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FEM modeling of external walls made of autoclaved aerated concrete blocks

МКЭ-моделирование ограждающих стен, выполненных из автоклавного газобетона

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Key words: external walls; autoclaved aerated concrete blocks; heating performance uniformity coefficient; reduced thermal resistance; modelling; FEM

Ключевые слова: наружные стены; блоки из автоклавного газобетона; коэффициент равномерности нагрева; снижение термического сопротивления; моделирование; МКЭ

Abstract. The FEM-analysis of factors influencing the heat transfer properties of external walls made of autoclaved aerated concrete blocks is presented. Using the ELCUT program, the external wall temperature fields made of autoclaved aerated concrete blocks were calculated for different values of thermal conductivity for laying cement mortar and laying with adhesive. The temperature field was calculated for a junction of a top floor slab with a two-layer external wall having a facing brick layer and no air cavity. The possibility of condensation of moisture on the surface of the ceiling is established. The values of heating performance uniformity of heat productivity, reduced thermal resistance and heat fluxes for external walls are determined. The calculated values of heating performance uniformity of heat output are obtained depending on the coefficient of thermal conductivity of autoclaved aerated concrete blocks. Further development of the research will be the use of data in calculating the payback period of energy efficiency measures for buildings.

Аннотация. Представлен МКЭ-анализ факторов, влияющих на теплопередающие свойства наружных стен, выполненных из блоков автоклавного газобетона. Используя программу ELCUT получены температурные поля внешней стены, выполненные из блоков автоклавного газобетона, рассчитывались при разных значениях коэффициентов теплопроводности для укладки цементным раствором и укладки клеящим раствором. Температурное поле было рассчитано для соединения верхней плиты перекрытия с двухслойной наружной стенкой, имеющей облицовочный кирпичный слой и воздушную полость. Установлена возможность конденсации влаги на поверхности потолка. Определены значения коэффициентов однородности теплопроизводительности, пониженного теплового сопротивления и тепловых потоков для наружных стен. Расчетные значения коэффициентов однородности теплопроизводительности получены в зависимости от коэффициента теплопроводности блоков автоклавного газобетона. Дальнейшим развитием исследований будет использования данных при расчете периода окупаемости мероприятий по энергоэффетивности зданий.

1. Introduction

1.1 Wall types with autoclaved aerated concrete blockwork applying

Unreinforced wall products of autoclaved aerated concrete (autoclaved aerated concrete blocks) is used as a structural and thermal insulation material in many countries with a cold climate.

The most used types of external walls made of autoclaved aerated concrete (AAC) blocks are shown in Figure 1:

– Type 1 – single-layer walls;

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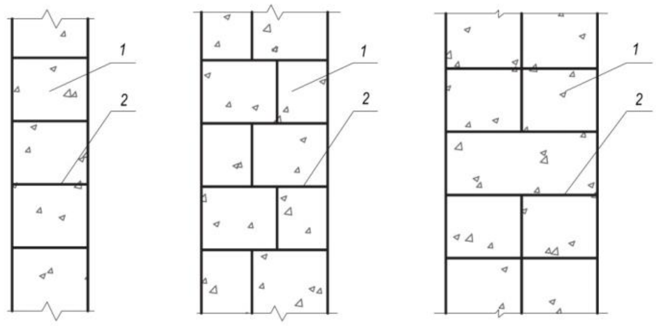
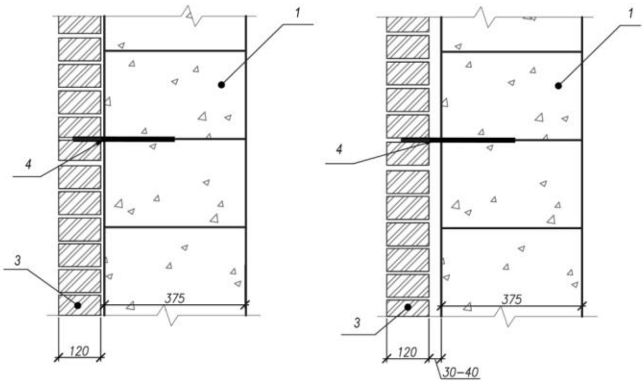
- Type 2 – two-layer walls with a facing brick layer; the inner autoclaved aerated concrete layer serves as a thermal protection and bares the load. The outer facing layer protects the structure from atmospheric precipitation; the wall structure may involve an air cavity;
- Type 3 – three-layer walls with a facing brick layer; the inner autoclaved aerated concrete layer serves as a thermal protection and bares the load; thermal insulation is provided to increase the thermal protection properties; the outer facing brick layer protects from atmospheric precipitation; the wall structure may involve an air cavity;

Type 1.



Type 2.



Type 3.

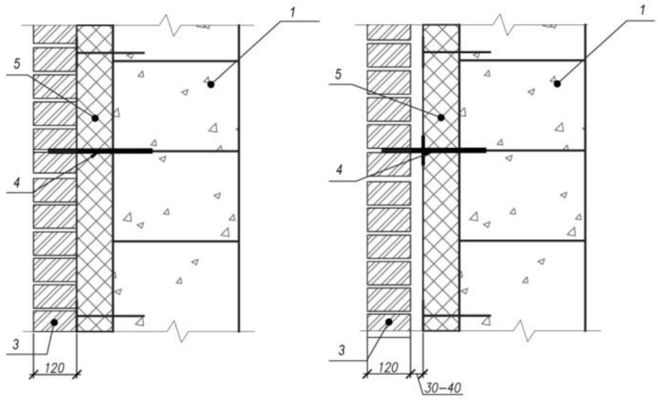


Figure 1. External walls types with autoclaved aerated concrete blockwork applying 1 – autoclaved aerated concrete blocks; 2 – joints; 3 – facing brickwork layer; 4 – flexible connections; 5 –thermal insulation

The peculiarity of external walls structural solutions, the quality and properties of the materials used, and the technology of building's erection have a significant effect on the physical processes of heat transfer in the structures of such walls and, accordingly, on their energy efficiency.

The main factors influencing the heating performance indicators are coefficient of thermal conductivity of autoclaved aerated concrete λ, W/(m·°C).

1.2 Coefficient of thermal conductivity of autoclaved aerated concrete

The thermal properties of autoclaved aerated concrete may vary depending on the materials used [1–5]. For a fixed composition of concrete, the coefficient is significantly dependent on humidity.

The fraction of pore volume in autoclaved aerated concrete products covers the range from 65 to 90 % [4] As a result, concrete easily absorbs water [6] and the thermal conductivity increases with increasing the moisture content [7, 8]. At the temperature below zero. one of the basic mechanisms of moving water for cellular concrete with a moisture content over 30 % by weight is non-isothermal liquid transport [9]. The moisture diffusivity of autoclaved aerated concrete is a function of both temperature and moisture content [10, 11].

The humidity and thermal conductivity of autoclaved aerated concrete given in the manufacturers' lists include mostly just the thermal conductivity in dry state and generic data for the specific heat capacity and water vapor diffusion resistance factor [12]. A Humidity of autoclaved aerated concrete products during the erection of buildings is 2–3 times higher [13, 14] than the design humidity in normative and reference documents used in the calculation of thermal insulation of buildings due to release moisture content of concrete is generally higher than 40 % [15]. Heat transfer through the exterior building envelope in real operating conditions is always unsteady [12]. Values of the thermal conductivity will reach the normalized values only in few years after the erection of the building [16, 17].

Russian Construction Rules SP 50.13330.2012 [18] use the coefficient of heating performance uniformity of the enclosing structure is the indicator of thermal properties of the entire enclosing structure:

$$r = \frac{R_0^r}{R_0^{con}}, \quad (1)$$

where R_0^r is reduced thermal resistance of the enclosing structure section (m^2·°C)/W,

$$R_0^r = \frac{A}{\sum_1^m \frac{A_i}{R_{0,i}^r}}, \text{ (m}^2\text{·°C)/W}, \quad (2)$$

where A is a total area of indicative partition of the enclosing structure equal to sum of areas of separate sections, m^2; A_i – area of ith section of indicative partition of enclosing structure, m^2; $R_{0,i}^r$ – reduced thermal resistance of ith section of indicative partition of the enclosing structure (m^2·°C)/W;

R_0^{con} – thermal resistance of section of uniform enclosing structure (m^2·°C)/W.

Thermal resistance of the uniform enclosing structure

$$R_0^{con} = \frac{1}{\alpha_{\text{int}}} + \sum_i \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{ext}}, \text{ (m}^2\text{·°C)/W}, \quad (3)$$

where α_{int} – heat transfer coefficient of the inner surface of the enclosing structure W/(m^2·°C);

α_{ext} – heat transfer coefficient of external surface of enclosing structure W/(m^2·°C);

δ_i – thickness of the ith layer of the enclosing structure, m;

λ_i – thermal conductivity coefficient of the ith layer of the enclosing structure, W/(m·°C);

m –, the number of sections of the building envelope with different reduced thermal resistance.

In works [5, 13, 19], a significant heating performance heterogeneity of autoclaved aerated concrete blockwork is indicated. According to the calculation results given in [20], an increase in the coefficient of thermal conductivity (density) of autoclaved aerated concrete blocks leads to an increase in the coefficient of thermotechnical uniformity coefficients. The results of the calculation differ from the values indicated in [19] up to 10 %. However, these data were obtained only for blockwork with cement-sand mortar having a density of 1,800 kg/m^3 and a 10 mm thickness of horizontal and vertical joints. The work [21] gives data only for joints on cement mortar; blockwork with adhesive solutions providing a joint thickness of 2 ± 1 mm is not considered.

Due to the fact that the thermal conductivity of cement mortars and adhesives is significantly higher than the thermal conductivity of autoclaved aerated concrete products, their effect must be considered when designing the external wallis [15]. The thermotechnical uniformity coefficients of autoclaved aerated concrete walls depends on the thickness and thermal conductivity of mortar joints in stationary and non-stationary conditions [15].

The use of polyurethane foam adhesive to bond the concrete blocks in the masonry walls is technically and economically feasible [19, 22].

Plastering of type 1 external walls (Figure 1) made of autoclaved aerated concrete blocks is performed directly on autoclaved aerated concrete laying (when homogeneous walls provide the required parameters of thermal protection) or on thermal insulation fixed on laying (two-layer structure). Both thick-layered (with an average layer thickness of more than 7 mm) and thin-layered plasters (with an average layer thickness of 7 mm or less) are implemented. External finishing of walls made of autoclaved aerated concrete blocks is obligated, because when there is no finishing, walls have high air permeability.

Different surface coatings [23] and exterior plaster [24–26] can contribute to moisture and thermal performance of external walls made of autoclaved aerated concrete.

1.3 Aims and objectives of the study

In [27–29] A.S.Gorshkov and others developed a mathematical model for estimating the discounted payback period of investments for reducing energy resources needed in building's development. The model allows to perform quickly and efficiently a comparison of various energy-saving solutions based on economic viability.

In order to use this model, in the case of autoclaved aerated concrete blocks, detailed initial data are required. This data must include the heat transfer performance uniformity factors and the coefficient of thermal conductivity with taking into account the influences of mortar joints, surface coatings and exterior plaster, floor slabs perforations, etc.

For fast calculations of all these parameters, a model based on the finite element method (FEM) was proposed.

In 2018 the first results of FEM analysis of data on the effect of joints of the autoclaved aerated concrete blocks on the heat transfer uniformity of exterior walls was carried out [21] with the use of "ELCUT" software.

The task of this research is the further development of the approach and its comparison with experimental data.

2. Materials and Methods

The coefficient of thermal conductivity of autoclaved aerated concrete is taken as a function of density. Data for thermal insulation material (of grade with an average density of not higher than D400), structural and thermal insulation material (of grade with an average density above D400 and below D700) and structural material (of grade with an average density of D700 and above) are given in Table 1.

Table 1. Coefficient values of thermal conductivity of autoclaved aerated concrete blocks

Bulk humidity of the material	Thermal conductivity coefficient, λ, W/(m·°C), a grade of the autoclaved aerated concrete block							
	D200	D300	D400	D500	D600	D800	D1000	D1200
In dry condition (recommended by [30])	0.048	0.072	0.096	0.120	0.140	0.190	0.240	0.280
4% [30]	0.056	0.084	0.113	0.141	0.160	0.223	0.282	0.329
5% [30]	0.059	0.088	0.117	0.147	0.183	0.232	0.293	0.342
8% [31]	-	-	0.140	-	0.220	0.330	0.380	-
12% [31]	-	-	0.150	-	0.260	0.370	0.430	-

According to Russian State Standard SP 50.13330.2012 while designing structures, the coefficient of thermal conductivity of autoclaved aerated concrete blocks is taken when bulk humidity is 12% [18].

The coefficient of heating performance uniformity of the enclosing structure can be determined on the basis of calculation of the temperature field of the structure.

In this case, the calculations are performed according to the dependencies:

– - reduced thermal resistance of a non-uniform section of the enclosing structure

$$R_0^r = \frac{t_{\text{int}} - t_{ext}}{q_0^r}, \text{ (m}^2\cdot\text{°C)/W},, \quad (4)$$

where q_0^r – heat flow rate of non-uniform section of enclosing structure, W/m^2;

– thermal resistance of a uniform section of enclosing structure, (m^2·°C)/W

$$R_0^{con} = \frac{t_{\text{int}} - t_{ext}}{q_0^{con}}, \text{ (m}^2\cdot\text{°C)/W}, \quad (5)$$

where q_0^{con} – heat flow rate for uniform section of enclosing structure, W/m^2;

– heating performance uniformity coefficient of enclosing structure

$$r = \frac{q_0^{con}}{q_0^r} \quad (6)$$

Let us consider as an example a two-dimensional temperature field of a single-layer external wall structure made of autoclaved aerated concrete blocks (St. Petersburg, Russian Federation):

– design temperature of outside air is –26 ° C;

– design temperature of inside air is +20 ° C;

– the outer wall is made of 375 mm thick autoclaved aerated concrete blocks of density grade D300;

– the thickness of the horizontal and vertical joints of the laying: with cement mortar – 10 mm; with adhesive solution – 2 mm.

For the block laying, a cement-sand mortar and adhesive cement with density of 1800 kg/m^3 are used.

The coefficients of thermal conductivity of materials are determined for the operating conditions of the enclosing structure:

– for blocks (λ_b, W/(m·°C)) – when bulk humidity of the material is 12 %,

– for cement-sand mortar and adhesive cement (λ_m, W/(m·°C)) – when bulk humidity of the material is 4 % [20].

Blockwork joint thickness is taken:

– with adhesive solution: horizontal and vertical – within 2 ± 1 mm;

– with cement mortar: horizontal - not less than 10 mm and not more than 15 mm; vertical – from 8 to 15 mm.

Calculation of the temperature field and heat fluxes of the external wall structure is carried out in the program of simulation of two-dimensional thermal fields by the ELCUT finite element method which is widely used in thermal fields calculation in constructions [32–36].

3. Results and Discussion

3.1. Results of calculation

The temperature fields of the external wall were calculated using ELCUT program within the range of values of the thermal conductivity coefficient of autoclaved aerated concrete blocks from 0.088 (D300 block) to 0.6 W/(m•°C). The example of calculation results is presented in Figure 2 in the form of fields of heat flows under design conditions.

According to the calculation data, the heat flow through the enclosing structure and its thermal resistance are determined depending on the coefficient of thermal conductivity of autoclaved aerated concrete blocks (Table 2). In comparison, data on a uniform structure are given (without regard to joints).

The temperature field of the junction of the top floor slab with the wall is calculated when the thermal insulating insert is placed along the entire length of the structure (plane problem – Figure 3). A two-layer external wall with a facing brick layer without an air cavity has been set. The grade of autoclaved aerated concrete block is D400. The calculation did not take into account the heterogeneity of the blockwork of autoclaved aerated concrete, which corresponds to the laying with adhesive solution applying. The values of thermal conductivity coefficients of autoclaved aerated concrete blocks are λ_b=0.117 W/(m·°C). The calculation is carried under the outside air temperature, which was –24 °C. The graph of the variation of the ceiling surface temperature is shown in Figure 4.

a) cement mortar blockwork **b) adhesive solution blockwork**

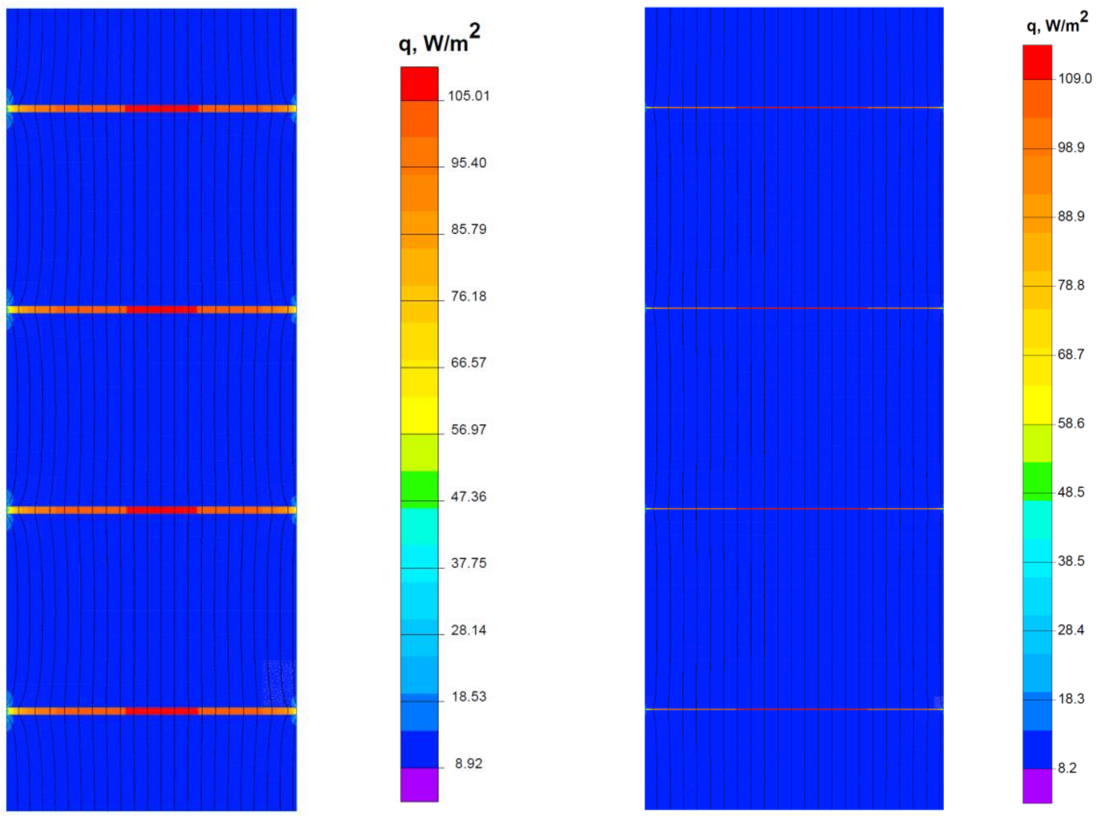


Figure 2. The example of heat flow calculation for external wall made of autoclaved aerated concrete blocks of density grade of D300

Table 2. Heat flow through the autoclaved aerated concrete blockwork and the thermal resistance of the structure

Thermal conduction coefficient of a block, λ_b, W/(m·°C)	Heat flow rate, q_i, W/m^2			Thermal resistance, (m^2·°C)/W		
	Uniform structure	laying: With cement mortar	laying: With adhesive solution	Uniform structure	laying: With cement mortar	laying: With adhesive solution
0.088	10.408	14.302	11.255	4.420	3.216	4.087
0.117	13.676	17.581	14.513	3.364	2.616	3.170
0.147	16.978	20.870	17.804	2.709	2.204	2.584
0.183	20.837	24.700	21.650	2.208	1.862	2.125
0.208	23.454	27.291	24.257	1.961	1.686	1.896
0.3	32.661	36.391	33.431	1.408	1.264	1.376
0.4	41.974	45.590	42.713	1.096	1.009	1.077
0.5	50.637	54.153	51.351	0.908	0.849	0.896
0.6	58.717	62.150	59.410	0.783	0.740	0.774

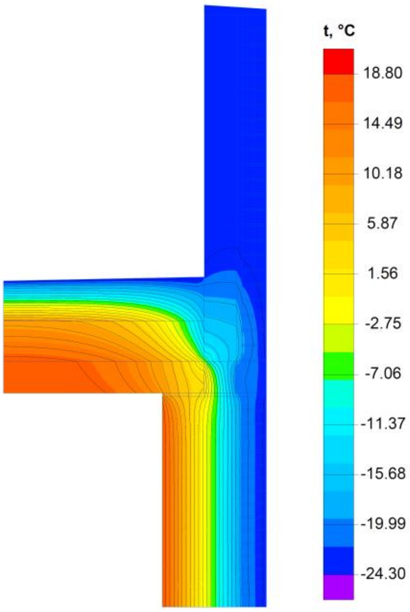


Figure 3. Temperature field of the junction of the top floor slab with an external wall made of autoclaved aerated concrete blocks of D400 grade of density and a brick facing layer

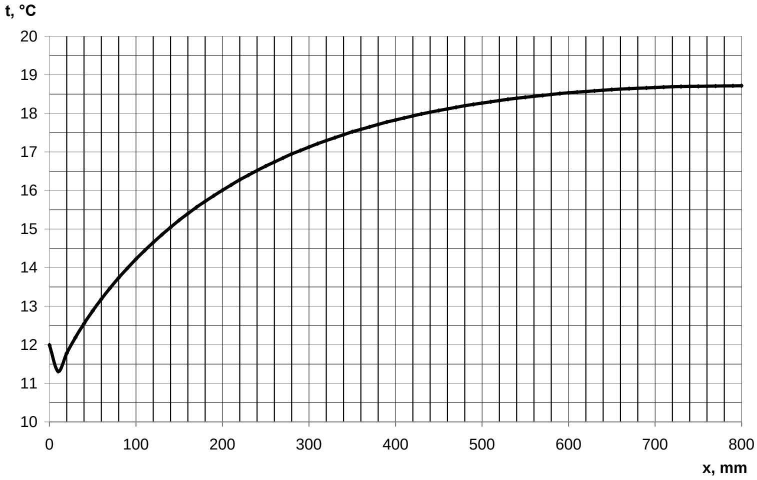


Figure 4. The graph of ceiling surface temperature changing (x – distance from the corner, mm)

3.2. Discussion

As it follows from the calculations performed, an increase in the coefficient of thermal conductivity (density) of autoclaved aerated concrete blocks leads to a decrease in the coefficient of heating performance uniformity (Table 2). The correlation between thermal conductivity coefficients of the joint material and of autoclaved aerated concrete blocks significantly affects the values of the heating performance uniformity coefficients of the blockwork with given thickness of joints (Figure 5).

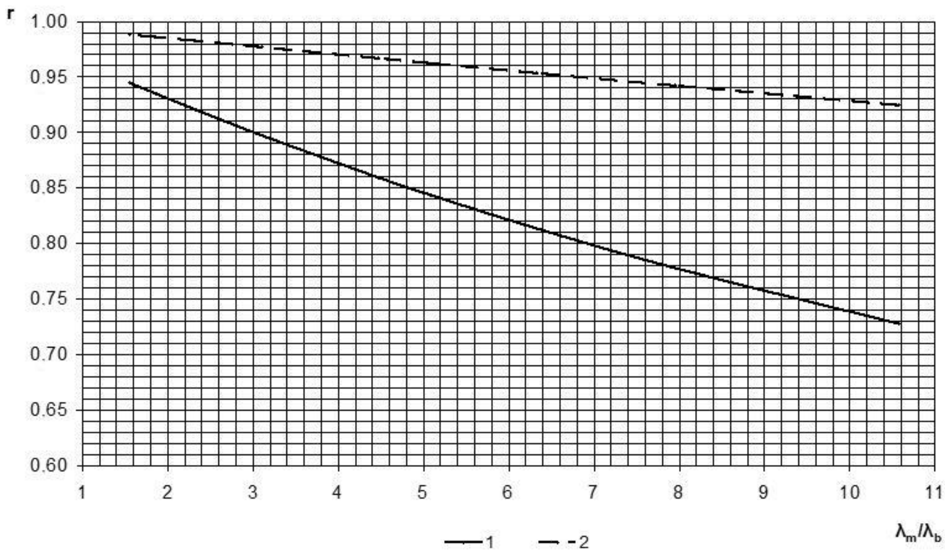


Figure 5. Dependence of the coefficient of heating performance uniformity on the ratio of the coefficients of thermal conductivity of the junction material and autoclaved aerated concrete blocks
1 – laying with using cement mortar with joint thickness of 10 mm; 2 – laying with using adhesive solution with joint thickness of 2 mm

During investigating the temperature field of the junction of top floor slab with the external wall made of autoclaved aerated concrete blocks of D400 density grade and the facing brick layer, the minimum surface temperature of the ceiling in the corner was determined equaling +11.3 °C (Figure 4). In this case, under internal air temperature of +20 °C and relative humidity of 58%, condensate falls out on the surface of the ceiling.

For junctions of intermediate floor slabs with an external wall, the minimum temperatures on the inner surface of the wall and the floor depend primarily on the thickness of the wall and the presence of perforation, or other thermal protective measures.

To further improve the laying of autoclaved aerated concrete blocks, it is required to develop adhesive solutions that are characterized by low values of the thermal conductivity coefficients [19, 22], while ensuring the required adhesion between the blocks and not impairing the performance of the enclosing structures in strength, stability, crack resistance, fire resistance, etc.

4. Conclusions

1. Design values of heating performance of buildings' external walls can be determined using the program of simulation of thermal fields by the ELCUT finite element method.

2. Thermal state of the external enclosing structures made of autoclaved aerated concrete was calculated and the design values of the coefficients of heating performance uniformity for laying with the use of cement mortar and adhesive solution were obtained depending on the ratio of the thermal conductivity coefficients of junction material and autoclaved aerated concrete blocks.

3. It was established that it is necessary to model thermal fields of junctions of building structural elements made of autoclaved aerated concrete blocks in order to test them for condensation of moisture on the surface.

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