MATEC Web of Conferences 143, 01005 (2018) https://doi.org/10.1051/matecconf/201814301005
YSSIP-2017

Influence of metal frame on heat protection properties of a polystyrene concrete wall

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Abstract. The use of novel thermal-efficient building materials and technologies that allow increasing the level of thermal protection of external envelope structures and reducing the time for construction are of practical interest and represent a relevant task in the conditions of rapidly changing and increasing requirements to energy efficiency of buildings. This research aims at simulating the process of spatial heat transfer in a multilayer non-uniform structure of an external cast-in-place framed wall produced from polystyrene concrete with a stay-in-place formwork. Based on the physico-mathematical model developed with the use of ANSYS and COMSOL software complexes, parametric analysis of the impact of various factors on thermal behavior of the external wall was performed with the account of heat-stressed frame elements. The nature of temperature fields distribution in a polystyrene concrete structure was defined, and its thermal protection properties were investigated. The impact of a metal frame on thermal protection properties of a wall was found to be insignificant.

Introduction

The issue of energy efficiency improvement in buildings under construction with regard to the price-quality ratio and reduction of the negative effect of energy-related technologies on the environment is the high-priority task all over the world. Low-rise buildings in Russia have high energy saving potential, for its share in the country exceeds 50% of the total number of newly built constructions [1]. Since heat loss in buildings through external walls can reach up to 45% [2], search for novel thermal-efficient building materials and technologies that provide high level of thermal protection of external envelope structures is a relevant task.

One of the techniques of constructing main building frame that is gaining popularity is construction of cast-in-place polystyrene concrete walls. This composite material consists of cement, mineral and porous filler, water and several admixtures to provide such properties as strength, decay resistance, water resistance, etc. [1].

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Due to low thermal conductivity of polystyrene concrete a conclusion can be made that thermal protection of buildings with such walls will be high enough and will allow constructing buildings in Siberia without additional insulation. However, metal frame put inside the wall structure may have negative impact on thermal protection properties of external walls [3, 4-8].

In this regard, the purpose of this paper is evaluation of metal frame elements' impact on thermal protection properties of cast-in-place external walls, which is a relevant task with high practical importance.

Numerical experiment

Polystyrene concrete is one of prospective building materials, [9, 10] so is the cast-in-place construction technology with a stay-in-place formwork [11, 12]. In [3], the technique is suggested for construction of quickly erected frame buildings from polystyrene concrete, structural scheme of which is presented in Figure 1. External wall of a building contains internal load-bearing frame consisting of columns 2 joint by cross-beams 3, with fixed formed studs 5, and a foundation 1 (Fig.1). For low-rise buildings (1-3 floors) load-bearing structures, columns, cross-beams and flooring beams can be produced, for example, from steel tubes with the cross-section of 50×100 mm and the wall thickness of 4 mm joint by welding. If necessary, in order to increase the bearing capacity, fire resistance and seismic resistance steel tubes can be filled with heavyweight and/or lightweight concrete. The complete technology of the building construction is presented in [3].

The subject of the study described in this paper is a cast-in-place wall produced from D200 polystyrene concrete with the thickness of $\delta 1$ (Fig. 2), operating in extreme conditions. The wall structure includes a stay-in-place formwork from magnesium oxide boards with the thickness of $\delta 2 = 10$ mm, fixed to U-shaped studs with the size of 50×50 mm and thickness of $\delta 3 = 0.4$ mm. The load-bearing frame is produced from tubes with rectangular cross-section, the size of 50×100 mm, and thickness of $\delta 4 = 4$ mm.

Numerical experiments were performed with the use of ANSYS Mechanical APDL 17.0. and COMSOL Multiphysics 5.2 software complexes and were aimed at defining the impact of studs and location of internal metal frame inside the wall on the common thermal state of the structure.

Thermal state is investigated for three types of wall thickness: variant 1 – $\delta 1 = 0.6$ m; variant 2 – $\delta 2 = 0.45$ m; variant 3 – $\delta 1 = 0.3$ m. The location of metal frame inside the wall is different for each variant: variant A – at the distance of 100 mm from the internal surface of the wall; variant B – in the center of the wall; variant C – 100 mm from the external surface of the wall.

Physico-mathematical statement of a problem

For mathematical problem statement, geometrical parameters of envelope structure elements and their thermophysical characteristics presented in Table 1 are considered given, generally they may depend on the temperature.

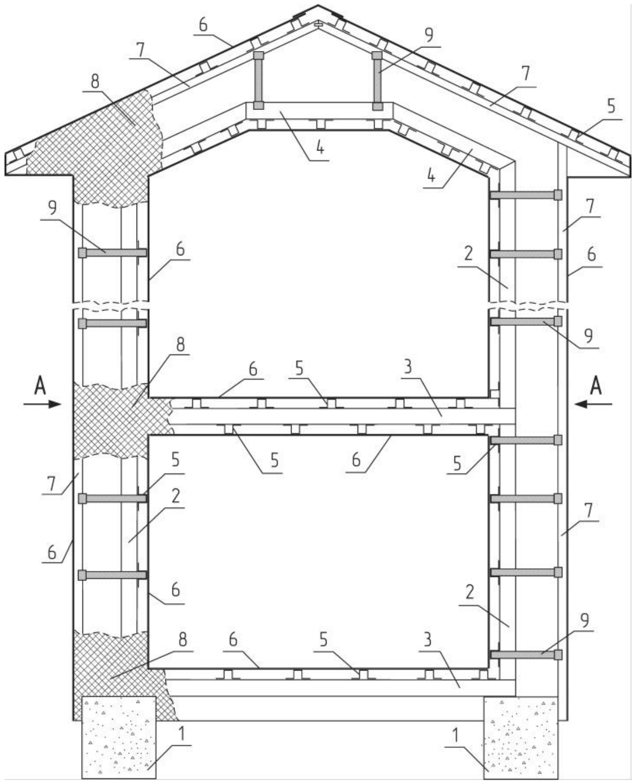

Fig. 1. Cross-sectional view of the building: 1 – foundation; 2 – column of internal frame; 3 – cross-beam of internal frame; 4 – flooring beam; 5 – formed stud; 6 – formwork board; 7 – external frame; 8 – lightweight concrete; 9 – temporary spacer.

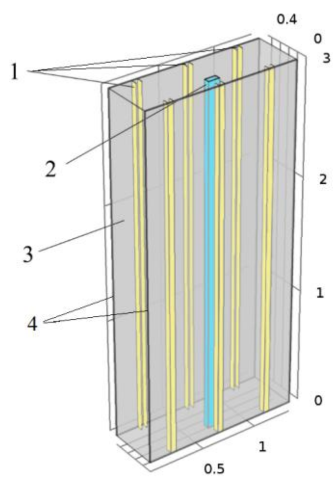

Fig. 2. Geometrical parameters of the structure: 1 – U-shaped stud; 2 – steel tube with rectangular cross-section; 3 – polystyrene concrete; 4 – magnesium oxide formwork.

Table 1. Values of thermal conductivity coefficients of wall materials.

No.	Material	Thermal conductivity coefficient λ, W/(m·°C),
1	Metal profile	57
2	Steel tube	50
3	Polystyrene concrete	0.07
4	Magnesium oxide	0.24

Established parameters are temperatures of outdoor t_{otd} and indoor t_{ind} air, as well as thermal conductivity coefficients for external and internal surfaces. The indoor and outdoor temperature values are +20 and -39 °C, and heat transfer coefficients for external and internal surfaces, respectively, are α_{otd}= 23 W/(m^2·°C) and α_{ind} = 8.7 W/(m^2·°C).

Stable spatial heat transfer in the studied wall fragment is described in Cartesian coordinate system as a system of nonlinear three-dimensional equations for thermal conductivity with corresponding boundary conditions for all structural elements' surfaces [8].

Calculation results

As the result of numerical study, the influence of studs and location of metal frame inside the wall on the common thermal state of the studied structure was determined.

Figure 3 illustrates temperature fields in the wall section for variant 1A in the raster image without (a) and with the account of studs (b).

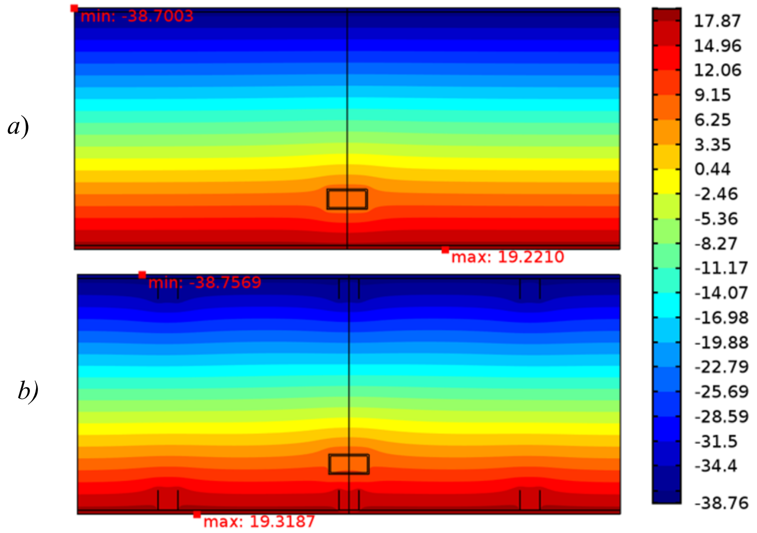

Fig. 3. Temperature field in the analyzed wall fragment: *a* – without studs; *b* – with studs

Comparative analysis of temperature fields in the considered variants of the wall structure demonstrates that presence of studs does not cause any remarkable variation in temperature field and their impact can be referred to as inconsiderable.

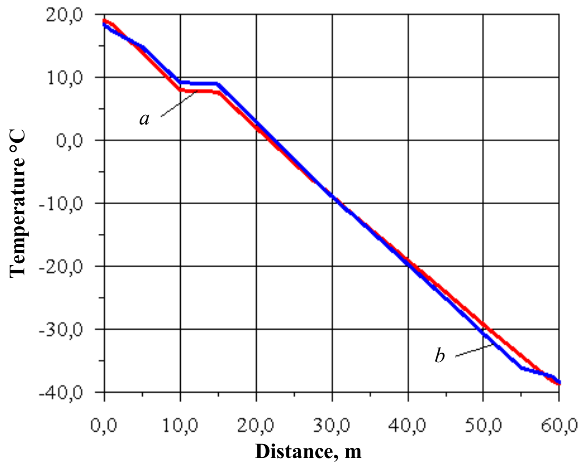

Fig. 4. Temperature distribution in the wall cross-section: *a* – without studs; *b* – with studs

This is supported by the calculation results given in Figure 4. It is visible from the Figure that the temperature difference of about 1 °C is observed in regions located around 10-15 cm away from the internal and external wall surfaces.

Based on such result a conclusion can be made that the impact of studs can be neglected when analyzing more geometrically complex spatial structures. This will enable to build a more uniform grid and simplify the task solution without considerable increase of error while dividing the analyzed area into finite elements.

Figures 5 and 6 demonstrate distribution of temperature in the wall thickness with different bearing frame locations for variants 1 and 2. According to the analysis of the presented results, the visible temperature variation is observed around the frame tubes. The maximum temperature difference in the studied cases is 5 °C. Such behavior of temperature distribution in the wall indicates the fact that location of the load-bearing frame also has no significant effect on thermal state of the structural fragment under study. However, if we consider the obtained data on temperature distribution from the point of creation of favorable microclimate in premises, location of the bearing frame in proximity to the internal wall is preferable, since half of the wall is in a higher temperature.

Figures 7 and 8 illustrate respectively the temperature field in a raster image and a vector image of the heat flow rate for a wall with the thickness of 0.6 m and a bearing frame located in the center.

The values of temperature and heat flow rates showed in these Figures visualize the thermal state of an envelope structure in different points of the studied wall fragment and enables to evaluate the impact of size and location of bearing frame elements.

The temperature of the internal surface of the wall for the considered case is higher than 19°C; it remarkably increases the dew point temperature which equals 15.2 °C even with quite high relative humidity φ = 75 %.

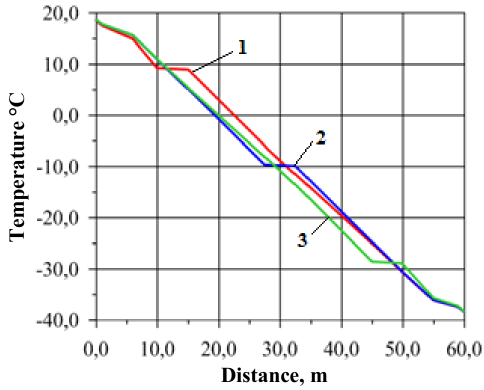

Fig. 5. Temperature distribution in the wall cross-section with different frame locations for variant 1:
1 – internal part of the wall; 2 – center; 3 – external part of the wall

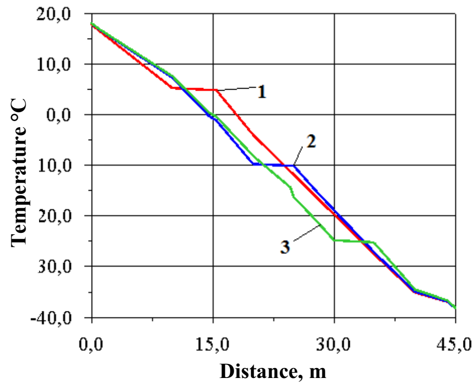

Fig. 6. Temperature distribution in the wall cross-section with different frame locations for variant 2:
1 – internal part of the wall; 2 – center; 3 – external part of the wall

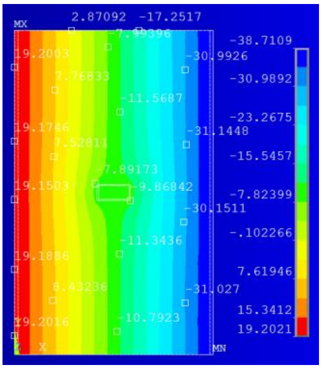

Fig. 7. Temperature field in the wall with the thickness of δ = 0.6 m

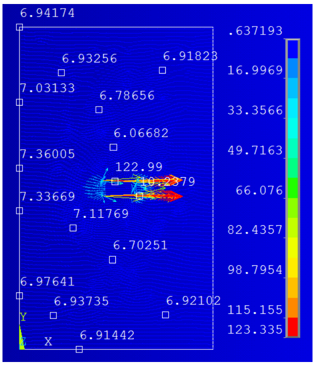

Fig. 8. Vector image of heat flow rate in the wall with the thickness of δ = 0.6 m

Since relative humidity of indoor air does not normally exceed 60%, this confirms operation efficiency of the analyzed types of envelope structures from the point of condensate formation on the internal surface of the studied types of walls in the given climate conditions. Similar situation is observed for other studied structures of walls with the thickness of 0.45 and 0.3 m. Due to performed analysis it was found that for a cast-in-place wall made of polystyrene concrete even with the thickness of δ = 0.3 m in the most heat-stressed region of a structure the temperature on the internal surface of the wall is higher than 16°C.

For the climate conditions of Tomsk city the standard value of thermal resistance of external walls currently is 3.75 $m^2{\cdot}°C/W$, whereas for the studied structured from polystyrene concrete such values are 4.08, 6.23 and 8.37 $m^2{\cdot}°C/W$ for walls with the thickness of δ = 0.3, 0.45 and 0.6 m respectively.

Thus, cast-in-place structure of an external wall produced from polystyrene concrete meets modern standard thermal protection requirements.

Conclusion

The obtained research results show that metal profile studs sized 50×50 mm have no significant impact on thermal state of structures for all considered types of walls; this enables to simplify the task solution without considerable increase of error and neglect such impact in further research.

It was found that location of load-bearing frame inside the wall also has insignificant effect on common thermal state of a structure. However, it is reasonable to install the bearing frame closer to the internal surface of the envelope structure for creation of a favorable microclimate in premises.

Based on the obtained numerical study results a conclusion can be made that the impact of metal studs can be neglected while performing further research on unstable thermal processes and while analyzing more geometrically complex spatial structures, including various heat-stressed elements. This will enable to build a more uniform grid while dividing the analyzed area into finite elements, reduce the analysis time and simplify the task solution without considerable increase of error.

The research was performed with the financial support of the Russian Foundation for Basic Research (project No. 16–48–700367 p_a).

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