

THE ANALYSIS OF THERMAL PROPERTIES OF A WALL FRAGMENT MADE WITH 3D CONSTRUCTION TECHNOLOGY

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Abstract: The article presents the results of the analysis of the effect of the parameters of the external wall of a building, constructed using 3D technology on its heat engineering properties. The dependence of the heat penetration coefficient λ (function Y) of the wall on the following factors has been constructed: the thickness of the outer walls d_1 (factor X_1), the thickness of longitudinal partitions between the voids d_2 (factor X_2), the number of voids in the wall cross section in the transverse direction m (factor X_3), the number of voids in the wall section per 1 m in the longitudinal direction n (factor X_4), the thermal conductivity coefficient of the heat-insulating material in the voids λ_1 (factor X_5), provided that the cross-sectional area of the bearing part of the wall, taken under the condition of ensuring strength. The data set for analysis was obtained by implementing a computational experiment. The analysis and optimization of the parameters was performed on the basis of a deterministic mathematical model that describes the presented dependence for the selected void formation scheme in the wall. The information may be useful for scientists, designers and technologists involved in the development of structural solutions of buildings using 3D printing technology.

Keywords: buildings in 3D technology, outer wall, air voids, heat engineering properties, heat penetration coefficient, heat conductivity coefficient, optimization, deterministic mathematical model

АНАЛИЗ ТЕПЛОТЕХНИЧЕСКИХ КАЧЕСТВ ФРАГМЕНТА СТЕНЫ ЗДАНИЯ, ВОЗВОДИМОГО В 3D ТЕХНОЛОГИИ

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Аннотация: В статье представлены результаты оригинального исследования по анализу влияния параметров наружной стены здания, возводимого в 3D технологии, на теплозащитные качества. Построена зависимость коэффициента теплопередачи стены U (функция Y) от следующих факторов: толщины внутренних стенок несущей части сечения стены d (фактор X_1), количества пустот в сечении стены в поперечном направлении m (фактор X_2), количества пустот в сечении стены на 1 мп в продольном направлении n (фактор X_3), коэффициента теплопроводности материала несущей части сечения стены U_1 (фактор X_4) и коэффициента теплопроводности изоляционного материала в пустотах U_2 (фактор X_5) при постоянной площади сечения несущей части стены, принимаемой по условию обеспечения прочности. Совокупность данных для анализа получена путем реализации вычислительного эксперимента. Анализ и оптимизация параметров выполнены на основе детерминистических математических моделей, описывающих представленную зависимость для двух вариантов конфигурации сечения. Информация может быть полезна для научных работников, проектировщиков и технологов, занимающихся развитием решений зданий в относительно новой 3D технологии.

Ключевые слова: здания в 3D технологии, наружная стена, теплотехнические качества, коэффициент теплопередачи, коэффициент теплопроводности, детерминистическая математическая модель

INTRODUCTION

A fundamentally new approach to the design of buildings is becoming more and more popular across the globe. It is based on the creation of an information (computer) model of a building that has a numerical description and organized information about the object, which is used not only at the stage of its design and construction, but throughout the entire life cycle of the building. This approach is called Building Informational Modeling or BIM for short. At present, digital models of buildings are being integrated with the construction industry, where 3D printers are used in the construction of buildings, which apply the concrete mixture layer by layer according to the programmed contour of the building structure, thereby making building structures of the building or “printing” the building.

The trend for digitalization refers to the construction industry in the Russian Federation, which has been moving towards the development and implementation of an information modeling approach for buildings since the beginning of the century [1-3]. Currently, digital models of buildings are being integrated in the construction industry, where 3D printers are used in the construction of buildings, which apply concrete mixture layer by layer, reproducing the process of “printing” the building in reality [4-6].

Information on the materials used for 3D printing of buildings is extremely limited. However, it is known that the developers of the Chinese company WinSun [7, 8] use a cement-sand mixture with waste from demolition of buildings, fiberglass and special additives in their technologies. When using products of processing building materials and micro-reinforcing, the density of the resulting mixture was from 2000 to 2200 kg/m³, the flexural strength of the concrete mixture was 8.2 MPa, and the compressive strength was 34.5 MPa. The width of the printed layer ranged from 30-60 mm [7,8].

One of the Russian companies, SPETSAVIA, [9] offers high-strength cement mix, fiberglass concrete, M300 sand concrete, kaolin mixture as

a material for 3D printing. The density of the material is 2200-2350 kg/m³, the compressive strength is from 30 MPa. The layer width is 20-50 mm, the thickness is 5-10mm.

The company “Loughborough University” in the UK, when creating 3D printer designs, uses high strength cement concrete (with compressive strength of 100-110 MPa, the density of which varies between 2250-2350 kg/m³. The width of the printed layer is 25 mm, the thickness is 25 mm [10].

As it is known, the outer walls of heated buildings must have the required heat-shielding qualities. The analysis of fragments of the horizontal section of walls erected in 3D technology in several firms [11-13] showed that this problem remains unsolved. The thickness of the outer walls is most often taken equal to 300mm. The walls have a hollow structure. The placement of voids forms a far from optimal configuration from the point of view of thermal protection. The wall thicknesses of the bearing part of the section vary within 30-50 mm for external walls, and 15-30 mm for internal walls. As an example, discussed further in the authors’ study, we present a fragment of a section of the wall of the company Contour Crafting (Figure 1) [14]. Using the AutoCAD software package, the authors calculated the area of the bearing part, which amounted to 0.186 m², for a fragment of this section 0,3×1 m² in size. The proportion of the bearing part in the total section area was 62.0%.

It is known [15] that the heat transfer resistance of a hollow product is significantly affected by the heat flux path length in the partitions between voids from the base material. Analyzing the Contour Crafting wall [14], one can notice that the path length of the heat flux in the partitions was not analyzed. It is not the best from this point of view, although the partitions of the sinusoidal voids somewhat extend the heat flow path. In this study, the authors of the article considered it appropriate to return to the orthogonal pattern of the placement of voids, in particular, with the placement of longitudinal voids in the wall and the displacement of their centers in adjacent rows by half the length (Figure 2).

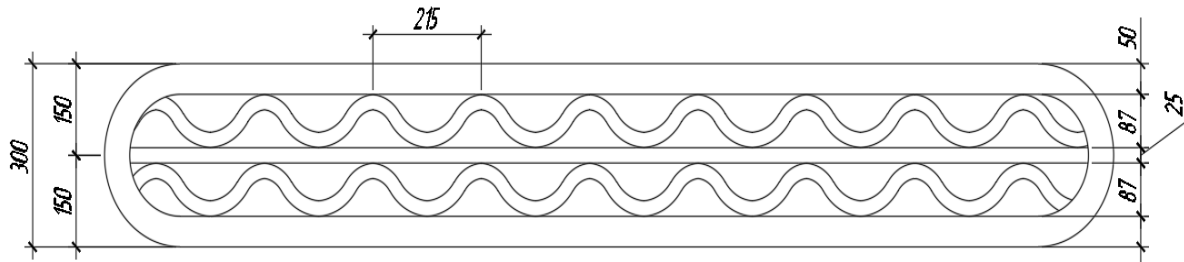


Figure 1. Contour Crafting Wall [14].

The authors assumed that by operating the number of voids in the section, as well as the thickness of the partitions between them, it is possible to provide a large number of options for the configuration of voids, which will allow installing a variant of a fragment of the wall with improved thermal properties.

The use of a large number of closed non-vented voids in the wall section is always complicated by the unequal conditions of their work, which affect the stability of their heat-shielding properties. The point is that with an increase in the thickness of voids inside them, the convective heat transfer increases, which does not increase, and sometimes reduces, the heat-shielding properties of voids [15, 16]. If cracks or damage occur in the wall sheath and the voids become ventilated, their heat-shielding properties are sharply reduced. On the other hand, the location of voids in the wall (in its outer or inner part) forms uneven temperatures on their surfaces, which affects the intensity of radiation heat transfer [15,16]. In the authors' opinion, in order to increase the thermal engineering reliability of walls with voids constructed in 3D technology, it is necessary fill the voids with various modern effective heat-insulating materials, which will not greatly complicate the technological part of the construction process [17-19].

The purpose of this study is to analyze the influence of the selected parameters of the external wall of the building, constructed in 3D technology, namely: the thickness of the external walls of the external wall d_1 (factor X_1), the thickness of the longitudinal partitions between the voids d_2 (factor X_2), the number of voids in the cross section of the wall in the transverse direction m

(factor X_3), the number of voids in the wall section per 1 m in the longitudinal direction n (factor X_4), the thermal conductivity coefficient of the heat-insulating material in the voids λ_1 (factor X_5) by the heat penetration coefficient of the wall fragment A (function Y) under the condition of constant cross-sectional area of the supporting walls, under the condition of ensuring the strength. The analysis is based on the deterministic mathematical model developed by the authors, which describes the studied dependence for the selected void formation scheme in the wall section. Using the model, the optimization procedure of parameters was carried out.

1. DESCRIPTION OF THE WALL FRAGMENTS UNDER STUDY

A fragment of the outer wall of a building constructed in 3D technology with a length $l_w=1.00$ m and a thickness $d_w=0.30$ m was selected as the object under study. The fragment variants differed in configuration and in the geometric parameters of voids in the section. First of all, a diagram of the configuration of voids in the wall was selected. Considering the data [15] on the influence of the heat flux path length in the partitions on the heat transfer resistance of a hollow product, in this study we adopted a scheme with orthogonal placement of longitudinal voids and a shift of their centers in adjacent rows by half their length (Figure 2). In order to increase the thermotechnical reliability of the wall in the fragments under study, it was also decided to fill the air voids with effective

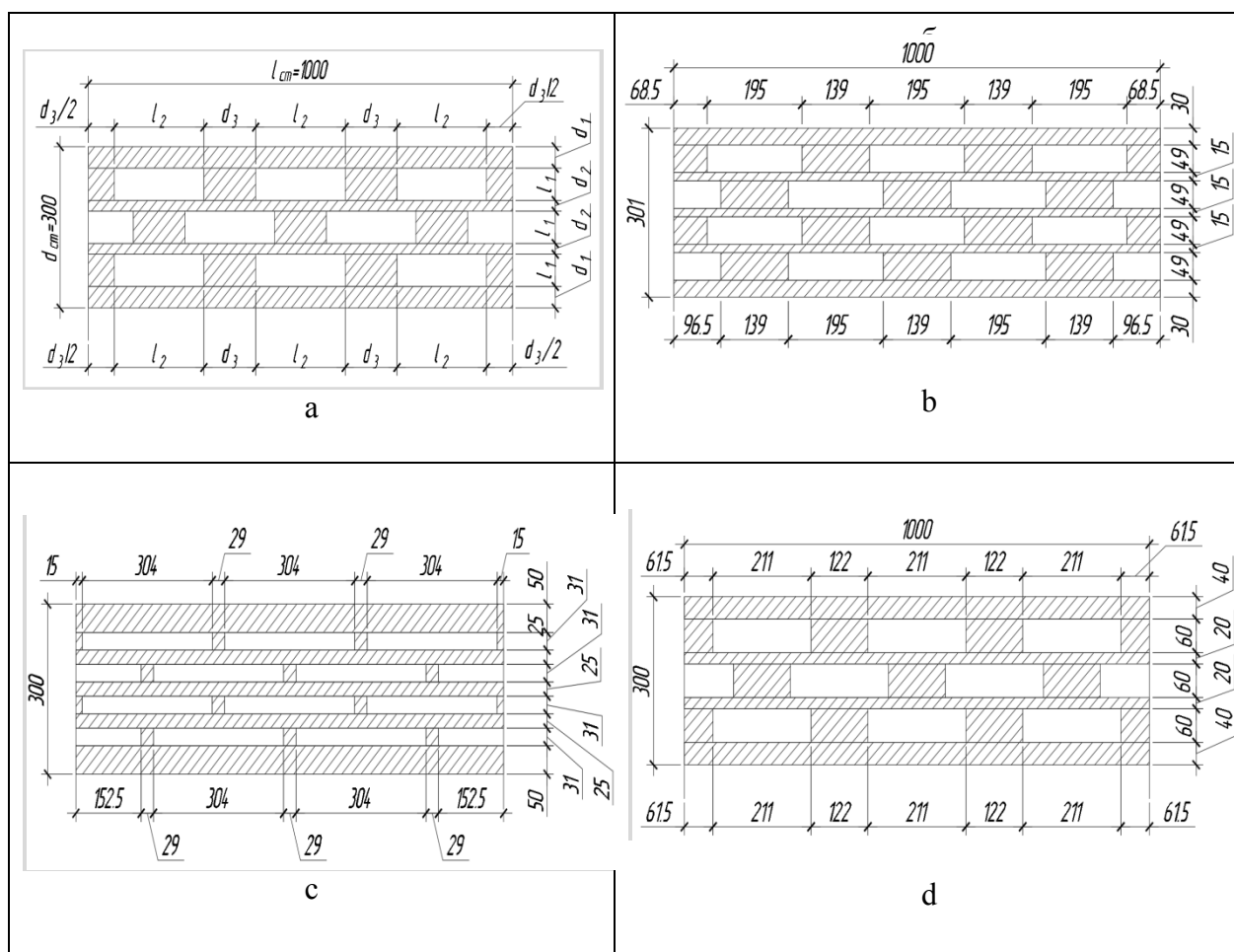


Figure 2. Options of a wall fragment in 3D technology with various configurations of voids in sections: a-general scheme; b-option # 5; option #8; option # 23 (numbering according to the plan in Table 1).

heat-insulating materials with a wide range of changes in the coefficient of thermal conductivity of the material of the liners.

The initial condition for all considered configuration options is the constancy of the cross-sectional area of the load-bearing part of the wall for each of the variants of void formation, adopted by the condition of ensuring strength and comprising 62% of the total cross-sectional area of the wall fragment, as recommended in [14]. This condition put forward the task of cutting voids in the wall with equally balanced configuration options, i.e. options with different configuration of voids, but with the same cross-sectional areas of the bearing part, comprising $0.30 \times 0.62 = 0.186 \text{ m}^2$. For cutting voids, the authors' program implemented in Exel was used.

2. METHOD OF CALCULATING HEAT PENETRATION COEFFICIENT λ OF THE WALL FRAGMENTS WITH HETEROGENEOUS INCLUSIONS

Heat penetration coefficient of wall fragments λ , W/(m² °C) was calculated using the formula for the amount of heat Q , transferred by the wall [16]:

$$Q=A(\tau_B - \tau_H) Fz, \quad (1)$$

where: τ_{in} is temperature of the inner surface of the wall, $^{\circ}\text{C}$; τ_{out} is temperature of the outer

1. Entering independent variables $d_1, d_2, m, n, \lambda_1$
2. Entering stabilized variables $d_w, l_w, t_{out}, t_{in}, \alpha_{out}, \alpha_{in}, \lambda_2$
3. Calculating geometric parameters of the configuration of voids $S_{HЧ}, S_{H3}, d_3, l_1, l_2$
4. Calculating temperatures and heat flux in the fragment under study τ_{in}, τ_{out}, q
5. Calculating thermal permeability coefficient of a wall fragment A

Figure 3. Block diagram of the calculation of the heat penetration coefficient of the wall fragment A with heterogeneous inclusions.

surface of the wall, $^{\circ}\text{C}$; F is the area of the wall, m^2 ; z is heat transfer duration, s.

If we assume $F = 1 \text{ m}^2$ and $z = 1 \text{ s}$, then we obtain the formula for the heat flux q , that simplifies finding of the value A :

$$A = q / (\tau_{in} - \tau_{out}) \quad (2)$$

Previously, with the help of the authors' program, in Excel we generated possible and valid options for cutting voids for wall fragments. Then, geometric calculation models of wall fragments, reduced to 1 m, were imported from Autodesk AutoCAD 2016 in the R12/LT2 DXF file extension.

Further, for each variant of wall fragments, using the Elcut software package, two-dimensional temperature fields were calculated. The calculations were performed for the climatic conditions of the city of Tambov. The boundary conditions were taken as follows: outdoor temperature $t_{out} = -28^{\circ}\text{C}$; heat transfer coefficient of the outer surface of the wall $\alpha_{out} = 23 \text{ W}/(\text{m}^2\text{ }^{\circ}\text{C})$; indoor temperature $t_{in} = 20^{\circ}\text{C}$; heat transfer coefficient of the inner surface $\alpha_{in} = 8.7 \text{ W}/(\text{m}^2\text{ }^{\circ}\text{C})$; for end parts of the structure heat flux $q = 0 \text{ W}/\text{m}^2$. The results of the calculations were the temperatures on the inner τ_{in} and outer τ_{out} surfaces of the wall, as well as the heat flux q along the inner surface of the wall. These values served as data for calculating the heat penetration coefficient of wall fragments A . Figure 3 presents a simplified block diagram of the complete calculation of the heat penetration coefficient.

3. MATHEMATICAL MODEL OF HEAT PENETRATION COEFFICIENT OF WALL FRAGMENTS WITH HETEROGENEOUS INCLUSIONS

to achieve the stated goal a scientific method of mathematical modeling was used, which allows using mathematical dependencies to describe the functioning of the object under study, determine the output parameters, and search for the optimal values of the object parameters. Using mathematical modeling makes it possible to avoid physical modeling, reduce the process of pilot testing and reduce the complexity of the study. The main component in this formulation is the mathematical model [20].

To ensure the practical usefulness of the model and its effectiveness, it is recommended to develop short models that use the most important factors that describe the properties being studied and provide information that consumers are interested in. Factors in the models must be controllable, compatible, unique, mutually independent and directly affect the properties studied [20].

In accordance with the purpose of the study, the heat penetration coefficient A of a wall fragment, $[\text{W}/(\text{m}^2\text{K})]$ is adopted as a function of the target Y , which was studied depending on five factors: the thickness of the outer walls of the outer wall d_1 , [m] (factor X_1), thickness of longitudinal partitions between voids d_2 , [m] (factor X_2), the number of voids in the cross section of the wall in the transverse direction m , [pcs] (factor X_3), the number of voids in the wall section per 1 m in the longitudinal direction n , [pcs] (factor X_4), coefficient of thermal conductivity of thermal insulation material in voids λ_1 , $[\text{W}/(\text{m K})]$ (factor X_5) with a constant cross-sectional

area of the supporting part of the wall, under the condition of ensuring strength in the amount of 62% of the total area of the fragment.

It was assumed that the desired dependence $Y=f(X_1, X_2, X_3, X_4, X_5)$ can be described by an algebraic polynomial of the second degree. In order to obtain data to describe this dependence, a five-factor computational experiment was performed according to a second-order plan (Table 1). A composite symmetric three-level plan, including 26 experiments, was used [21]. To calculate the values of Y_i in 26 lines of the plan, the Elcut software package was used.

When choosing ranges of factors, the data on structural solutions of the external walls of buildings erected in 3D technology, taken from several foreign and domestic companies, which are presented by the authors in the overview part of the article, were taken into account. So for factor X_1 (thickness of the outer walls of the outer wall d_1), the following levels were accepted: 0.030 (-1) - 0.040 (0) - 0.050 (+1) m.

Factor X_2 (the thickness of the longitudinal partitions between the voids d_2) was adopted at the levels: 0.015 (-1) - 0.020 (0) - 0.025 (+1) m. The thickness of the transverse partitions between the voids d_3 , exactly like the sizes of voids l_1 , l_2 , were not were controlled, because otherwise it was impossible to fulfill the condition of constant cross-sectional area of the bearing part of the wall, adopted under the condition of ensuring strength. However, the minimum value of d_3 for the corresponding options for technological reasons was taken as not less than the thickness d_2 at the lower level, i.e. equal to 0.015 m. The maximum thickness d_3 was determined by the results of cutting the section into voids. The values of d_3 , l_1 , l_2 were required to calculate the heat penetration coefficient λ of the wall fragment and they are given in Table 1. Factor X_3 (the number of voids in the cross section of the wall in the transverse direction m) ranged between: 2(-1) - 3(0) - 4(+1). Factor X_4 (the number of voids in the wall section per 1 m in the longitudinal direction n) considered in the range of variation: 3 (-1) - 5(0) - 7(+1). It was taken into account that factors X_3 and X_4

were integer and cannot take fractional values. The last factor X_5 (thermal conductivity coefficient of the insulating material in voids λ_1) was considered in a wide range of changes: 0.028(-1) - 0.070 (0) - 0.112(+1) W/(m²K).

The integer values of the listed above factors $\dot{X}_1, \dot{X}_2, \dot{X}_3, \dot{X}_4, \dot{X}_5$ and the corresponding coded values in brackets X_1, X_2, X_3, X_4, X_5 are presented in Table 1. Transition from natural values \dot{X}_i to coded values X_i was carried out according to the formula [22]:

$$X_i = [2\dot{X}_i - (\dot{X}_{imax} + \dot{X}_{imin})] / (\dot{X}_{imax} - \dot{X}_{imin}) \quad (3)$$

where: \dot{X}_i , \dot{X}_{imax} , \dot{X}_{imin} are current, maximum and minimum natural values of the i -factor, respectively.

Accepted levels of selected factors allowed for the wall section under consideration to generate 3x3x3x3=81 configuration option for voids subject to the initial conditions. The remaining input parameters are taken at a constant level. The wall thickness is taken equal $d_w=0.300$ m; the estimated length of the wall section $l_w=1.000$ m. Given the fact that firms most often use dense (2200 kg/m³) and strong concrete for the bearing part of the wall section, the thermal conductivity coefficient of the material of the bearing section is assumed to be constant and equal to $\lambda_2 = 1.650$ W/(m K).

Based on the calculation results (Table 1) using the least squares method [22], a dependency model $Y=f(X_1, X_2, X_3, X_4, X_5)$ is constructed in the form of a second-order regression equation:

$$\begin{aligned} \hat{Y} = & 1.815 - 0.198X_1 - 0.027X_2 - 0.433X_3 + \\ & 0.336X_4 + 0.199X_5 - 0.018X_1X_2 + 0.004X_1X_3 - \\ & 0.033X_1X_4 + 0.005X_1X_5 - 0.044X_2X_3 - 0.032X_2X_4 - \\ & 0.042X_2X_5 - 0.037X_3X_4 + 0.029X_3X_5 - \\ & 0.064X_4X_5 - 0.007X_1^2 - 0.015X_2^2 + 0.060X_3^2 - \\ & 0.088X_4^2 - 0.008X_5^2. \end{aligned} \quad (4)$$

When assessing the adequacy of the model, it was taken into account that deterministic models are characterized by a one-to-one correspondence between external influence and reaction to this effect. In this regard, only one calcu-

lation is performed at each point in the plan. For testing, Fisher's criterion F was used, which showed how many times the scattering decreased with respect to the obtained regression equation compared with the scattering with respect to the mean [20,22]:

$$F = \frac{S_y^2(f_1)}{S_r^2(f_2)}$$

where: S_y^2 is variance of the mean; S_r^2 is residual variance;

f_1, f_2 are degrees of a system;

$$f_1 = (N-1) = 26-1 = 25; \quad f_2 = (N-N_b) = 26-21 = 5.$$

N is the number of experiments in a plan;

N_b is the number of coefficients in the regression equation.

The regression equation describes the experimental results adequately if the value F exceeds the tabular F_t at a significance level of p and degrees of freedom f_1 and f_2 . As calculations showed, $F = 0.2834/0.0020 = 141.9716$; tabular value $F_t = F_{0.05; 25; 5} = 2.60$ [22]. Therefore, the value F is many times higher than F_t , which confirms the adequacy of the model and its suitability for further analysis. The determination coefficient $R^2 = 0.9986$ also confirms the high efficiency of the model.

4. ANALYSIS OF RESEARCH RESULTS BASED ON MATHEMATICAL MODEL

The influence of the studied factors on the heat penetration coefficient λ of a wall fragment was analyzed on a mathematical model (4). For convenience and a better understanding, a discussion of the results was carried out using the natural values of the variables. Of greatest interest were the parameters of the wall fragment, which provided the smallest value of the thermal penetration coefficient λ . From this point of view, the factors comprised two groups that gave beneficial effects if the coefficient λ decreased with their

increase and useless (negative) effects if the coefficient λ increased with their increase.

Analyzing the constructed model, it was revealed that in the center G_p of the factor space, which is characterized by coordinates $d_1 = 0.040$ m; $d_2 = 0.020$ m; $m = 3$; $n = 5$; $\lambda_1 = 0.070$ W/(m K), the coefficient λ is 1.815 W/(m²K). Using the G_p point as a reference point, the influence of individual factors was estimated. It turned out that, taking into account the selected intervals of variation, the factor m (X_3) has the most powerful and useful effect on λ . When the value m changed from 2 to 4 voids in the transverse direction (the other factors in the analysis are characterized by coordinates for the G_p point), the value λ decreased from 2.308 to 1.442 W/(m²K), i.e. there was a decrease of 37.6%. Moreover, due to the small quadratic effect of this factor, an increase in the number of voids m from 2 to 3 reduced λ by 21.4%, but when m increased from 3 to 4, the value λ decreased by 16.2%. The uneven nature of the change in λ is due to the fact that with an increase in the number of voids in the wall section at a constant thickness, the thickness of voids filled with a heat insulator decreased, and thus their thermal resistance decreased.

Factor d_1 (X_1) had a weaker beneficial effect when the thickness of the outer walls of the outer wall changed from 0.030 to 0.050 m, λ decreased from 2.006 to 1.610 W/(m²K), i.e. by 19.7%, with a slight quadratic effect. The weakest beneficial effect was achieved by factor d_2 (X_2) - with a change in the thickness of the longitudinal partitions between voids from 0.015 to 0.025 m, a decrease in λ from 1.827 to 1.773 W/(m²K) was observed, i.e. by 3.0%.

Other factors had a negative effect - with their increase, λ increased. So, when n (X_3) changed from 3 to 7 voids in the longitudinal direction, λ grew from 1.391 to 2.063 W/(m²K), i.e. increases by 48.3%. Due to the significant quadratic effect, this growth was uneven: when n varied from 3 to 5 voids, λ increased by 30.5%, and when n changed from 5 to 7 voids, λ increased by 17.8%. This influence of factor n was due to the fact that with the increase in its value, the number of thermal bridges in the form

Table 1. Plan of a computational experiment for five factors if $N = 26$ experiments.

Nr	(X_1) d_1	(X_2) d_2	(X_3) m	(X_4) n	(X_5) λ_l	A_s $W/(m^2K)$	l_1/l_2	d_3
1	-1 0.030	-1 0.015	-1 2	-1 3	+1 0.112	2.198	0.113/0.169	0.164
2	+1 0.050	-1 0.015	-1 2	-1 3	-1 0.028	1.344	0.093/0.205	0.128
3	-1 0.030	+1 0.025	-1 2	-1 3	-1 0.028	1.868	0.108/0.177	0.157
4	+1 0.050	+1 0.025	-1 2	-1 3	+1 0.112	1.880	0.088/0.217	0.116
5	-1 0.030	-1 0.015	+1 4	-1 3	-1 0.028	0.893	0.049/0.195	0.139
6	+1 0.050	-1 0.015	+1 4	-1 3	+1 0.112	1.272	0.039/0.245	0.088
7	-1 0.030	+1 0.025	+1 4	-1 3	+1 0.112	1.417	0.041/0.230	0.103
8	+1 0.050	+1 0.025	+1 4	-1 3	-1 0.028	0.562	0.031/0.304	0.029
9	-1 0.030	-1 0.015	-1 2	+1 7	-1 0.028	2.644	0.113/0.072	0.071
10	+1 0.050	-1 0.015	-1 2	+1 7	+1 0.112	2.506	0.093/0.088	0.055
11	-1 0.030	+1 0.025	-1 2	+1 7	+1 0.112	2.848	0.108/0.076	0.067
12	+1 0.050	+1 0.025	-1 2	+1 7	-1 0.028	2.217	0.088/0.093	0.050
13	-1 0.030	-1 0.015	+1 4	+1 7	+1 0.112	2.133	0.049/0.084	0.059
14	+1 0.050	-1 0.015	+1 4	+1 7	-1 0.028	1.307	0.039/0.105	0.038
15	-1 0.030	+1 0.025	+1 4	+1 7	-1 0.028	1.642	0.041/0.099	0.044
16	+1 0.050	+1 0.025	+1 4	+1 7	+1 0.112	1.397	0.031/0.130	0.013
17	-1 0.030	0 0.020	0 3	0 5	0 0.070	2.015	0.067/0.114	0.086
18	+1 0.050	0 0.020	0 3	0 5	0 0.070	1.602	0.053/0.143	0.058
19	0 0.040	-1 0.015	0 3	0 5	0 0.070	1.808	0.063/0.120	0.080
20	0 0.040	+1 0.025	0 3	0 5	0 0.070	1.792	0.057/0.134	0.066
21	0 0.040	0 0.020	-1 2	0 5	0 0.070	2.331	0.100/0.114	0.086
22	0 0.040	0 0.020	+1 4	0 5	0 0.070	1.419	0.040/0.143	0.058
23	0 0.040	0 0.020	0 3	-1 3	0 0.070	1.332	0.060/0.211	0.122
240	0 0.040	0 0.020	0 3	+1 7	0 0.070	2.122	0.060/0.091	0.052
25	0 0.040	0 0.020	0 3	0 5	-1 0.028	1.604	0.060/0.0127	0.073
26	0 0.040	0 0.020	0 3	0 5	+1 0.112	2.011	0.060/0.127	0.073

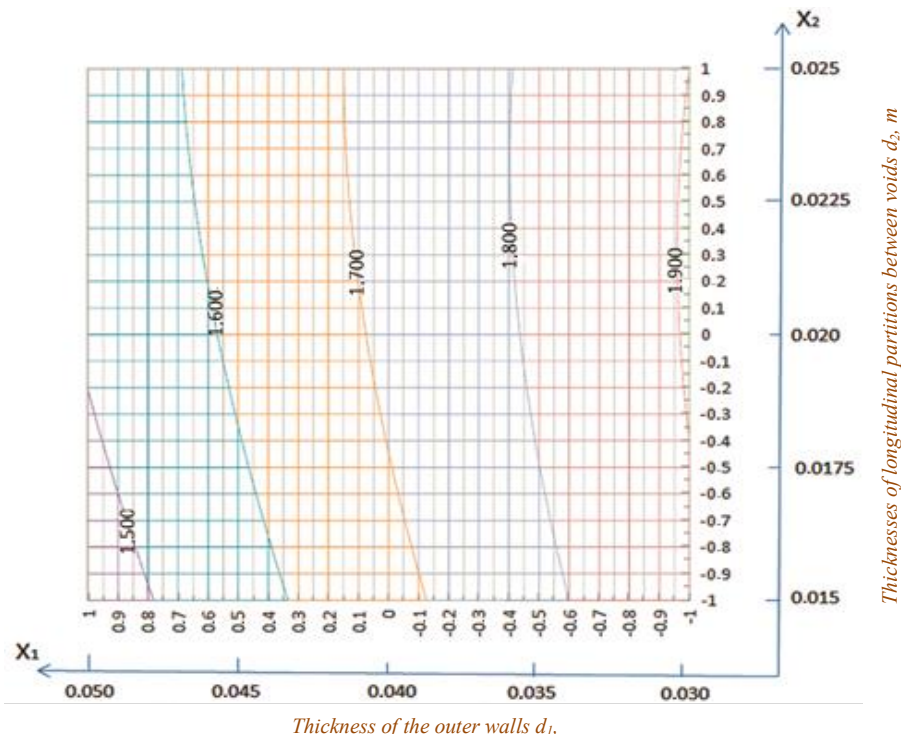


Figure 4. Correlation of heat penetration coefficient Λ , $W/(m^2K)$ (Y) of the wall fragment and the thickness of the outer walls d_1 , m (X_1) and thicknesses of longitudinal partitions between voids d_2 , m (X_2) if: the number of voids in the cross section of the wall in the transverse direction $m=3$ pcs. (X_3), the number of voids in the wall section per 1 m in the longitudinal direction $n=5$ pcs. (X_4), thermal conductivity coefficient of thermal insulation material in voids $\lambda_1=0.070$ [$W/(m K)$] (X_5) and a constant proportion of the cross-sectional area of the bearing part of the wall 62% of the total area of the fragment.

of partitions between the ends of the voids increased and the path length of the heat flux decreased.

A weaker negative effect was revealed by factor $\lambda_1(X_5)$. When the thermal conductivity coefficient λ_1 of the heat-insulating material in the voids changed from 0.028 to 0.112 $W/(m K)$, the value Λ increased from 1.608 to 2.006 $W/(m^2K)$, i.e. increased by 24.8% with a small quadratic effect.

The nature of the influence of factors is also shown in Figure 4 for correlation $Y=f(X_1, X_2)$ and Figure 5 for correlation $Y=f(X_2, X_5)$.

Based on model (4), the optimization procedure was performed and the extreme values of the heat penetration coefficient Λ of the wall fragment were determined, and the optimal values of the studied factors providing extrema were established. It turned out that the maximum value

of the heat penetration coefficient Λ equal to 2.938 $W/(m^2K)$, is achieved at $d_1=0.030$ m; $d_2=0.015$ m; $m=2$; $n=7$; $\lambda_1=0.112$ $W/(m K)$. On the contrary, the minimum value of Λ we are interested in, equal to 0.552 $W/(m^2K)$, is provided at $d_1 = 0.050$ m; $d_2 = 0.025$ m; $m=4$; $n=3$; $\lambda_1=0.028$ $W/(m K)$. These parameters should be considered optimal and recommended for solving the wall in 3D technology, since they provide the highest level of thermal protection. The range of values of the heat penetration coefficient Λ with varying factors was $2.938-0.552 = 2.386$ $W/(m^2K)$, which was 432.3% with respect to the minimum value of the heat penetration coefficient.

Thus, as a result of the study, it was revealed that for a constant area of the bearing part of the wall section constructed in 3D technology, by changing the configuration parameters of voids, namely,

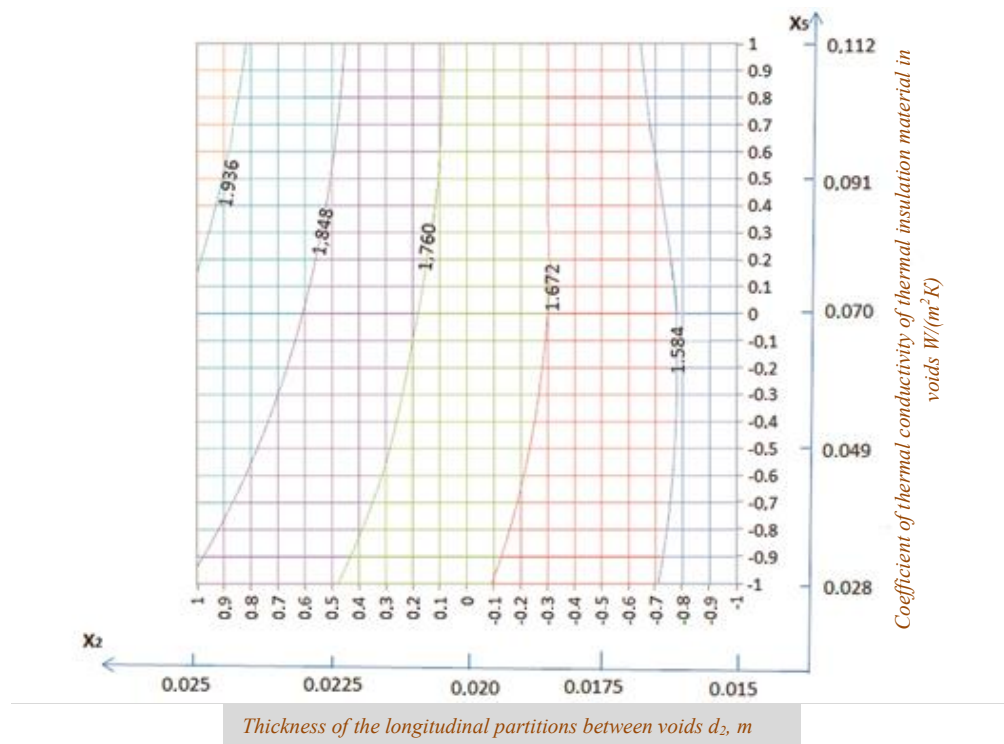


Figure 5. Correlation of heat penetration coefficient λ , $W/(m^2K)$ (Y) of the wall fragment and the thickness of the longitudinal partitions between voids d_2 , m (X_2) and coefficient of thermal conductivity of thermal insulation material in voids λ_1 , $[W/(m K)]$ (X_5) if: the thickness of the outer walls $d_1=0.040$ m (X_1), the number of voids in the cross section of the wall in the transverse direction $m=3$ pcs. (X_3), the number of voids in the wall section per 1 m in the transverse direction $n=5$ pcs. (X_4) a constant proportion of the cross-sectional area of the bearing part of the wall 62% of the total area of the fragment.

the number of voids in the transverse and longitudinal directions and the thickness of the partitions, as well as the corresponding choice of material for thermal liners in voids, it is possible to significantly reduce the value of the penetration coefficient λ of the wall. This indicates the potential of the proposed method for improving the heat-shielding qualities of walls with voids constructed in 3D technology.

CONCLUSIONS

1. The proposed deterministic mathematical model made it possible to assess the nature and degree of influence of the selected parameters of the wall constructed in 3D technology on the heat penetration coefficient λ of the wall fragment.
2. The heat penetration coefficient λ of the wall fragment decreases with an increase in the number of voids m in the transverse direction of the wall section, the thickness d_1 of the outer walls and the thickness d_2 of the longitudinal partitions between the voids, as well as with a decrease in the number of voids n in the longitudinal direction and the thermal conductivity coefficient λ_1 of the thermal insulation material in voids.
3. The minimum value of the heat penetration coefficient λ of the studied wall fragment is 0.552 $W/(m^2K)$ and is achieved at $d_1=0.050$ m ; $d_2=0.025$ m ; $m=4$; $n=3$; $\lambda_1=0.028$ $W/(m K)$. These parameters provide the highest level of thermal protection and are optimal for

solving the problem of constructing the wall in 3D technology.

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