Mathematical Simulation of Porous Glass Thermal Processes at Annealing Stage

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Abstract. The mathematical model of the porous glass heat field under conditions of complex heat exchange in the process of the technological stage of annealing is presented. The model includes calculations of the radiation, convective and molecular components. The mathematical model is based on the finite element method. The model is realised in the software Ansys. The statement of the problem is given. The object under study, i.e., model structural features, is presented. The method of model structure obtaining, the initials and boundary conditions are given. The theoretical basis of the methods, approaches and of the optimal calculation parameters choice principles are presented. The estimation of the model adequacy by means of the experimental verification is given. The comparison of the obtained data with the experimental results is performed. The relative error of calculation using the developed model does not exceed 15%.

1. Introduction
Currently, new insulation materials based on porous glass (foam glass) are widely spread and are used, as a rule, as an external insulation of facades of buildings and structures for civil and industrial applications [1,2]. They are distinct in quite high thermal insulation, mechanical strength and chemical resistance combined with a relatively low cost of their production.

Annealing is one of the fundamental technological stages of production that determines the above mentioned properties of porous glass [3,4]. According to the results [5], even while obtaining porous glass optimum for all parameters, poor-quality annealing can lead to a sharp increase in defects in finished products.

Difficulties in studying the processes of annealing porous glass and working out its modes are due to the fact that the duration of this stage is approximately 5-6 times greater than the time of foaming (10-12 hours on average).

The aforenamed allows us to conclude that the creation of a mathematical model for simulation of thermal processes taking place in a porous glass will make it possible to solve these difficulties. The review of mathematical models of the technological stages during porous glass production [6] made it possible to determine the finite element method as the most promising for mathematical simulation of the heat exchange processes for the desired material.

The objective of this research is to develop the implementation principles for a control system based on magnetic levitation [7-10] of the test sample by active correction of the current in...
magnetizing coils of the magnetic system to ensure the set parameters of the sample movement: aperiodic nature of the movement and acceleration restriction and save a high accuracy and timeframe of the installation in a measuring position.

2. Formulation of the problem
The target (Figure 1) of the research is a porous glass sample with the dimensions of $30 \times 30 \times 30$ mm, perforation ratio of 0.2589, average pore diameter of 3 mm placed on a $100 \times 100 \times 3$ mm support.

![Figure 1. Target of the research.](image)

A porous glass sample was obtained according to the traditional powder technology based on the conclusions of previous scientific works [7]. Raw materials were grinded in a ball mill with a volume of 5 liters until the total passage through the strainer No. 0315, the charge surface area size is 552 m²/g.

While heating a finely grinded mixture of glass matrix and foaming agent (charge consisting of 30% ash and slag, 70% cullet, 5% borax and anthracite in excess of 100% of the main components [7]) to 825 °C, gases formed as a result of oxidation or dissociation of the blowing agent, bloat softened glass. The foaming and annealing of the porous glass sample were carried out in a muffle electric furnace with electric heaters in accordance with the proposed temperature-time mode (figure 2).

![Figure 2. Temperature-time mode of porous glass sample manufacturing.](image)

Due to the rapid increase in the viscosity of the glass when it is cooled after foaming, the cellular structure is fixed without undergoing significant changes. The porous glass with a fixed structure is
then annealed for 200 minutes (12,000 seconds) at a temperature of 600 °C with a preliminary 30 minutes soak.

3. Theoretical part

The algorithm for conducting thermal analysis with the help of the PC Ansys [8] contains the following basic steps: constructing a model, specifying boundary conditions and initial properties of materials, obtaining a solution and reviewing the results.

In the presented analysis the pore material is described by a certain number of spherical cavities of a small diameter (approximately 3 mm) and a constant composition possessing the properties of gas (CO₂) [5]. The values of carbon dioxide thermal conductivity at the upper and lower boundary curves, at the critical point and isobars from 30 to 200 kG/cm² to a temperature of 1,000 °C, are presented as a temperature dependence [9,10]. The material of the stand is 12X18H9T [11,12]. The thermal conductivity and the specific thermal capacity of the porous glass matrix were determined by the laser flash method [13] in the temperature range 25-700 °C at the TC-9000H thermal conductivity measuring device at the shared knowledge center "Technologies and Materials of the Belgorod State University", Belgorod.

Mathematical simulation of the heat transfer process in the target object is based on the numerical solution of the initial-boundary value problem for the heat equation:

\[
\rho c \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left( \lambda_x \frac{\partial T(x,y,z,\tau)}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_y \frac{\partial T(x,y,z,\tau)}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_z \frac{\partial T(x,y,z,\tau)}{\partial z} \right)
\]  

(1)

where \( T(x, y, z, \tau) \) is the sought temperature distribution function; \( \lambda_x, \lambda_y, \lambda_z \) are the coefficients of thermal conductivity in the direction of the \( x, y, z \) axes; \( \rho \) is the density; \( c \) is the specific thermal capacity of the environment; \( \tau \) is the duration of the annealing step, s.

The stationary heat equation for an isotropic medium has the form:

\[
\text{div}(\lambda \text{grad}T) = 0
\]  

(2)

where \( \lambda \) is the coefficient of thermal conductivity.

To solve the non-stationary problems of thermal conductivity, the Transient Thermal module was used with the following boundary conditions.

3.1. Boundary condition of the first kind

The boundary condition of the first kind is given in the form of a temperature distribution at the computational domain boundaries \( T_v=f(x_v, y_v, z_v, t) \) (Project > Model (A4) > Transient Thermal (A5) > Temperature…). In the considered example this condition was set on the outer surface (Fig. 3) in the form of a linear temperature decrease from 600 °C to 25 °C within 12,000 s.

![Figure 3. Solid model of the sample on a metal stand.](image-url)
3.2. **Boundary condition of the third kind**

The boundary condition of the third kind is formed by setting the ambient temperature and the principle of heat exchange between the boundary and the environment (*Project > Model (A4) > Transient Thermal (A5) > Convection...*). This type of heat exchange is called heat transfer, and the principle of heat exchange is determined by the heat transfer coefficient. The boundary condition of the third kind is set only at the solid boundaries of the computational domain, in the problem considered - on the surface of the sample and the support.

Radiation sets the ambient temperature and the coefficient of radiation of the body (*Project > Model (A4) > Transient Thermal (A5) > Radiation/Surface to Surface...*).

Theoretical positions on the calculation of the radiant-heat transmission between the emitting and absorbing gas and the surrounding closed gray shell are described in detail in the literature [14].

The degree of blackness of each radiating component depends on the number of its molecules in the gas mixture and on its temperature $T_g$. The number of emitter molecules of electromagnetic energy, naturally, is proportional to the partial pressure $p_{CO_2}$ of the gas mixture, as well as the so-called gas layer thickness $l$. The gas layer thickness is determined by the formula $l = 3.6 \frac{V}{F}$, where $V$ is the volume of the gas body; $F$ is the area of the solid surface surrounding it.

The release of gases in the internal parts of the sample during the temperature decrease gradually stops, and it already leaves the furnace practically in a state of equalized pressure. In the course of annealing with further cooling, a necessary reduction in the pressure of the gases occurs in separate cells, so that the finished annealed porous glass is characterized by a considerable rarefaction in the cells constituting 1/3 of the atmosphere (33.8 kPa) [15]. Then the required degree of blackness in the range of temperature decrease on average will be 0.01. In order to estimate the contribution of the radiation component to the overall temperature distribution, the assumption is made that the degrees of blackness of the charge and the initial glass are the same ($\varepsilon_{st} = 0.94$) [16].

Radiation from the surface of the stand is set in a similar way with its blackness values. At the same time, the value of "Correlations" variable is set to "To ambient".

3.3. **Boundary condition of the fourth kind**

The boundary condition of the fourth kind corresponds to the heat exchange of the contacting solid bodies, when the temperature of the bodies in contact is equal. Contact regions are used in the assembly for transfer of heat from one body (sample) to another (stand). Since the elements are initially in contact, heat transfer occurs between them.

The boundary condition of the fourth kind - the heat exchange of contiguous solid bodies - is formed automatically when the surface of the sample and the support coincide (*Project > Model (A4) > Connections > Contact > Contact Region...*).

In order to verify the efficiency of the proposed approach to the evaluation of heat transfer in porous glass, the numerical studies of thermal processes in the sample were carried out, the main task of which was to reveal the distribution of the temperature field in the sample volume with a change (decrease) in the temperature at the outer boundary of the calculated region (the outer surface of the sample and the support) in accordance with the given annealing process (figure 2). The maximum value of the time step was determined according to the recommendations in [17] and equals 10 seconds.

The results of calculating the temperature are made at the reference points (Figure 4). The change in temperature over the cross section of the sample (along the lines, Figure 4) for 12,000 s time points is shown in Figure 5. The time points correspond to the 25 °C temperature at the boundary of the calculated region.

4. **Results of experimental studies**

In order to assess the adequacy of the calculated data, experimental verification was carried out. In order to determine the dependence of the thermal field in the sample at every instant, the test sample on the metal substrate was placed into a muffle furnace and underwent heat treatment according to a
predetermined mode [7]. The temperature was measured by means of two chromel-alumel thermocouples located centrally in the bulk of the material and in the center of the upper plane of the sample (for determining the temperature-time regime). The potentiometer PP-63 is used to register the EMF of thermocouples. The temperature was determined from the standard tables for the thermocouples used.

The deviation of calculated and experimental data is within the permissible error and does not exceed 15% (figure 6).

**Figure 4.** Location of points and lines of temperature measurement (for example, line 1).

**Figure 5.** Temperature change in the sample at time point 12,000 s.

**Figure 6.** Temperature change in the sample at time point 12,000 s.
5. Conclusion

1. A mathematical model for calculating the complex heat transfer in a porous glass is created taking into account the radiation, molecular, and convective components. The percentage error in determining the temperature does not exceed 15%.

2. The nature of the field variation in a sample of porous glass corresponds to the assumptions presented in the literature [3,4,18-20]. The obtained temperature distribution over the volume of a porous glass sample is the initial one for the calculation of its stress-strain state.

Acknowledgments

The article is prepared based on the research findings carried out with the financial support of the Russian Foundation for Basic Research within the framework of the scientific project No. 16-33-60177mol_a_dk.

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