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MODELING OF TEMPERATURE FIELD DISTRIBUTION OF THE FOAM GLASS BATCH IN TERMS OF THERMAL TREATMENT OF FOAM GLASS

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Abstract: Applications of foam glass is currently quite wide. This material is applied directly to construction and other human activities. Recent years the attention of scientists aimed at modeling the thermal processes in the production of foamed glass. Appear works in which the developed mathematical model allows to predict the distribution of temperature fields in the foam glass material at various stages of heat treatment of the material. The emergence of these models reveals a number of promising directions in the improvement of technology of producing foamed glass. Within the phenomenological formulation of the problem it is necessary to consider three-dimensional temperature field in the charge of foam-glass and inside the metal mold for foaming. It is necessary to consider the nonstationarity of the process and dynamics of change in macrovisiontm values. It is also worth noting that in the conditions of heat treatment of charge materials occurs difficult the heat transfer. The distribution of temperature fields in the foam glass material is from near-surface regions of the charge to the center. The first objective of the study is to find and describe the distribution of temperature fields in the volume of the foam glass of the charge to reflect changes in microphysically parameters in foam glass batch due to the gradual formation of porosity of the material of the charge from the periphery to the center. The second task is to find conditions for the uniform formation of the pore volume of the material. The paper presents a boundary-value problem of heat transfer in foam glass material for the metal mold on the x coordinate. This illustration of temperature field distribution inside the metal mold for foaming.

Keywords: foam glass, heat treatment regime, a mathematical model of heat transfer, temperature field

МОДЕЛИРОВАНИЕ РАСПРЕДЕЛЕНИЯ ТЕМПЕРАТУРНЫХ ПОЛЕЙ ПЕНОСТЕКОЛЬНОЙ ШИХТЫ В УСЛОВИЯХ ТЕРМИЧЕСКОЙ ОБРАБОТКИ ПЕНОСТЕКЛА

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Аннотация: Область применения пеностекла в настоящее время достаточно широка. Данный материал применяется как непосредственно для строительства, так и в других областях человеческой деятельности. Последние годы внимание ученых направлено на моделирование термических процессов при получении пеностекла. Появляются работы в которых, разработанные математические модели позволяют прогнозировать распределение температурных полей в пеностекольной шихте на различных стадиях термической обработки материала. Появление данных моделей открывает ряд перспективных направлений при усовершенствовании технологии получения пеностекла. В рамках феноменологической постановки задачи необходимо рассматривать трехмерные температурные поля как внутри самой пеностекольной шихты, так и внутри металлической формы для вспенивания. Необходимо учитывать нестационарность процесса по времени и динамику изменения макрофизичесикх величин. Так же стоит отметить, что в условиях термической обработки материала шихты происходит сложный теплообмен. Распределение температурных полей по пеностекольной шихте проходит от приповерхностных областей шихты к центру. Первая задача исследования состоит в том, чтобы найти и описать распределение температурных полей в объеме пеностекольной шихты с учетом изменения макрофизических параметров в пеностекольной шихты вследствие постепенного формирования пористости материала шихты от периферии к центру. Вторая задача состоит в том, чтобы найти условия для равномерного формирования пор по объему материала. В работе представлена краевая задача теплопереноса в пеностекольной шихте для металлической формы по координате *x*. Даны иллюстрации распределения температурных полей внутри металлической формы для вспенивания.

Ключевые слова: пеностекло, режим термической обработки, математическая модель теплопереноса, температурные поля

1. INTRODUCTION

Currently, the scope of the foam glass use is rather broad. This material is involved in construction as well as other spheres of human activity. Scientists and engineers face a wide range of challenges the most pressing of which are the following:

1) optimization of the foam glass batch composition [5-9];
2) selection of the most efficient gas-forming agents to achieve an equally distributed porous structure of the material;
3) development of economically viable and energy efficient technologies for the foam-glass batch foaming and annealing [15];
4) modeling of heat treatment for the foam glass batch at all stages of the process aimed at obtaining the necessary material [1, 3, 4, 12, 13].

The recent years saw an increased attention of scientists to the model of thermal processes when obtaining foam glass. The papers are being published showing the developed mathematical models which allow predicting the distribution of thermal fields in the foam glass batch at different stages of the heat treatment for the material. These models open a range of promising directions in improving the technology of foam glass obtaining:

1) mathematical model of the glass foaming process [3];
2) mathematical model of the foam glass annealing [1];
3) mathematical model of the dynamics in the formation of the foam glass porous structure [13];
4) mathematical model of the processes for the foam glass batch heating [4];
5) mathematical model of the most appropriate foam glass batch compositions [7,15].

Undoubtedly, the presented directions of research in the mathematical models of heat treatment for the foam glass batch allow describing certain aspects of the above-mentioned process to a certain degree and predicting some of the end physical parameters of the material. The process of obtaining foam glass consists of several stages thus requiring development of universal mathematical tools which give the opportunity to plan and predict some of the physical parameters of the material.

2. STATEMENT OF THE RESEARCH TASK

Within the framework of the phenomenological task statement, it is necessary to account for three-dimensional thermal fields both inside the foam glass batch itself and inside the metal mould for foaming. The process instability over time and the dynamics of changes in macrophysical values must be taken into account. A complex heat exchange which takes place under conditions of heat treatment for the batch material is also worth noting.

The theoretical basis for modeling heat treatment processes, for developing engineering methods for their calculation and optimization is represented by the heat transfer theory, considering the interrelationship and interdependence between the thermal characteristics of the treated material and the source of high temperature.

The physical nature of the process must also be taken into account as thermal characteristics are directly dependent on other physical parameters that change over time and under the influence of temperature changes. Definitely, we cannot ignore the fact that, before exposure to the necessary temperatures, the foam-glass batch has a porous structure where pores take the form of microspaces unfilled with crushed glass or a gas-forming agent. Another important fact is that the heat transfer in the crushed foam glass batch takes place in the following ways: by heat conductivity through the solid and gaseous phase, namely, heat conductivity through the solid and gaseous phase, successively or simultaneously, and by radiation between the surfaces of solid particles.

The foam glass batch placed in a metal mould for the purpose of foaming is represented by a chaotic structure which causes certain difficulties in mathematical description that is why this model must be replaced by a well-ordered one which would reflect all the major peculiarities of the basic structure.

It is also necessary to describe processes which occur during gradual heating of the foam glass batch.

Moisture present in the foam glass batch starts evaporating and moving from the foam glass batch to the furnace chamber for foaming. When the values of temperature in the furnace chamber are close to those when the glass starts melting, the surface layers are the first to start melting as they directly contact with metal faces of the mould for foaming, somewhat later the layer heated due to convection starts melting as well. Surface melting of the foam glass batch is taking place – the central areas of the material are not heated yet (doe to low heat conductivity of the surrounding material). Consequently, sources of gas formation do not function in these pores, while the batch material surrounding the center is already foaming and here the increase in the pore radius is continuing. Thus, in terms of pore formation, the batch material is created inhomogeneously which affects the quality of the final product thermophysical properties.

If the time of the foam glass batch exposure to heat for the purpose of foaming is insufficient for the glass to melt all over the material, centers of the foam glass batch do not have enough time to melt and therefore remain non-porous. If the foaming time considerably exceeds the melting time of the glass, fusing of the surface layers in the foam glass batch is taking place, since the sources of gas formation through heating are completely burned while the glass viscosity decreases and the surface tension does not give the opportunity to retain the isolated gaseous phase in the formed pore areas, thus the phase is transferred to the foaming furnace chamber, at the same time the central part of the foam glass batch becomes more porous than in the surface layers of the batch.

Therefore we assume that the distribution of thermal fields in the foam glass batch is taking place in the direction from surface areas of the batch to its center. The primary task of the research consists in finding and describing the distribution of thermal fields in the foam glass batch considering changes in the heat conductivity coefficient for the foam glass batch due to gradual formation of pores in the material from the periphery to the center – $a(t,x,y,z)$. This task can be solved in two ways:

1. development of a mathematical model for the thermal field distribution taking into account and obtaining theoretical dependence of the heat conductivity coefficient changes on time and coordinates under certain initial and boundary conditions.
2. development of a mathematical model for the thermal field distribution in case of computer simulation for the heat conductivity coefficient $a(t,x,y,z)$ changes depending on time and coordinates under certain initial and boundary conditions.

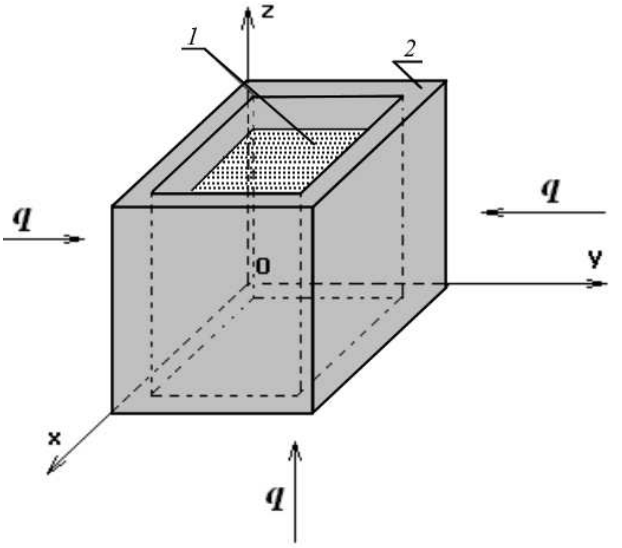
The second task is to find conditions which would ensure equal formation of pores throughout the material. For example, such conditions can be created with different technical means and technologies allowing to influence the foam glass batch in real time, e. g. use of vibration platforms or ultrasound exposure, as well as the use of powders with different gas formation properties (activity), a combination of the above-mentioned or other influences is also possible.

The complexity of accounting for all the factors stated above during development of a unified mathematical description leads to the need for creating simplified (approximate) mathematical models of heat transfer. Owing to this, there is a generally accepted approach where the solution to the task of conjugate heat transfer inside a solid body and in the boundary layer of the heat carrier is replaced by the solution to the boundary-value problem of the interrelated substance transfer within the material where the heat carrier impact is taken into account through the values determined by the heat transfer laws under boundary conditions.

The system of differential transfer equations along with the initial and boundary conditions represents a mathematical model of the real process. The solution for this system allows to see the overall picture of the heat and moisture distribution in the body over time and to analyze the process kinetics and dynamics.

The use of computer developments enables us to reduce a non-linear problem to a linear one. Using the zonal calculation method proposed by S. P. Rudobashta [11] and the method of "microprocesses", introduced by S. V. Fedosov [14], while dividing the entire process into n elementary microprocesses, thermal and physical phase parameters being regarded as constant within each of them, the nonlinear problem of heat and mass transfer can be reduced to a combination of n linear problems. It is worth noting that this method yields good results on condition that the numerical calculation is used jointly with the Laplace integral transformation method [2]. This is associated with the fact that sufficiently accurate results are achieved in the field of large Fourier numbers when only several of the first terms in the Fourier series are used. When the Fourier number (of the time for the process execution) decreases, the number of Fourier components to be taken into account in order to ensure the established accuracy of calculations increases. Nevertheless, modern IT technology is able to meet this challenge. Moreover, the Laplace transformation gives the opportunity to present the solution in two formats: with Fo> 0.1 and Fo << 0.1, it is this fact that provides for the advantage of the transformation mentioned above.

Fig. 1 shows a scheme of the “metal mould – foam glass batch” system.



<u>Figure 1.</u> Model of the “metal mould – foam glass batch” system 1 – metal mould; 2 – foam glass batch.

In general, the boundary value problems of substance heat and mass transfer can be represented by nonlinear nonhomogeneous differential equations of parabolic type in partial differential coefficients:

– boundary value problem of thermal conductivity:

$$\rho\left(u,t\right)\cdot c\left(u,t\right)\frac{\partial t\left(x,\tau\right)}{\partial \tau}=\frac{\partial}{\partial x}\left[\lambda\left(u,t\right)\frac{\partial t\left(x,\tau\right)}{\partial x}\right], \tag{1}$$

where $\rho(u,t), c(u,t), \lambda(u,t)$ are thermophysical properties of the foam glass charge material (density, heat capacity, thermal conductivity) generally depending on the moisture content and temperature.

– initial condition:

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

– boundary conditions:

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

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

The initial condition (2) shows that there is a general temperature distribution along the coordinate in the foam glass charge material at a time point taken as a reference point.

The boundary condition (3) shows the fact that temperatures of the metal and foam glass charge material are the same in the contact zone of the metal foaming mold and foam glass charge material walls, from which the $\boldsymbol{x}$ coordinate is measured. The condition (4) shows that problem can be considered as symmetric.

At the first stages of modeling, it is necessary to define boundary conditions and solve a plane problem for one of the coordinates. Figure 2 shows the boundary value problem of heat transfer in a foam glass charge material for a metal mold along the $\boldsymbol{x}$ coordinate.

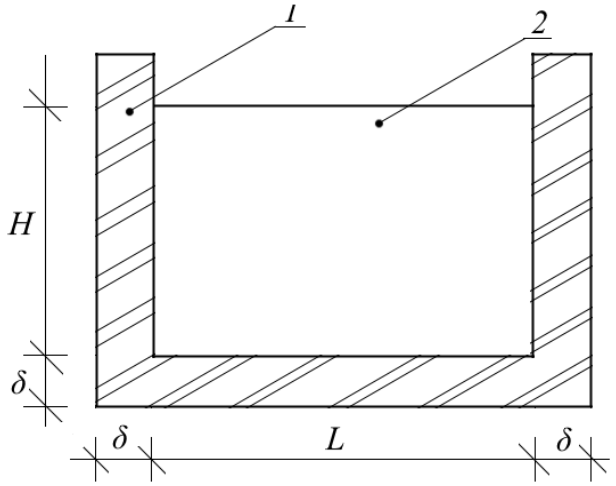


Figure 2. Foam glass charge material (2) – metal mold (1) model.

Under these conditions, the boundary value problem of heat transfer in a foam-glass charge material for a metal mold is as follows:

$$\rho c\frac{\partial t(x,\tau)}{\partial \tau}=\lambda\frac{\partial^2 t(x,\tau)}{\partial x^2};\ \tau>0;\ 0\le x\le\frac{L}{2} \tag{5}$$

$$t(x,\tau)\big|_{\tau=0}=t_0(x) \tag{6}$$

$$t(x,\tau)\big|_{x=0}=t_н \tag{7}$$

$$\left.\frac{\partial t(x,\tau)}{\partial x}\right|_{x=\frac{L}{2}}=0 \tag{8}$$

where ρ, c, λ are density, thermal capacity and thermal conductivity of the foam glass charge material, respectively.

Let's enter dimensionless variables:

$$T(\bar{x},Fo)=\frac{t(x,\tau)-t_0}{t_н-t_0};\ Fo=\frac{a\tau}{(L/2)^2};\ \bar{x}=\frac{x}{(L/2)} \tag{9}$$

And then the problem (5)-(8) will be as follows:

$$\frac{\partial T(\bar{x},Fo)}{\partial Fo}=\frac{\partial^2 T(\bar{x},Fo)}{\partial \bar{x}^2};\ Fo>0;\ 0\le\bar{x}\le 1 \tag{10}$$

$$T(\bar{x},Fo)=\frac{t(x,\tau)-t_0}{t_н-t_0}=T_0(\bar{x}) \tag{11}$$

$$T(\bar{x},Fo)\big|_{\bar{x}=0}=\frac{t_н-t_0}{t_н-t_0}=1 \tag{12}$$

$$\left.\frac{\partial T(\bar{x},Fo)}{\partial \bar{x}}\right|_{\bar{x}=1}=0 \tag{13}$$

3. STUDY RESULTS

Now we give the final solution of the boundary value problem in the field of originals, omitting simple but cumbersome transformations:

$$T(\bar{x},Fo)=1-\frac{4}{\pi}\sum_{n=1}^{\infty}\frac{1}{(2n-1)}\sin\left[\frac{\pi}{2}(2n-1)\bar{x}\right]\cdot \exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right]+ 2\sum_{n=1}^{\infty}\sin\left[\frac{\pi}{2}(2n-1)\bar{x}\right]\cdot\int_0^1 T_0(\xi)\cdot \sin\left[\frac{\pi}{2}(2n-1)\xi\right]d\xi\cdot\exp\left[-\frac{\pi^2}{4}(2n-1)^2 Fo\right] \qquad (14)$$

The expression (14) calculation results are shown in Fig. 3 in the form of curves presenting the change of dimensionless temperatures along the dimensionless coordinate depending on the dimensionless process time.

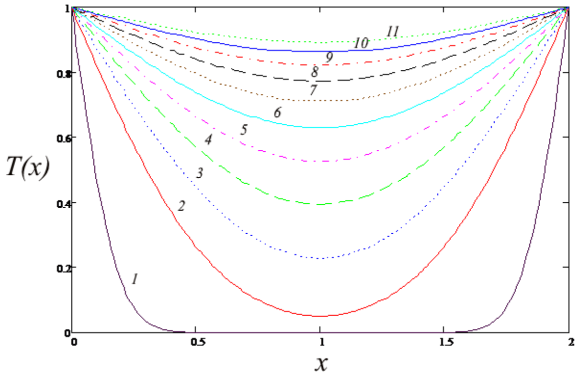


Figure 3. Expression (6) calculation presentation Fo: 1) 0.01; 2) 0.1; 3) 0.2; 4) 0.3; 5) 0.4; 6) 0.5; 7) 0.6; 8) 0.7; 9) 0.8; 10) 0.9 11) 1.

The curves in Fig. 3 present the dynamics of the dimensionless temperature fields in the space of the foam glass charge material (in accordance with Fig. 2, the coordinate origin, $\bar{x}=0$, is positioned at the left wall plane of the metal mold, and $\bar{x}=L$ is the right wall plane of the metal mold).

It is notable how the symmetrical heating of the foam glass charge material flows: prior to achievement of a value around 0.15 by the Fourier criterion, there is a gradually tapering zone between the walls of the metal foaming mold with conserved initial temperature of the foam glass charge material. Then, the temperature curves are joined and, when $Fo \geq 1{,}0$, the zone between the metal mold walls is practically uniformly heated.

4. KEY FINDINGS

Thus, the set of equations (5-8) with initial (2) and boundary (3-4) conditions is called the boundary value problem of heat transfer and, in general terms, determines the behavior of the considered system "metal form - foam glass charge material".

To verify the model for adequacy, it is necessary to develop an algorithm for its implementation to real physical phenomena.

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