are the most important factor. At the design stage the working conditions of the material ought to be predicted and conversion of the λ_D coefficient to the λ_{ob} value conducted. Material conductivity is a function of its density, humidity content, temperature, and time elapsed from the production of the material:

$$\lambda_{ob} = \lambda_D \cdot F_T \cdot F_M (or F_\Psi) \cdot F_a \quad (1)$$

where:

λ_{ob} - calculated value of the thermal conductivity coefficient,

λ_D - declared value of thermal conductivity coefficient,

F_T - conversion temperature factor,

F_a - conversion factor dependent of the time of material production,

F_M - conversion humidity factor which takes into account the mass humidity of the material or the volume humidity of the material (F_Ψ).

Various approaches have been described for determining the value of thermal conductivity indices of materials constituting building partitions [5, 12, 18–20]. Thermal exchange occurs due to temperature differences. In engineering issues the T temperature field is established by means of the dependency of temperature on spatial coordinates (x, y, z) and time (t). Methods of analyzing thermal exchange problems usually require simplifying assumptions for the long run, which sometimes makes those solutions hardly useful. Thus, it seems valid to apply effective numerical methods described in [15], among others.

In order to fulfil the requirements of the directive [2] and the regulation [17], as well as increasingly rigorous technical and environmental standards, new materials and technical solutions are sought. Optimization of the thermal quality of a building's shell guarantees a decrease in thermal losses occurring by means of conductivity and thus, consequently, leading to the building's demand for energy (EU EK and EP) being minimized and levels of CO₂ emission to the atmosphere being lowered. For this reason it is valid to use building materials which have a low thermal conductivity coefficient λ [W/(m·K)].

An example solution, within the scope of energy saving and thermal protection of buildings, is to use small-size hollow wall bricks (elements), with a thermally heterogeneous structure (a combination of construction materials – plain concrete or cellular concrete with a heat insulation material (polystyrene or polyurethane foam)). In such cases, when determining the thermal conductivity coefficient λ , it is reasonable to use software which provides thermal analysis of stationary heat circulation (at constant ambient temperature) under various boundary conditions. The equivalent thermal conductivity coefficient λ_{eq} [W/(m·K)] of a building element consisting of various building materials defines the thermal conductivity of a homogenous substitute building material, cuboid in shape and of the same dimensions, which when in place of the whole building element in the installed condition allows the same thermal effect to be obtained.

In the EAD (European Assessment Document) compliant method [3] detailed calculations of thermal bridges are conducted in three dimensions with a load bearing thermal insulation element. Here, a detailed model of the complex structure of the load bearing thermal insulation element is created and the thermal bridge heat loss is determined. On the basis of the resulting thermal loss the equivalent thermal conductivity coefficient λ_{eq} is calculated as well as the equivalent thermal resistance R_{eq} . The calculations are conducted with the use of professional software for calculating physical parameters of thermal bridges (using boundary parameters in accordance with PN-EN ISO 6946:2008 [14]).

Described below 5 stages presents the calculation algorithm for determining, with the use of software, the thermal calculated coefficient λ_{eq} [W/(m·K)] of a building element consisting of several heterogeneous building materials.

Stage I

Defining thermal flux Φ [W] flowing through an element using computer software which provides thermal analysis of stationary thermal circulation (at constant ambient temperature), under different boundary conditions.

Stage II

Defining the thermal conductivity coefficient of the element according to the equation:

$$U = \frac{\Phi}{A \cdot (t_i - t_e)} \quad (2)$$

where:

Φ - the thermal flux flowing through the item [W],

A - surface area of the item through which the conductivity occurs [m²],

$(t_i - t_e)$ - temperature difference [K].

Stage III

Defining the total thermal resistance according to the equation:

$$R_T = \frac{1}{U} \quad (3)$$

where:

R_T - total thermal resistance of the element from environment to environment [(m²·K)/W],

U - thermal conductivity coefficient of the element [W/(m²·K)].

Stage IV

Defining the thermal resistance of the item:

$$R_i = R_T - (R_{si} + R_{se}) \quad (4)$$

where:

R_i - thermal resistance of the item [(m²·K)/W],

R_T - total thermal resistance of the item from environment to environment [(m²·K)/W],

R_{si} - thermal transfer resistance o the inner surface of the partition [(m²·K)/W],

R_{se} - thermal transfer resistance o the outer surface of the partition [(m²·K)/W].

Stage V

Defining the thermal conductivity coefficient of a thermally heterogeneous item:

$$\lambda'' = \frac{d_i}{R_i} \quad (5)$$

$$\lambda_{eq} = \frac{d_i}{R_i} \quad (6)$$

where:

d_i - thickness of the item [m],

R_i - thermal resistance of the item [(m²·K)/W].

3 Determining the thermal conductivity coefficient of thermally heterogeneous hollow wall bricks on the basis of numerical calculations

Hollow wall bricks of thermally heterogeneous structure, made from regular concrete or cellular concrete with a filling of heat insulating material, constitute an alternative solution to traditional wall elements used in the construction industry (e.g. hollow ceramic bricks with a mineral wool filling, or lightweight expanded clay aggregate with a polystyrene filling). Figure 1 presents the geometry of analyzed masonry units, of dimension 24×40 cm, selected for calculations. This is a proposal for a material solution which has not been commonly used in construction as yet. This type of solution is a modification of previously-used hollow aggregate bricks (PC, EF, Gamma, Welo, KJ ceramic wall bricks) [23]. The tested material solutions, when used as elements for erecting external walls, are an alternative to homogeneous brickwork made of cellular concrete or 24 cm thick porcelain ceramics. Later in this work, conceptual calculations are presented for determination of the heat transmission coefficient λ of a heterogeneous brick, using a professional computer program for analysis of stationary heat flow in a two-dimensional (2D) field.

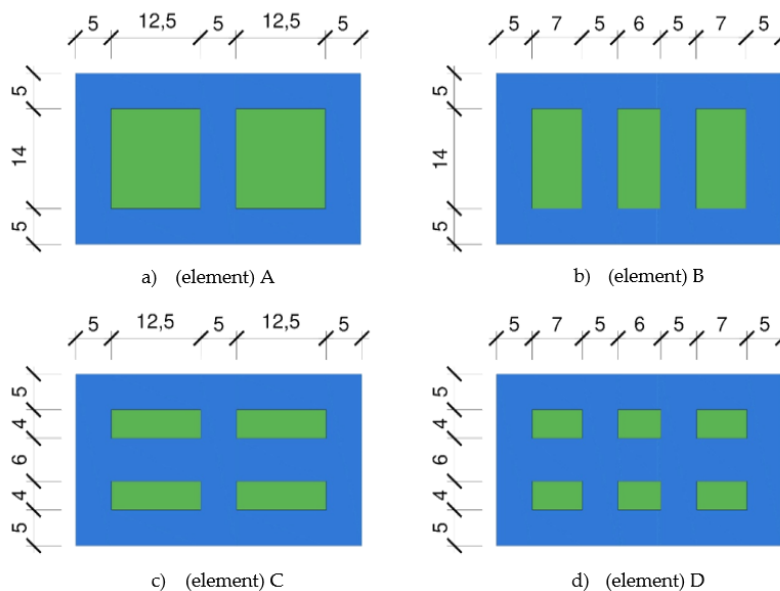


Figure 1. Geometry of the analyzed hollow bricks

For the calculations (for the four hollow bricks A, B, C, D) the following material solution was adopted:

- Plain concrete: $\rho=2200 \text{ kg/m}^3$, $\lambda_{ob}= 1.70 \text{ W/(m}\cdot\text{K)}$,
 Styrofoam: $\rho=30 \text{ kg/m}^3$, $\lambda_{ob}= 0.035 \text{ W/(m}\cdot\text{K)}$,
 PUR foam: $\rho=35 \text{ kg/m}^3$, $\lambda_{ob}= 0.022 \text{ W/(m}\cdot\text{K)}$,
- Light concrete: $\rho=1000 \text{ kg/m}^3$, $\lambda_{ob}= 1.70 \text{ W/(m}\cdot\text{K)}$,
 Styrofoam: $\rho=30 \text{ kg/m}^3$, $\lambda_{ob}= 0.035 \text{ W/(m}\cdot\text{K)}$,
 PUR foam: $\rho=35 \text{ kg/m}^3$, $\lambda_{ob}= 0.022 \text{ W/(m}\cdot\text{K)}$,
- Autoclaved cellular concrete: $\rho=600 \text{ kg/m}^3$, $\lambda_{ob}= 0.21 \text{ W/(m}\cdot\text{K)}$,
 Styrofoam: $\rho=30 \text{ kg/m}^3$, $\lambda_{ob}= 0.035 \text{ W/(m}\cdot\text{K)}$,
 PUR foam: $\rho=35 \text{ kg/m}^3$, $\lambda_{ob}= 0.022 \text{ W/(m}\cdot\text{K)}$.

The described elements are to constitute only a part of a two-layer wall, which is intended to be insulated on the external side with a thermal insulation material in accordance to principles specified in [9, 10], which is an update of

[7, 8], themselves based on documents [6, 22]. The elements analyzed in the further part of the article are not intended to be used in enhanced homogeneous walls (without outer thermal insulation).

The hollow bricks were designed as a flow-through type, without a horizontal diaphragm in the form of a bottom. The assumption behind their use is their incorporation with traditional bricklaying binders (cement/limestone) or modified thermally absorbent ones up to 15 mm thick. In accordance with the standard [1], supporting and vertical binders made with traditional mortars should be no less than 6 millimetres in their actual thickness, yet no bigger than 15 millimetres (nominally 10 mm). The lack of a horizontal diaphragm in the form of a bottom makes it impossible to use hollow bricks for construction of walls raised with the use of thin binders of 3 mm thick (from 0.5 millimetre up to 3 millimetres (2mm on average)), yet, as mentioned earlier, the wall elements under analysis still have to be insulated with thermal insulation material to the height of vertical partitions being raised using them.

Numerical calculations were conducted using the program TRISCO-KOBRU 86 [16]. A grid of finite elements with a uniform side equal to 1 mm was adopted, in accordance with specifications of the standard PN-EN ISO 10211:2008 [13]. In the software version used [16] it is possible to determine a constant temperature between the edges of particular blocks. After creating the geometry and adopting the boundary conditions ($t_i = -20^\circ\text{C}$, $R_{si} = 0.13 \text{ (m}^2\cdot\text{K)/W}$, $t_e = -20^\circ\text{C}$, $R_{se} = 0.04 \text{ (m}^2\cdot\text{K)/W}$) the calculation process was launched. Temperature field calculations are conducted with the aid of a linear equation matrix. Having conducted the calculations, a graphic and digital result is obtained, which contains the temperatures and heat fluxes of the analyzed building element (Fig. 2.).

According to the software manual the calculating parameters were as follows:

- maximum number of iterations – 10000,
- absolute error in calculated temperatures – 0.0001 °C,
- absolute error in calculated heat fluxes in the connector – 0.001

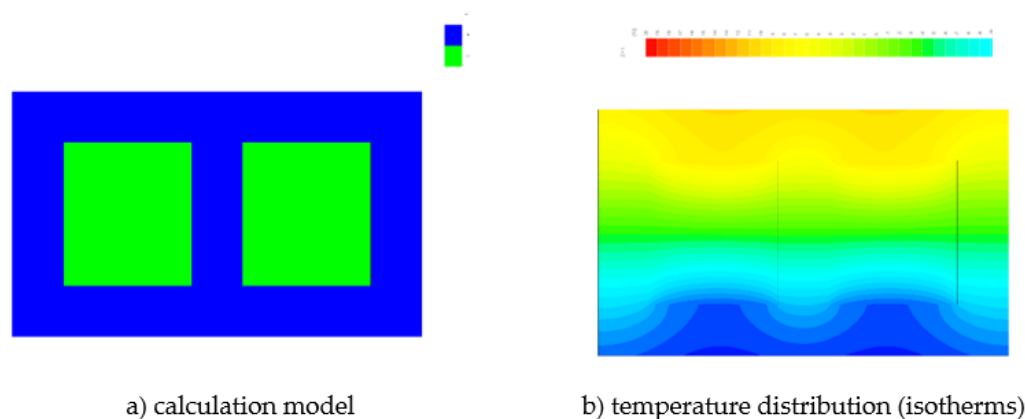


Figure 2. Graphic depiction of results of numerical analysis of a selected hollow brick (element)

In tables 1, 2 and 3 the thermal conductivity coefficient λ_{eq} [W/(m·K)] calculation results are listed for building elements consisting of several different building materials in three calculation variants.

The values of conductivity coefficient λ_{eq} [W/(m·K)] of hollow wall bricks of homogenous structure depend on the value of the thermal conductivity coefficient λ [W/(m·K)] of individual materials (plain concrete, light concrete, autoclaved cellular concrete, Styrofoam, PUR foam) as well as the composition of the construction and insulation layers – shown in figure 2. Each change in the geometry of the wall elements requires repeated individual calculations. The analyzed hollow wall bricks may be used, for instance, as a construction layer in the outer layer walls of the building. It must be pointed out, however, that the load-bearing capacity (compression resistance [MPa]) of the analyzed hollow bricks will vary depending on the proportion and type of the construction material ((plain concrete, light concrete, autoclaved cellular concrete). Identification and analysis of resistance characteristics will be the next stage of the research.

In order for the amount of thermal energy required to be kept at a sufficiently low level to render use of a particular partition rational in construction of a building for an intended purpose, the partitions inside the building should be designed in such a way that the values of the thermal conductivity coefficient U_c [W/(m²·K)] of outer partitions and doors, and the installation technique, conform to the following requirement of thermal insulation: $U_c \leq U_{c(max)}$.

Table 1. Results of thermal conductivity coefficient calculations λ_{eq} [W/(m·K)] for hollow wall bricks (plain concrete, thermal isolation material) – own elaboration

Calculation variants			Φ [W]	U [W/(m ² ·K)]	R_T [(m ² ·K)/W]	R [(m ² ·K)/W]	λ_{eq} [W/(m·K)]
1.	Hollow brick A	I	32.83	2.052	0.487	0.317	0.757
2.	Hollow brick A	II	32.48	2.030	0.493	0.323	0.743
3.	Hollow brick B	I	39.10	2.444	0.409	0.239	1.004
4.	Hollow brick B	II	38.91	2.432	0.411	0.241	0.996
5.	Hollow brick C	I	34.75	2.172	0.460	0.290	0.828
6.	Hollow brick C	II	34.27	2.142	0.467	0.297	0.808
7.	Hollow brick D	I	41.00	2.563	0.390	0.220	1.091
8.	Hollow brick D	II	40.76	2.548	0.392	0.222	1.081
Plain concrete ($\rho=1700$ kg/m ³) $\lambda_{ob}= 1.70$ W/(m·K), variant I – Styrofoam $\lambda_{ob}= 0.035$ W/(m·K), variant II – PUR foam $\lambda_{ob}= 0.022$ W/(m·K)							

 Table 2. Results of thermal conductivity coefficient calculations λ_{eq} [W/(m·K)] for wall hollow bricks (light concrete, thermal isolation material) – own elaboration

Calculation variants			Φ [W]	U [W/(m ² ·K)]	R_T [(m ² ·K)/W]	R [(m ² ·K)/W]	λ_{eq} [W/(m·K)]
9.	Hollow brick A	I	23.11	1.444	0.693	0.523	0.459
10.	Hollow brick A	II	22.66	1.385	0.722	0.552	0.435
11.	Hollow brick B	I	28.06	1.754	0.570	0.400	0.600
12.	Hollow brick B	II	27.79	1.737	0.576	0.406	0.591
13.	Hollow brick C	I	24.86	1.554	0.644	0.474	0.506
14.	Hollow brick C	II	24.23	1.514	0.660	0.490	0.490
15.	Hollow brick D	I	29.77	1.861	0.537	0.367	0.654
16.	Hollow brick D	II	29.44	1.840	0.543	0.373	0.643
Light concrete ($\rho=1000$ kg/m ³) $\lambda_{ob}= 1.70$ W/(m·K), variant I – Styrofoam $\lambda_{ob}= 0.035$ W/(m·K), variant II – PUR foam $\lambda_{ob}= 0.022$ W/(m·K)							

The $U_{c(max)}$ coefficients values have been listed in the regulation [17]. Table 4 lists calculation results of thermal conductivity coefficient U_c [W/(m²·K)] values of layer walls selected using selected hollow wall bricks insulated with Styrofoam or PUR foam slabs. The calculations were conducted in accordance with the procedure presented in PN-EN ISO 6946:2008 [14].

The value of thermal conductivity coefficient λ (λ_{eq}) [W/(m·K)] of the insulating material has a significant influence on the value of the thermal conductivity coefficient U [W/(m²·K)] of a building partition. Within one overall type of insulation this value may range considerably depending on the product, as a result of the fast pace of development

Table 3. Results of thermal conductivity coefficient calculations λ_{eq} [W/(m·K)] for wall hollow bricks (autoclaved cellular concrete, thermal isolation material) – own elaboration

Calculation variants			Φ [W]	U [W/(m ² ·K)]	R_T [(m ² ·K)/W]	R [(m ² ·K)/W]	λ_{eq} [W/(m·K)]
17.	Hollow brick A	I	7.37	0.461	2.196	1.999	0.120
18.	Hollow brick A	II	6.79	0.424	2.358	2.188	0.110
19.	Hollow brick B	I	8.61	0.538	1.859	1.689	0.142
20.	Hollow brick B	II	8.21	0.513	1.949	1.779	0.135
21.	Hollow brick C	I	8.29	0.518	1.931	1.761	0.136
22.	Hollow brick C	II	7.61	0.476	2.101	1.931	0.124
23.	Hollow brick D	I	9.39	0.587	1.704	1.534	0.156
24.	Hollow brick D	II	8.94	0.559	1.789	1.619	0.148
Autoclaved cellular concrete ($\rho=600$ kg/m ³) $\lambda_{ob}=0.21$ W/(m·K), variant I – Styrofoam $\lambda_{ob}=0.035$ W/(m·K), variant II – PUR foam $\lambda_{ob}=0.022$ W/(m·K)							

 Table 4. Results of thermal conductivity coefficient calculations λ_{eq} [W/(m·K)] for wall hollow bricks (autoclaved cellular concrete, thermal isolation material) – own elaboration

Calculation variants			λ_{eq} [W/m·K]	Thermal conductivity coefficient U_c [W/(m ² ·K)] insulated with					
				Styrofoam $\lambda_{ob}=0.035$ W/(m·K)			PUR foam slabs $\lambda_{ob}=0.022$ W/(m·K)		
				10 cm	12 cm	15 cm	10 cm	12 cm	15 cm
1.	Hollow brick A	I	0,757	0.30	0.26	0.21	0.20	0.17	0.14
2.	Hollow brick A	II	0.743	0.30	0.25	0.21	0.20	0.17	0.14
7.	Hollow brick D	I	1.091	0.31	0.26	0.21	0.20	0.17	0.14
8.	Hollow brick D	II	1.081	0.31	0.26	0.22	0.20	0.17	0.14
9.	Hollow brick A	I	0.459	0.28	0.24	0.20	0.19	0.16	0.13
10.	Hollow brick A	II	0.435	0.28	0.24	0.20	0.19	0.16	0.13
15.	Hollow brick D	I	0.654	0.29	0.25	0.21	0.20	0.17	0.13
16.	Hollow brick D	II	0.643	0.29	0.25	0.21	0.20	0.17	0.13
17.	Hollow brick A	I	0.120	0.20	0.18	0.15	0.15	0.13	0.11
18.	Hollow brick A	II	0.110	0.19	0.18	0.15	0.14	0.13	0.11
23.	Hollow brick D	I	0.156	0.22	0.19	0.17	0.16	0.14	0.12
24.	Hollow brick D	II	0.148	0.22	0.19	0.16	0.16	0.14	0.12
Bolded values in the table marks thermal conductivity coefficient U_c of outer walls matching the requirement: $U_c \leq U_{c(max)}=0.20$ W/(m ² ·K) – according to the regulation [4]									

of the thermal insulation materials market as well as increasingly advanced production technologies. The thermal conductivity coefficient U_c [$\text{W}/(\text{m}^2 \cdot \text{K})$] is the basic parameter used to check the thermal criterion ($U_c \leq U_{c(max)}$). With changing values of $U_{c(max)}$ certain construction/material solutions for outer walls do not meet the basic criterion ($U_c \leq U_{c(max)}$) – see table 4. The defined values U_c are used in further calculations within the scope of thermal and humidity analysis of partitions and a whole building (e.g. the conductivity heat loss coefficient H_{tr} [W/K], the demand for usable energy EU, the final energy EK and primary energy EP [$\text{kWh}/(\text{m}^2 \cdot \text{year})$]). It must also be highlighted that, while shaping the composition of outer walls material layers and their joints, it is also necessary to take into consideration the following criteria: thermal insulation, surface and inter-layer condensation, acoustic insulation, fire protection, as well as load bearing capacity and durability of the structure.

4 Conclusions

This work presents a calculation procedure and calculation results of an equivalent thermal conductivity coefficient λ_{eq} [$\text{W}/(\text{m} \cdot \text{K})$] of wall elements (hollow bricks) consisting of several different building materials. It must be highlighted that the presented method of calculations may be used in regard to many partitions of thermally heterogeneous structure, e.g. closely-ribbed hollow ceiling bricks with thermal insulation material filling or isothermal binders in the case of binding an outer wall with a balcony slab.

Knowing the value of coefficient λ_{eq} [$\text{W}/(\text{m} \cdot \text{K})$] of individual elements allows for thermal and humidity analyses to be conducted within the scope of the energy saving and thermal protection criteria of a building as well as the humidity criterion (surface and inter-layer condensation). Valid determination of the thermal conductivity of elements of a thermally heterogeneous structure requires use of professional software meeting the defined legal and standard requirements.

Due to the introduction of tight requirements in the scope of energy saving and thermal protection of buildings, to limit both thermal losses of building partitions and a building's demand for non-renewable primary energy, it is valid to introduce modern construction and material solutions implemented at the design and construction stage of buildings. This work presents a calculation procedure and results for the thermal conductivity coefficient λ_{eq} [$\text{W}/(\text{m} \cdot \text{K})$] of wall elements (hollow bricks) of thermally heterogeneous structure obtained using numerical methods (professional computer software). Knowing the value of coefficient λ_{eq} [$\text{W}/(\text{m} \cdot \text{K})$] allows thermal and humidity analyses to be conducted within the scope of the energy saving and thermal protection criteria of a building as well as the humidity criterion (surface and inter-layer condensation).

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