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MATHEMATICAL MODELING AND EXPERIMENTAL INVESTIGATION OF THE PROCESS OF NON-STATIONARY HEAT TRANSFER IN A BLOCK FOAM GLASS SAMPLE AT THE ANNEALING STAGE

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Abstract. The specifics of the technology for the production of block foam glass are presented, the results of experimental studies of the properties of the material are presented, a method for improving production based on mathematical modeling of heat transfer processes is proposed. It is shown that the processes of high-temperature processing of foam glass make a key contribution to the formation of a high-quality porous structure, therefore, this area of research needs the development of adequate methods for calculating the main macrophysical parameters based on the theory of heat transfer. A technique for checking the adequacy of the mathematical model of heat transfer is presented using the example of spontaneous cooling of a foam glass block. The entire procedure for checking the adequacy of the mathematical model was carried out in three stages. At the first stage, the degree of validation of the model is assessed, functional dependencies with the results of an experimental study based on the Pearson determination coefficient. The main stage includes the evaluation of the confidence intervals of the experimental data and the discussion of the convergence of the results of the analytical calculation with the results of the experimental data. The final stage, at which a comprehensive assessment of the adequacy of the mathematical model is given, includes both the results of the preparatory and the main stages. The results of the study showed that it can be concluded that the calculated data have sufficient convergence with the experimental data and indicate the adequacy of the developed mathematical model of heat transfer.

Keywords: mathematical modeling, foam glass, raw mix, heat treatment, heat transfer, Pearson's criterion, Student's criterion

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ И ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПРОЦЕССА НЕСТАЦИОНАРНОГО ТЕПЛОПЕРЕНОСА В ОБРАЗЦЕ БЛОЧНОГО ПЕНОСТЕКЛА НА СТАДИИ ОТЖИГА

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Аннотация. Представлена специфика технологии производства блочного пеностекла, приведены результаты экспериментальных исследований свойств материала, предложен способ совершенствования производства на основе математического моделирования процессов теплопереноса. Показано, что процессы высокотемпературной обработки пеностекла вносят ключевой вклад в формирование качественной пористой структуры, поэтому данная область исследования нуждается в разработке адекватных методик расчета основных макрофизических параметров на основе теории теплопереноса. Представлена методика проверки адекватности математической модели теплопереноса на примере самопроизвольного остывания блока пеностекла. Всю процедуру проверки адекватности математической модели проводили в три этапа. На первом этапе проводится оценка степени валидации модели, функциональных зависимостей с результатами экспериментального исследования на основе

коэффициента детерминации Пирсона. Основной этап включает в себя оценку доверительных интервалов экспериментальных данных и обсуждение схождения результатов аналитического расчета с результатами экспериментальных данных. Заключительный этап, на котором дается комплексная оценка адекватности математической модели, включает в себя как результаты подготовительного, так и основного этапов. Результаты исследования показали, что расчетные данные имеют достаточную сходимость с экспериментальными данными и свидетельствуют об адекватности разработанной математической модели теплопереноса.

Ключевые слова: математическое моделирование, пеностекло, сырьевая смесь, термическая обработка, теплоперенос, критерий Пирсона, критерий Стьюдента

INTRODUCTION

The technology of foam glass production is characterized by a long sequence of different technological operations often complicated by destructive factors. Therefore, the development, analysis and implementation of advanced technologies require a wide range of physico-chemical and physico-technological studies to obtain a final product with optimal operational properties.

The crucial factor that determines the processes of change in the foam glass structure is the temperature-time mode of foaming and holding (annealing) of the material, which is also called the mode of high-heat treatment [1-3]. In the process of high-heat treatment of the raw material mixture for foam glass production, structural transformations are intensified, from softening to reaching the level of glassy state of the material. The necessity of theory development in this area is caused both by the factors of development and improvement of research methodology of foam glass technology as well as by reduction of unit production cost of finished products. It should be noted that modeling of heat transfer processes as a result of high temperature effect on the material plays an important corrective role.

For production of foam glass nowadays, both domestic raw materials and domestically recycled materials are used. The use of waste glass (recyclable sheet or industrial glass) solves the problem of disposal of waste glass, which contributes to solving a number of environmental problems.

There are various technologies of foam glass production, the most effective being the two-stage powder technology [4,5] which was first proposed by I.I.Kitaygorodskiy and T.N. Keshishyan [6].

The principal process diagram of block foam glass production is presented in Figure 1 [7].

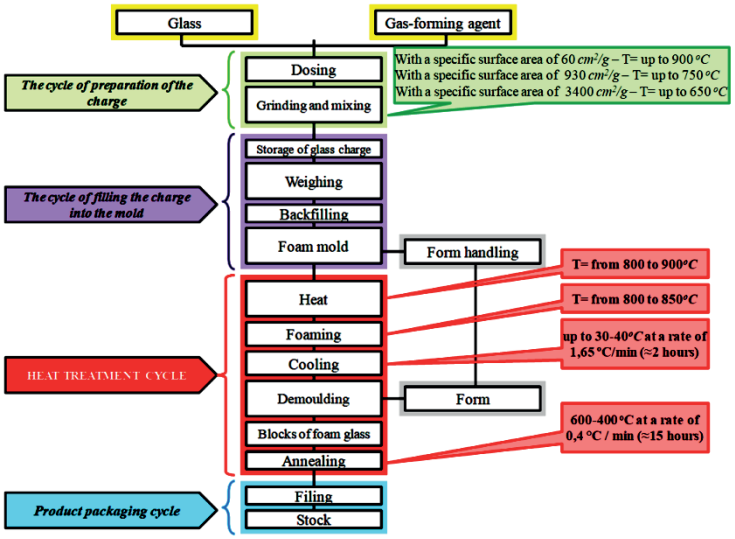


Figure 1. Process flowchart for foam glass production under two-stage powder technology

The operational sequence of the block foam glass production by means of the two-stage powder method is as follows: the feed raw material mixture being in a mold is transported into a lehr oven on ceramic rollers (Figure 2) [8,9].

In the first kiln (the section of thermal influence on the raw material mixture), the raw material mixture is heated, sintered, foamed and the foamed glass-crystalline structure is stabilized (Figure 3), then the foam glass blocks are extracted from the molds (Figure 4).



Figure 2. Loading the raw material mixture into the molds



Figure 3. Section of heating, sintering, foaming and stabilizing oven



Figure 4. Stage of extracting the finished foam glass blocks from molds

The used molds are returned on the conveyor belt to the stage of loading the raw material mixture (Figure 5), and the extracted blocks are transported to the annealing furnace (the section of thermal influence on foam glass) (Figure 6).



Figure 5. Fragment of the conveyor belt



Figure 6. Fragment of a foam glass annealing furnace

The powder method for foam glass production is as follows: crushed and milled glass and gas-forming agent (0.5-5% of glass weight) are loaded into the forms, heated to thermal decomposition temperature of gas-forming agent and annealed [9,10].

While the temperature increases, the glass particles are actively softened. For most types of glass, the active softening stage begins at temperatures of about 600°C [9,11]. The viscosity values of the milled glass remain high during this time. At further heating, thermal decomposition of the gas-forming agent occurs, and viscosity indices begin to decrease. Gases at the beginning of thermal decomposition of gas-forming agent form pores in the glass melt. Such kinetics of the process leads to growth of the pore diameter due to stretching of the glass mass shell. When the given size is reached, the heating process is stopped and the temperature is reduced to stabilize the foam glass structure [12,13].

When developing and improving the technology of foam glass production with taking into account the peculiarities of high-heat treatment and time parameters of its production, our researchers carry out their work in two main directions. The first one is the experimental determination of possible compositions of raw material mixtures for production of foam glass and selection of thermal treatment modes by means of the method of correction of quantitative parameters of raw material mixture composition [14-20]. The second research

direction is based on the development of theoretical and numerical methods of modeling of thermal processes occurring during foam glass production [21-28]. The second direction seems to be the most promising in terms of research of foam glass production technology as it allows us to reveal the regularities of material structure formation as well as to take into account the external and internal factors contributing to optimization of the process of foam glass production. However, it is worth noting that it would be practically impossible to develop any theoretical foundations without having the results obtained by the researchers applying the first experimental approach in their works, so it is necessary that theory and practice should exist in symbiotic relationship and complement and confirm the results obtained.

Modeling of heat treatment processes is based on the heat transfer theory, which allows us to take into account the influence of macro-physical parameters on each other. When developing a mathematical model being able to take into account changes in the physico-chemical properties of the raw charge, there arise some difficulties that might require the use of simplified (or approximate) mathematical models of heat transfer [29-33].

The system of differential equations worked out by A.V.Lykov and some physical concepts developed by him with respect to the moisture removal mechanism [34] constitute the theoretical basis for studying the heat and mass transfer processes occurring as a result of high-temperature effect on materials.

Application of exact analytical methods for solving nonlinear problems is practically impossible with modern methods of mathematical analysis, so numerical methods are becoming more and more popular. Solutions of partial differential equations are found using computer programs. The approaches described are applicable when the patterns of heat transfer have already been established, so it is required to obtain equations for simpler models, and, at the first stages of modeling, it is advisable to set boundary conditions and solve a plane problem for one of the coordinates (Figure 7).

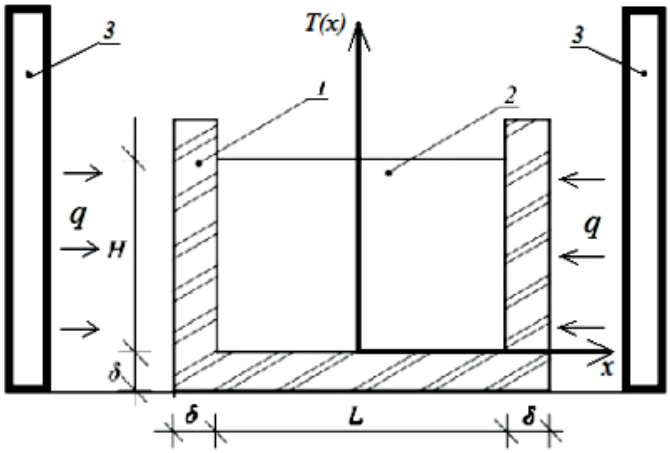


Figure 7. Geometric model used for setting up a problem: 1 - metal wall of the mold; 2 - raw material mixture; 3 - heat source; δ, L - thickness of the mold wall and raw material mixture

Under these conditions, the boundary problem of heat transfer in the raw material mixture placed in a metal mold is written as follows [35]:

$$\rho c \frac{\partial t(x,\tau)}{\partial \tau} = \lambda \frac{\partial^2 t(x,\tau)}{\partial x^2}; \tau > 0; 0 \le x \le \frac{L}{2}, \quad (1)$$

where ρ, c, λ are respectively: density, heat capacity and thermal conductivity of the raw material mixture.
- initial condition:

$$t(x,\tau)\big|_{\tau=0} = t_0(x); \tag{2}$$

- boundary conditions, respectively, of the first and second kind:

$$t(x,\tau)\big|_{x=0} = t_H\ ; \tag{3}$$

$$\frac{\partial t(x,\tau)}{\partial x}\bigg|_{x=\frac{L}{2}} = 0. \tag{4}$$

To solve a boundary value thermal conductivity problem, the Laplace transform method is used. The final solution of the boundary heat conduction problem is as follows:

$$T\left(\bar{x}, Fo\right) = 1 - \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n-1)}\sin\left[\frac{\pi}{2}(2n-1)\bar{x}\right]\cdot\exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right] + 2\sum_{n=1}^{\infty}\sin\left[\frac{\pi}{2}(2n-1)\bar{x}\right]\cdot\int_0^1 T_0(\xi)\cdot$$
$$\cdot\sin\left[\frac{\pi}{2}(2n-1)\xi\right]d\xi\cdot\exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right]\cdot \tag{5}$$

We transform the equation (5) into a dimensional form and obtain:

$$t(x,\tau) = t_H - (t_H - t_0)\cdot\left(\frac{4}{\pi}\cdot\sum_{n=1}^{\infty}\frac{1}{(2n-1)}\sin\left[\frac{\pi}{2}(2n-1)\cdot\bar{x}\right]\cdot\exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right] + \right.$$
$$\left. + 2\sum_{n=1}^{\infty}\sin\left[\frac{\pi}{2}(2n-1)\cdot\bar{x}\right]\cdot\int_0^1 T_0(\xi)\cdot\sin\left[\frac{\pi}{2}(2n-1)\cdot\xi\right]d\xi\cdot\exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right]\right). \tag{6}$$

The main requirements for mathematical models are adequacy, universality and efficiency.
A model is considered adequate if it reflects the given properties with acceptable accuracy. Accuracy is defined as a degree of coincidence of values of output parameters of the model and the object. Model accuracy is different in different conditions of technological process functioning. These conditions are characterized by external parameters. In the space of external parameters, it is necessary to identify the area of model adequacy, where the error is less than the specified maximum permissible error. Determining the area of model adequacy is a complex procedure that requires large computational efforts that rapidly increase with increasing the dimensionality of the space of external parameters. This problem can considerably exceed by its volume the problem of parametric optimization of the model itself, so it may not be solved for newly designed processes.

During the simulation of temperature fields in a foam glass block, the task of checking the adequacy of the mathematical models developed becomes many times more complicated due to the influence of a wide range of factors both on the simulated system and on the conditions of full-scale test. The authors present a method of research of developed mathematical model of heat transfer on the surface of foam glass during spontaneous cooling (annealing).

RESEARCH METHODS

For carrying out computational and full-scale experiments, a foam glass block was removed from the conveyor belt at the stage of extraction of blocks from the molds (extraction station) and placed on a pallet (in the air).
Figure 8 shows schematically the placement of thermocouples in a foam glass block.

Thereafter, we will consider the temperature change at Points 1 and 2 that are the center and surface of the foam glass block respectively, as their location can give the closest possible description of the temperature change features on the block interaction boundary, namely, the surface of its sides and the center of the material (Fig. 9).

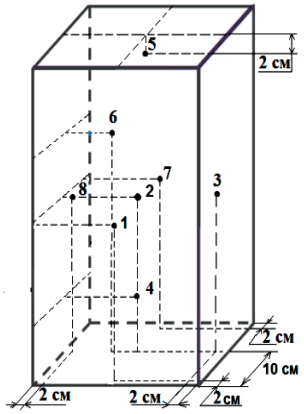


Figure 8. Distribution of thermocouples on the block under study

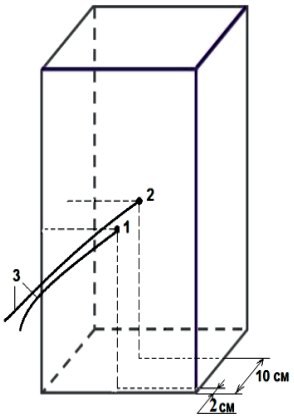


Figure 9. Distribution of thermocouples at Points No.1 and No.2 i.e. the center and the surface of the foam block respectively

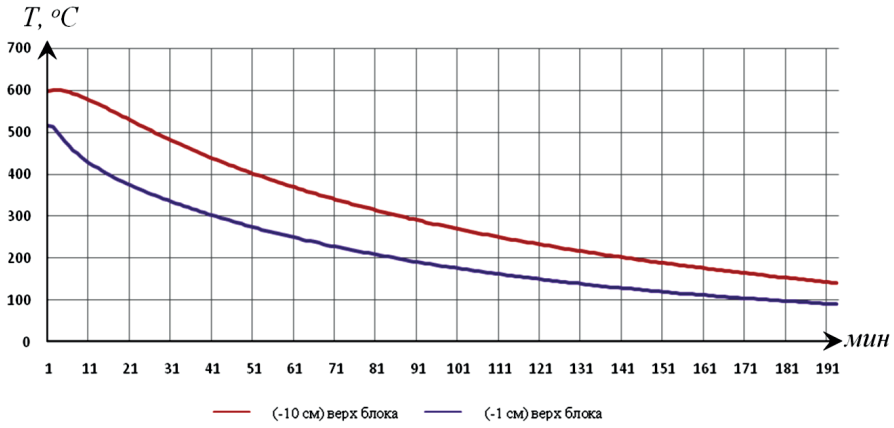


Figure 10. Temperature values in the center and on the surface of the block

As shown in the graphs (Fig. 10), in the process of spontaneous cooling of the foam glass block, the temperature values at the surface and in the center show similar dynamics with the presence of a stable difference binding. This fact indicates that there is a complex process of heat transfer. The porous structure of the material itself should also be considered as it contributes to the retention of heat within the foam glass block. The initial cooling conditions and interaction of the outer boundaries of the foam glass block with the surrounding air did not lead to a sharp decrease in temperature at its borders due to the closed pore structure, which can also be said about the temperature indicators in the center of the block.

To verify the adequacy of the mathematical model, we calculate the temperature values in the center and on the surface of the foam glass block. For calculations, we use a model (6).

For implementation of numerical modeling, we assume that the initial temperature of the foam glass block is 600±10 °C. The surface temperature (25±5°C) corresponds to the air temperature in the shop at the time of the experiment.

Calculations for the control point №1 are carried out at a time of 1 minute, the calculated value of

the Fourier number at this time is taken equal to 0.001. Based on the results of the calculations, we plot the graphical dependence of the temperature distribution in the foam glass block.

For descriptive reasons, we build a general functional dependence of the distribution of temperature fields from 1 to 90 minutes (Figure 11).

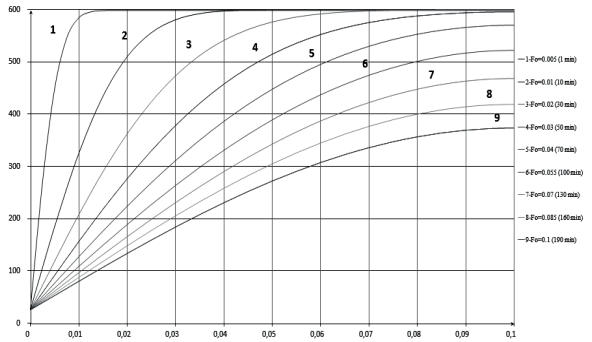


Figure 11. Graph of temperature field distribution on the surface of the foam glass at its cooling, taking into account the data obtained by a thermoelectric transducer at the Control Point No.1

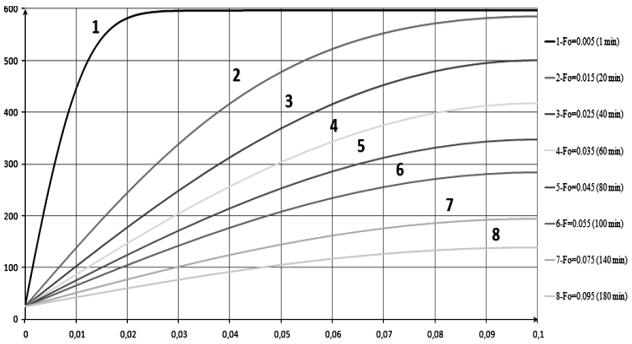


Figure 12. Graph of temperature field distribution in the center of the foam glass at its cooling, taking into account the data obtained by a thermoelectric transducer at the Control Point No. 2

Calculations for Control Point No. 2 are carried out at a time of 1 minute, the calculated value of the Fourier number at this time is 0.005. The difference of the Fourier number values compared with the values for the surface is due to the fact that the temperature gradient is directed from the center not only in the direction under consideration, but also in three other directions, so unlike the parameters on the surface, the temperature change rate at Control Point No.2 will be higher. In our calculations, we took it as being 3 times higher. Based on the results of the calculations, we plot the graph of temperature distribution indicators for the foam block (Figure 12).

As can be seen from the graphs of calculated and experimental values of temperature changes during cooling down of the block at the Control Point at 2 cm from the surface during 190 min (Fig. 13), the temperature dynamics is nonlinear, indicating the presence of an area of intense cooling and an area of temperature stabilization. The most intensive cooling is observed in the time intervals from 0 to 50 seconds, then a relative stabilization of the temperature is observed.

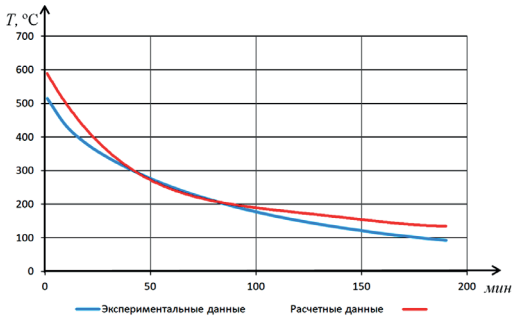


Figure 13. Diagram of changes in calculated and experimental values of temperature when cooling down the block at the Control Point for the center within 190 min.

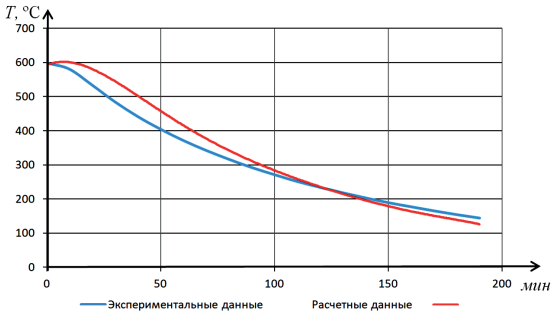


Figure 14. Diagram of changes in calculated and experimental values of temperature when cooling down the block at the Control Point for the surface within 190 min.

On the graphs of changes in calculated and experimental values of temperature when cooling down the block at the Control Point for the center for 190 min (Fig. 14), the temperature dynamics is also non-linear, indicating a complex heat transfer in the center of the foam glass block. Heat transfer by heat conduction (pore walls) as well as by convection (gas phase inside the pores) is observed. The key influence on the peculiarities of heat transfer in the center of the foam glass block is exerted by a closed pore structure inside the material.

Assessment of mathematical model adequacy includes preparatory, main and final stages.

At the preparatory stage, we evaluate the degree of validation of the model, functional relationships with the results of the experimental study on the basis of the Pearson determination coefficient.

The main stage includes the estimation of confidence intervals of experimental data and a discussion of the convergence of analytical calculation results with the results of experimental data.

The final stage which provides a comprehensive assessment of the adequacy of the mathematical model includes both the results of the preparatory and main stages.

RESEARCH RESULTS

According to the data presented in Fig. 15, we can draw the following conclusions:

- the calculated data for the model are close in value to the mean estimates of the experimental data and are contained within the confidence interval along the entire time axis;
- the maximum deviation of the calculated data is observed at the beginning and at the end of the time axis, which demonstrates the correct choice of the diffusion model of experimental data;
- the deviation of the calculated data from the experimental data is directed toward the upper exact limit, which provides the necessary margin for modeling the process of cooling the foam glass block.

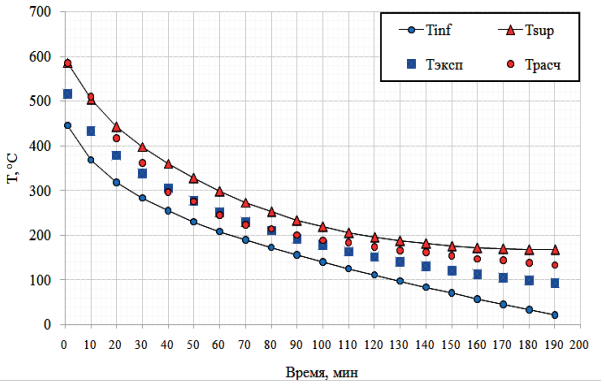


Figure 15. Comparison of calculated and experimental values of temperature when cooling down the block on the surface

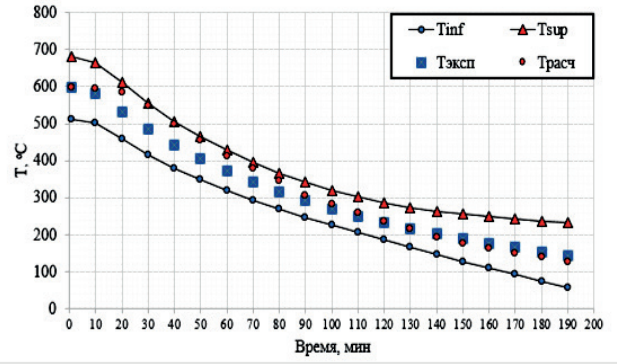


Figure 16. Comparison of calculated and experimental values of temperature when cooling down the block in the center

The data presented in Figs. 15, 16 demonstrate the following conclusions:

- the calculated model data are close in value to the mean estimates of the experimental data and are contained within the confidence interval along the entire time axis;
- the maximum deviation of the calculated data is observed at the beginning of the time axis, which is similar to the results of the estimation on the surface, also the data demonstrate the correct choice of the dispersion model of the experimental data;
- the deviation of the calculated data from the experimental data is directed toward the upper precise limit, which provides the necessary

margin in modeling the cooling process of the foam block.

CONCLUSIONS

A comprehensive assessment of the adequacy of a model has been carried out on the basis of processing the experimental data using Pearson's criterion and Student's criterion, taking into account of scattering the data relative to the center. The data for a comprehensive assessment are presented in Table 1.

To estimate the intervals in further engineering calculations, it is necessary to take into account the fact that the least upper bound (T_{sup}) is the evaluation of the experimental study.

Table 1. Results of assessment of the adequacy of a mathematical model

Control points for temperature measurements	STAGES OF ASSESSMENT OF THE ADEQUACY OF A MATHEMATICAL MODEL				
	Pearson's Cr. R^2	Student's Cr., t_p (P,k)	Complex data error, $S_e$max	Max. experimental scatter, ΔT_{max}	Conclusion
on the surface	R^2=0.969	P=0.2; k=19; t_p =1,33	$S_e$max=52.82 ^{O}C $S_e$min=27.68 ^{O}C	ΔT_{max}=70 ^{O}C ΔT_{min}=37 ^{O}C	adequate
in the center	R^2=0.985	P=0.2; k=19; t_p =1.33	$S_e$max=63.91 ^{O}C $S_e$min=33.50 ^{O}C	ΔT_{max}=85 ^{O}C ΔT_{min}=44 ^{O}C	adequate

Based on the data in Table 1, we can estimate the actual experimental temperature-time scatter by the formula $P_{empir}=\Delta T_{max}/T_{max}$:

– at Control Point No.1 of the foam glass block $P_{empir}=\Delta T_{max}/T_{max}$=0,13;

– at Control Point No. 2 of the foam block $P_{empir}=\Delta T_{max}/T_{max}$ = 0,14.

The data obtained show the correct choice of the confidence probability P=0.2 in estimating the quantile of the Student's t-distribution.

Taking into account Pearson's criterion values close to 1 and the maximum confidence probability in calculating Student's criterion, we can conclude that the calculated data have sufficient convergence with the experimental data and show the adequacy of the developed mathematical model.

The developed mathematical model of heat transfer at the stage of spontaneous cooling down of foam glass blocks enables us to conduct research of peculiarities of temperature distribution of foam glass blocks and to estimate convergence of functional dependence between time and temperature at the given control points according to the results of experimental data. The conducted study of mathematical model adequacy shows high convergence of the results of modeling and experimental measurements of temperature values at the given points of control. The obtained estimated values of Pearson's coefficient of determination - 0.969 for Control Point No. 1 and 0.985 for Control Point No. 2 demonstrate the presence of a stable functional relationship between the indicators of temperature dynamics obtained from the calculation of the mathematical model developed, and the data obtained from the experimental measurement of temperature using the applicable means of control.

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