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SOLVING HEAT ENGINEERING PROBLEMS USING THE FINITE ELEMENT METHOD

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Abstract

Introduction: In the course of the study, we examined energy-efficient and environmentally friendly heat-insulating materials based on gypsum and gypsum-containing primary components. **Purpose of the study:** We aimed to assess the effectiveness of using gypsum materials in wall structures, by using the finite element method based on the ANSYS Steady State Thermal module. Porous materials of different densities (structural, structural and heat-insulating, and heat-insulating gypsum concrete) were used as wall materials. These materials were obtained as a result of the interaction between residual sulfuric acid adsorbed on the grains of "acidic" fluoroanhydrite and carbonate flour. **Methods:** The finite element method based on the ANSYS Steady State Thermal module was used. The thermal conductivity of the structures was evaluated in a three-dimensional coordinate system. The experimental values of thermal and physical characteristics were adopted for the walling fragments. **Results:** The problem was solved numerically, by using the finite element method based on the ANSYS Steady State Thermal module. We established that the developed structural and heat-insulating gypsum concrete is more effective since, under the set design conditions, the temperature of the inner surface of such a wall at the minimum (510 mm) and maximum (770 mm) structure thickness exceeds the temperature of the inner surface of walls made of different materials.

Keywords

Fluoroanhydrite, gypsum concrete, calcium compounds, structure formation processes, finite element method, wall material, thermal conductivity.

Introduction

To implement the strategic tasks of resource and energy saving, we need to search for innovative technologies and justify the likelihood of improving the competitiveness of materials used for walling insulation. Among the currently used materials, energy-efficient and environmentally friendly heat-insulating materials based on gypsum and gypsum-containing primary components can be mentioned. Materials based on gypsum binders are characterized by high strength, heat and sound insulation properties, as well as fire and water resistance (Chernyshov et al., 2016; Pukharenko and Kharitonova, 2018; Zavadsky et al., 2003).

To reduce the average density of gypsum materials, porous aggregates as well as gas- and foam-forming admixtures can be used. Besides, admixtures generating gas in chemical reactions are also quite popular. This method is not new. Many researchers have been exploring this direction (Belov et al., 2012; Garkavi et al., 2018). However, their approaches to gas formation processes differ. We suggest using fluoroanhydrite raw materials as a pore-forming admixture, with sulfuric acid adsorbed on its grains and additional components generating gas in reactions with acid (Anikanova et al., 2020, 2021; Volkova and Anikanova, 2020). The implementation of this approach made it possible to develop structural, structural and heat-insulating, and heat-insulating gypsum concrete. However, evaluation of their effectiveness (as compared with traditional materials) is a labor- and time-consuming task. To assess the effectiveness of using gypsum materials in wall structures, we applied the finite element method based on the ANSYS Steady State Thermal module.

Materials and methods

Normally hardening gypsum of medium grinding, G-5 AII grade (State Standard GOST 125–2018), was used to manufacture wall materials. As a pore-forming component, "acidic" fluoroanhydrite (Specifications TU 2141–030-07622928–2019) was used together with calcium carbonate (State Standard GOST 32802–2014). According to the results of preliminary studies, without additional processing and chemical modification, fluoroanhydrite cannot be used to manufacture building products due to slow hydration and setting as well as poor strength characteristics. We used acidic fluoroanhydrite modified in a disintegrator, with sulfuric acid adsorbed on its grains, where fluoroanhydrite served as the “carrier” of the acid.

As a plasticizer, we used Steinberg superplasticizers with a concentration of 1, 1.6, 2, 5, and 10%, calculated with reference to the dried substance. They were introduced into the gypsum binder together with mixing water. The technical characteristics of Steinberg MP-4 and Steinberg PR-1S(A) superplasticizers were described by Lesovik et al. (2012) and Ponomarenko and Kapustin (2011). Citric acid (State Standard GOST 908–2004) was used as inhibiting the setting time of gypsum plaster.

The optimal amount of water was determined empirically until the normal consistency of gypsum dough was reached (according to State Standard GOST 125–2018). Using these materials, we formed standard samples of structural, structural and heat-insulating, and heat-insulating gypsum concrete and studied those in combination with masonry.

The problems were solved numerically, by using the ANSYS Steady State Thermal module, which is based on the finite element method. The thermal conductivity problems were solved in a full three-dimensional formulation. The experimental values of thermal and physical characteristics were adopted for the walling fragments.

As part of the calculation of temperature fields, a finite element (FE) mesh was assigned for each of the walling options.

Results and discussion

As a result of the research, we obtained samples of wall materials with adjustable characteristics (strength and average density). The porous structure of the material was formed as a result of the interaction between residual acid and carbonate flour. Since fluoroanhydrite represents a waste product of hydrofluoric acid production, and carbonate flour was obtained by grinding natural limestone, the cost of the materials is reduced significantly. Having analyzed the impact of the superplasticizers on the strength of the samples, we established the following: the use of Steinberg MP-4 plasticizer in the amount of 2% of the gypsum weight is optimal to ensure high strength, which is 27 MPa. This is due to a decrease in the water demand of the raw mixture and the participation of polycarboxylate in the gypsum stone structure formation (Fedorchuk, 2005; Garkavi et al., 2018). A gradual decrease in strength with a plasticizer concentration of more than 2% in the mixture is due to the impact of the polycarboxylate component on the hardening kinetics and stone structure. The admixture ensures additional entrainment of air bubbles and, therefore, makes it possible to obtain a less dense composite structure (Anikanova et al., 2018, 2019). The use of Steinberg PR-1S(A) plasticizer reduces the strength characteristics of the samples. The maximum strength, which is 7.4 MPa, was obtained at a plasticizer concentration of 2% of the gypsum weight, which is 2.5 times lower than the reference value (Erofeev et al., 2020; Medvedeva and Sautkina, 2019). The heat engineering characteristics of the structure were studied in accordance with Table 1.

The thermal conductivity problems were solved in a full three-dimensional formulation. Figures 1–3 show options of walling models considered in the study.

The geometric parameters of solid masonry (option 1) (figure 1) are as follows: thickness (a): 510, 640, and 770 mm; the height (b) and length of the samples were taken as 1000 mm.

The geometric parameters of three-layer masonry (option 2) (figure 2) are as follows: total thickness (a): 490, 620, and 750 mm; the height (b) and length of the samples were taken as 1000 mm; thickness of the bearing layer (1, c): 250, 380 510 mm; thickness of the insulation layer (2, d): 120 mm for all cases; thickness of the facing layer (3, c): 120 mm for all cases.

The geometric parameters of masonry with plastering (option 3) (figure 3) are as follows: total thickness (a): 560, 690, and 820 mm; the height (b) and length of the samples were taken as 1000 mm; thickness of the bearing layer (1, c): 510, 640, 770 mm; thickness of the plaster layer (2, d): 50 mm for all cases.

Table 1. Initial characteristics of the wall materials

Material	Thermal conductivity coefficient, λ (W/(m·°C))	Heat capacity, c (J/(kg·°C))	Density, ρ (kg/m3)
Masonry	0.64	880	1600
Structural gypsum concrete (type 1)	0.51	1090	1900
Structural and heat-insulating gypsum concrete (type 2)	0.23	840	1300
Heat-insulating gypsum concrete (type 3)	0.12	840	500

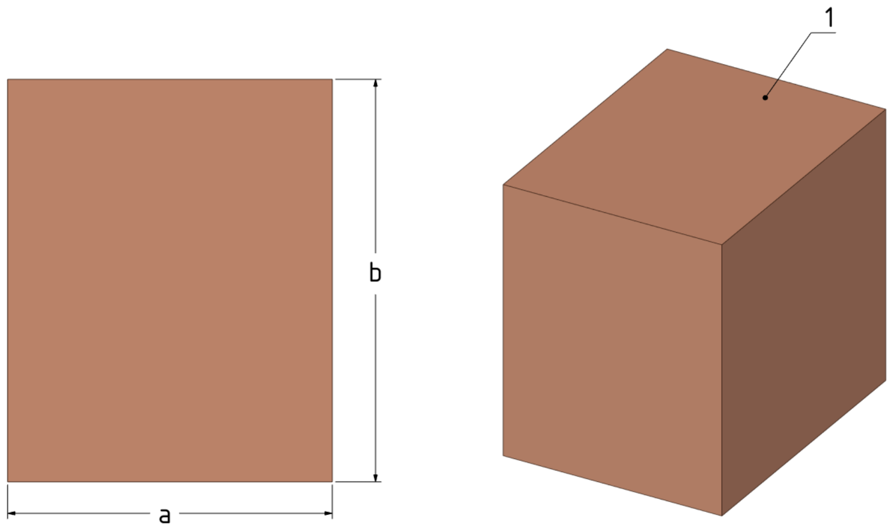

Figure 1. General view of a 3D model of a solid wall (option 1): thickness (a); height (b); solid wall material (1) — masonry, gypsum concrete (type 1, type 2)

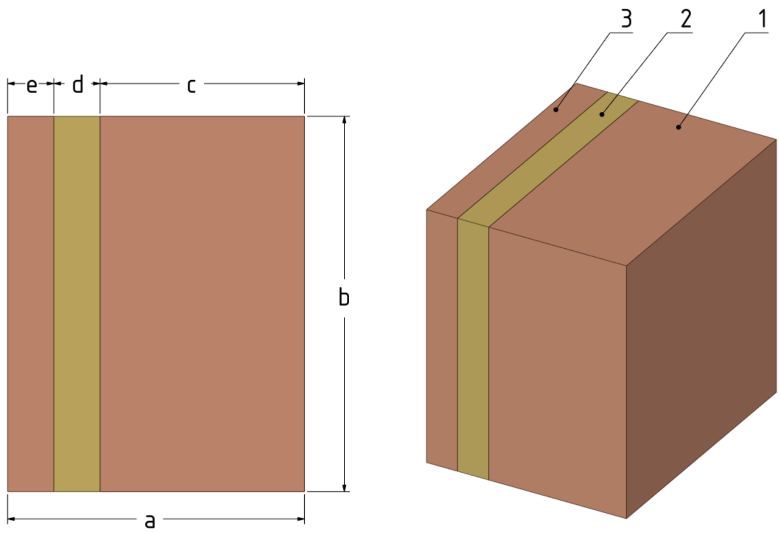

Figure 2. General view of a 3D model of a three-layer wall (option 2): thickness (a); height (b); bearing layer (c); insulation layer (d); facing layer (e); bearing layer material (1) — masonry; insulation layer material (2) — gypsum concrete (type 3); facing layer material (3) — masonry

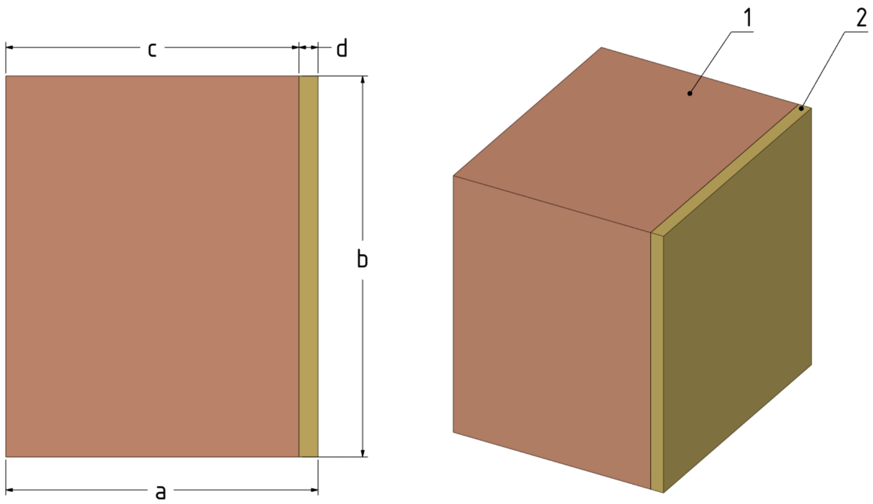

Figure 3. General view of a 3D model of a wall with plastering (option 3): thickness (a); height (b); bearing layer (c); insulation layer (d); bearing layer material (1) — masonry; plaster layer material (2) — heat-insulating gypsum concrete (type 3)

As part of the calculation of temperature fields, a finite element (FE) mesh was assigned for each of the walling options (figure 4). For option 1, the size of the FE mesh was 50 mm; for option 2 (insulation and facing layers) — 60 mm; for option 3 (plaster layer) — 12.5 mm. Thus, depending on the option as well as the varying thickness of the walls and layers, the dimension of the problems ranged from 4000 to 30,964 FEs.

A low order SOLID70 element, which has a 3D stationary or transient thermal conduction capability, was used as a FE (Znobishchev and Shamraeva, 2019). The element has eight nodes with a single degree of freedom (figure 5).

Initial and boundary conditions

As initial conditions in the computational domain, a temperature field was determined for each element (layer) of the structure, corresponding to the solution of the following stationary problem:

$$t_i\big|\tau = 0 = t_0\left(x, y, z\right), \quad i = 1,\dots,N, \quad x, y, z \in \Omega.$$

All inner and outer surfaces of the considered structural fragments are characterized by boundary conditions of the third kind, which take into account heat exchange between these surfaces and the environment. For inner surfaces, they can be written in the following form:

$$-\lambda_{n,m}\frac{\partial t_m}{\partial n}\bigg|_{n=0} = \alpha_{int}\left(t_{int} - t_{surf,ext}\right),$$

where n — the direction of the normal to the corresponding surface; m — the number of the structural element that contacts with internal air; $\lambda_{n,m}$ — thermal conductivity coefficient of the element material; t_{surf} — the temperature of the contacting surface.

At the interface of two adjacent elements, boundary conditions of the fourth kind were applied. In accordance with these conditions, the temperatures and heat fluxes shall be equal:

$$t_{bound,m}\big|_{bound} = t_{bound,m+1}\big|_{bound};$$

$$-\lambda_{n,m}\frac{\partial t_m}{\partial n}\bigg|_{bound} = -\lambda_{n,m+1}\frac{\partial t_{m+1}}{\partial n}\bigg|_{bound}.$$

For all ends of the considered structural fragments, symmetry conditions, corresponding to boundary conditions of the second kind with zero heat flux density, were established:

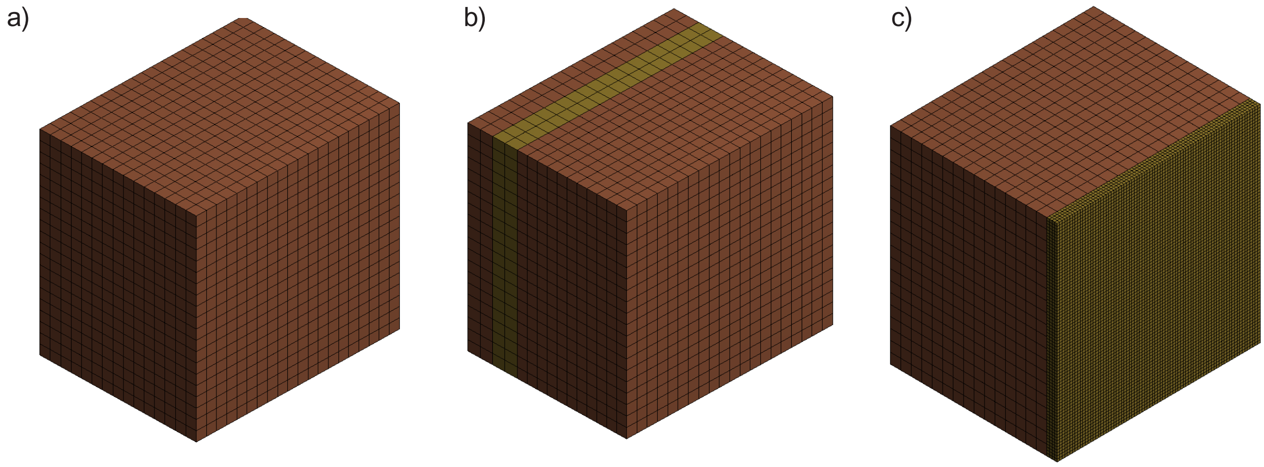

Figure 4. General view of the FE mesh for the options under consideration: option 1 (a); option 2 (b); option 3 (c)

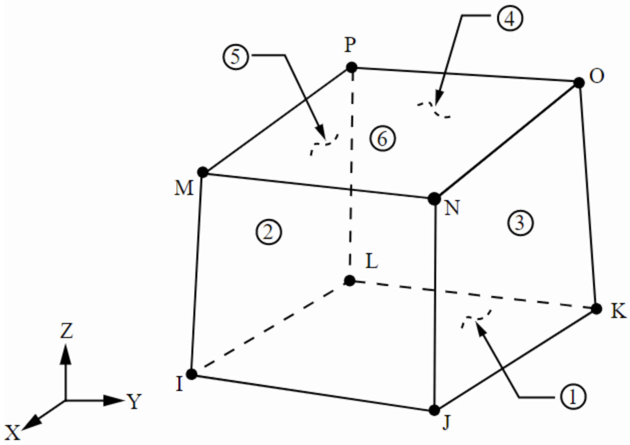

Figure 5. General view of the SOLID70 FE mesh

$$q\big|_{\text{bound}} = 0.$$

External temperature was t_{ext} = –39°C and internal temperature was t_{int} = 23 °C. The problems take into account the convection component in accordance with Regulations SP 50.13330.2012 “Thermal performance of the buildings”. The heat transfer coefficients were as follows: on the outer surface — α_{ext} = 23 W/(m2·°C), on the inner surface — α_{int} = 8.7 W/(m·°C) (figure 6).

Conclusions

Following the calculations, we obtained temperature fields for each of the considered walling options and materials used. The paper presents the results for design options with a maximum thickness of 770 mm. Figure 7 shows the temperature distribution for three walling options with a thickness of 770 mm. To compare the results of the temperature fields, Figure 7a shows an option of masonry with the required thickness.

According to the results presented in Figure 7, the inner surface of the walls has the following temperatures: in the case of option 1, 17.76 °C (a); in the case of structural and heat-insulating gypsum concrete — 20.97 °C (b); in the case of three-layer masonry with heat-insulating concrete — 19.72 °C (c); in the case of masonry with plastering using heat-insulating concrete — 18.99 °C (d).

Based on the presented research results, the following conclusions can be drawn:

1. Heat engineering problems can be solved numerically, by using the ANSYS Steady State Thermal module, which is based on the finite element method, to assess the effectiveness of using gypsum concrete in wall structures.
2. For the presented types of structural, structural and heat-insulating, and heat-insulating gypsum concrete with the particular thermal conductivity coefficients, heat capacity, and average density (Table 1), we developed three options of 3D walling models, calculated temperature fields for each of the considered walling options and materials used with a thickness of 770 mm, and compared the results with those in the case of masonry.
3. The presented model options in terms of temperature distribution throughout the wall thickness are comparable with masonry and make it possible to increase the temperature of the inner surface of walls from 17.76 (masonry) to 20.97 °C when using structural and heat-insulating gypsum concrete, without masonry of the same thickness.

Thus, in terms of the temperature of the inner surface of walls, the results obtained are comparable with those for masonry with a standard thickness of 770 mm. The developed structural and heat-insulating gypsum concrete (type 2, Table 1) is more effective than masonry since, under these particular design conditions, the temperature of the inner surface of a wall exceeds the temperature of the inner surface of masonry by 3 °C on average.

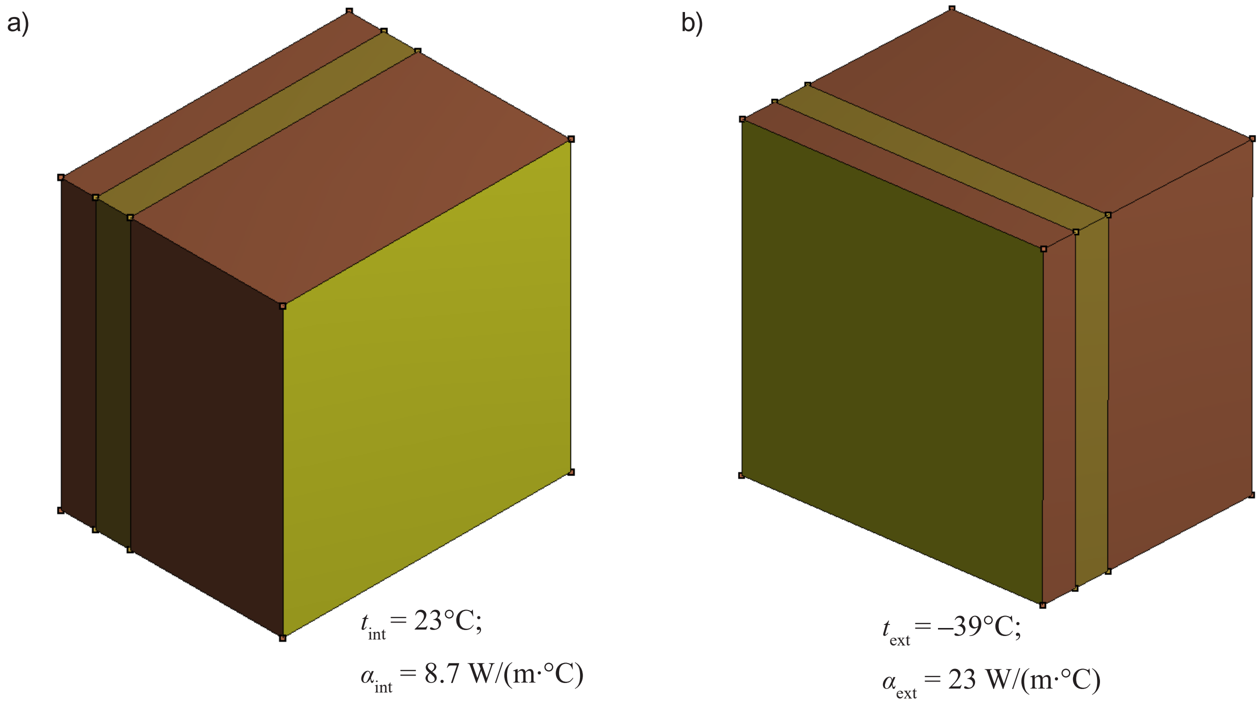

Figure 6. General principle of applying boundary conditions: the inner surface of the wall (a); the outer surface of the wall (b)

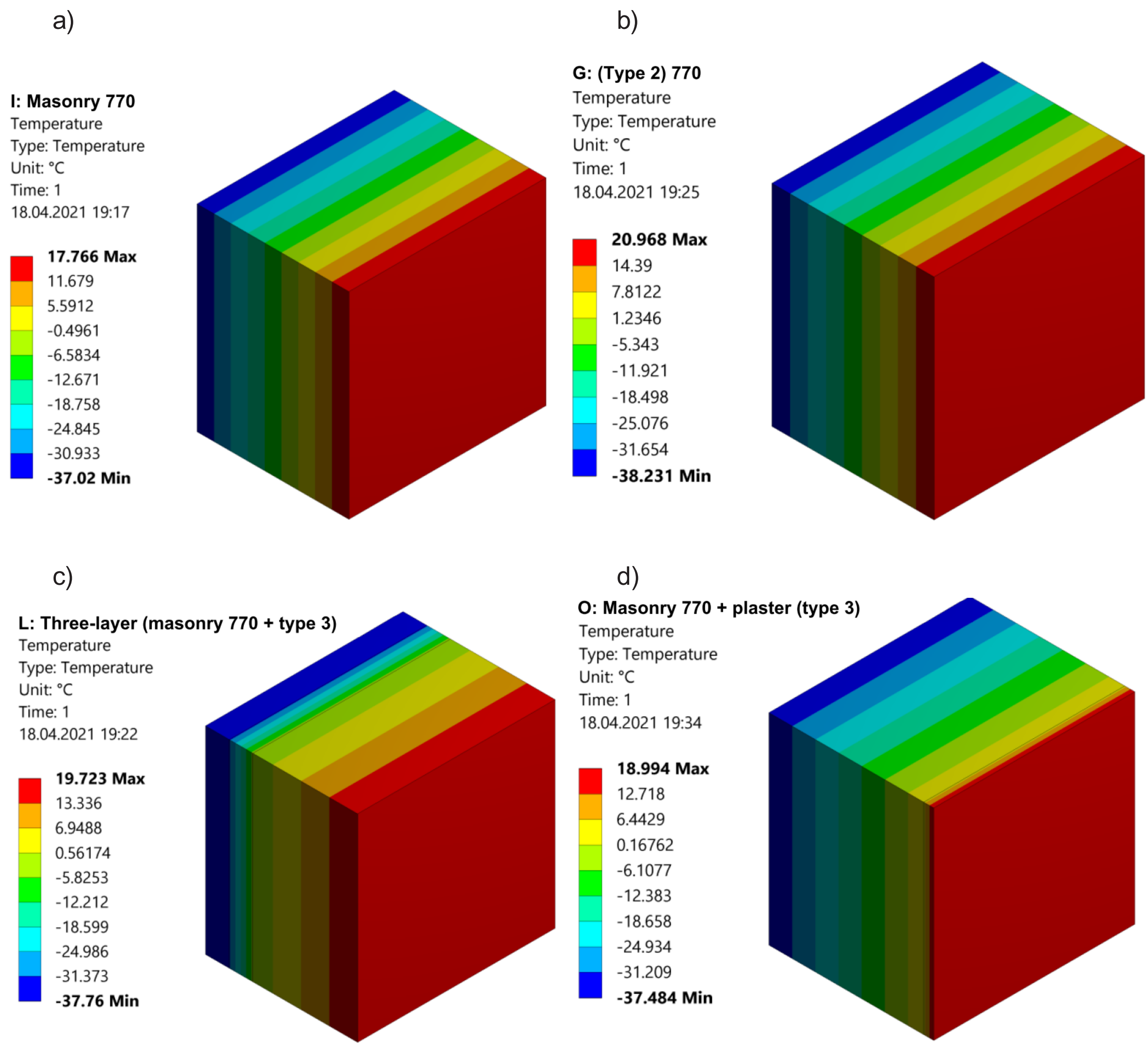

Figure 7. Temperature distribution in a 770 mm thick wall: option 1, masonry (a); option 2, structural and heat-insulating gypsum concrete (b); option 3, three-layer masonry with heat-insulating concrete (c); option 4, masonry with plastering using heat-insulating gypsum concrete (d)

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РЕШЕНИЕ ТЕПЛОТЕХНИЧЕСКИХ ЗАДАЧ С ИСПОЛЬЗОВАНИЕМ МЕТОДА КОНЕЧНЫХ ЭЛЕМЕНТОВ

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Аннотация

Изучение энергоэффективных экологически безвредных теплоизоляционных материалов на основе гипсовых и гипсосодержащих исходных компонентов. **Цель исследования:** Оценка эффективности применения гипсовых материалов в стеновых конструкциях, используя метод конечных элементов модуля STEADY-STATE THERMAL программного комплекса ANSYS. В качестве стеновых материалов использован поризованный материал разной плотностью (конструкционный, конструкционно-теплоизоляционный и теплоизоляционный гипсобетон), полученный путем взаимодействия остаточной серной кислоты, адсорбированной на зернах «кислого» фторангидрита и карбонатной муки в процессе протекания химической реакции взаимодействия. **Методы:** Метод конечных элементов модуля STEADY-STATE THERMAL программного комплекса ANSYS. Решение задач оценки теплопроводности конструкций осуществлялось в трехмерной системе координат. Для фрагментов ограждающей конструкции приняты экспериментальные значения теплофизические характеристики. **Результаты:** Численное решение задачи с помощью модуля STEADY-STATE THERMAL программного комплекса ANSYS, работа которого основана на методе конечных элементов, показало, что разработанный конструкционно-теплоизоляционный гипсобетон является более эффективным, поскольку при данных условиях расчета температура внутренней поверхности стены при минимальной толщине конструкции (510 мм) и максимальной (770 мм) превышает температуру внутренней поверхности стен из различных материалов.

Ключевые слова

Фторангидрит, гипсобетон, соединения кальция, процессы структурообразования, метод конечных элементов, стеновой материал, теплопроводность.