An integrated model of the raw material mixture high-temperature treatment process to produce foam glass. Problem statement

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Abstract. The paper considers the demanded porous building materials, as well as the main stages of their production technology. The advantage of block foam glass as a porous building material compared to other building materials is shown, and the basic technologies for its preparation are considered. It is noted that the priority technology for the foam glass production is a two-stage powder production technology. A schematic diagram of the foam glass production according to the two-stage powder technology is presented, where the cycle of heat treatment of the raw mix for producing foam glass is noted and the sequential steps of the process are considered, in which the raw material charge is exposed to high temperature. The physical and chemical features of the phenomena inherent in the individual phases of the raw mixture transition from heating, foaming and annealing to the finished material (foam glass) are analyzed. Fragmentation of the scientific ideas about the foam glass heat treatment process is noted; it hinders the adequate and optimal technological modes’ development for the foam glass production, which directly affect its further cost. The necessity of developing a general methodological approach to the study and modeling of high-temperature maintenance regimes of the raw material mixture TT for producing foam glass, the creation of rational technological approaches to the producing block foam glass process as a part of its production concept, the identification and study of the TT high-temperature maintenance regimes laws with such models and predicting the final operational properties of the finished material are emphasized.

Introduction
Building materials and products with high porosity and low thermal conductivity, as well as low average density, are the heat-insulating building materials. The scope of their application is wide enough and covers both the thermal insulation of residential and industrial buildings, as well as the surfaces of technological equipment, heating and other devices (furnaces, pipelines, etc.). The basic principle that
determines the scope of their operation is to minimize heat exchange between the enclosing elements (structures) and the environment [1].

The widespread use of heat-insulating building materials in the construction of buildings and structures can significantly reduce the thickness and weight of the building structures (walls, roofs), reduce the cost of other materials and, accordingly, lower the total cost of the structure, reduce fuel consumption during the operational period, etc. [2]. For the equipment used in various technological cycles, heat-insulating materials can reduce their heat loss, ensure optimal operating temperature, as well as save energy resources and improve the working conditions. To maximize the effect of the thermal insulation materials’ use, the necessary calculations, which are based on specific types of body insulation and their characteristics, are carried out. The presented methods contribute to effective solution of saving fuel and energy resources problems.

A specific feature of thermal insulation materials is their inherent high porosity. The gas phase in the pores is characterized by minimal thermal conductivity in comparison with the condensed phases (solid and liquid) surrounding it. With the pore sizes of 0.1–2.0 mm, the thermal conductivity of air in them is equal to 0.023–0.030 W/(m·K). The porosity of thermal insulation materials can be up to 90-98 %, and for very thin glass fiber - up to 99.5 %. However, the porosity of such materials as heavy concrete is 9 – 15 %, granite marble – 0.2 – 0.8 %, ceramic brick – 25–35 %, steel – 0 %, etc.

Taking into account the physical factors affecting the overall or effective thermal conductivity in heterogeneous porous bodies, it is necessary to consider the key technologies for producing the presented heat-insulating materials: porous-fibrous (mineral and glass wool, wood-fiber materials using asbestos, etc.), porous-granular (perlite, vermiculite, lime-siliceous, etc.); cellular (aerated concrete, foam concrete, foam glass, polystyrene, etc.). The difference between them lies both in the composition and structure of the finished product, and in the technological method of pore formation [3].

For the heat-insulating properties’ formation in materials, the following artificial foaming methods are used:

1) The method of gas formation. The components are added to the raw material mixture to activate the chemical reactions in which the evolution of the gas phase occurs. Gases, trying to get out of the manufactured material’s volume at the stage of the plastic mass hardening, form a porous structure by their own pressure. This way, aerated concrete, gas silicate, gas ceramics, foam glass, gas-filled plastic, etc. can be received.

2) The method of pore formation. The essence of the presented method is to add the pore-forming substances into the water for mixing binders. The foam bubbles formed are the air pores that determine the structure of foam concrete, foam silicate, foam ceramics, and others. Fatty acid salts, namely sodium and potassium soaps, glucose rosin blowing agent, aluminon-sulfia-naphthalene blowing agent and hydrolyzed blood are used as blowing agents. To improve the foam resistance, carpentry glue, alumina sulfate, resins, etc. are used as stabilizers.

3) The method of increased water dissolution. To implement this method, a large volume of water is used in the preparation of molding materials; after its evaporation, pores are preserved during drying. This method is used in the manufacture of fiberboards, peat and other materials.

4) The method of expansion. The essence of the method is to heat slags and rocks of a certain type to high temperatures. Due to the presence of chemically bound and zeolite water in the feed, vapors and gases are released. Vermiculite, perlite, obsidian, some types of clays, especially those containing low-melting iron oxide (II), serve as the raw materials for expansion. After expansion in a rotary or shaft furnace with a rapid rise in temperature to 800–1000 °C and subsequent cooling, these and some other raw materials form the corresponding heat-insulating materials with a developed porous structure - expanded clay, vermiculite, perlite, slag pumice, etc.

5) The method of fluffing. The method is based on the manufacture of dense mineral raw materials formless mass of fibrous material, followed by giving it the shape of the product. This method is widespread in the production of mineral and glass wool and products from them. Rocks and metallurgical slags serve as the raw materials for mineral wool, and glass break and glass waste are used to produce glass wool. Also, this method is used to obtain the organic thermal insulation materials.
6) The method of the burnable organic substances introduced into the raw materials as gas-forming additives. Sawdust, crushed coal, etc. are added to ceramic raw materials (diatomite, tripoli, clay, etc.). This method makes it possible to use the non-swellable raw materials, given the scarcity of intumescent clays.

Discussions and Results
The most effective heat-insulating material that meets the requirements for the buildings and structures’ energy efficiency is foam glass - cellular glass having a combination of insulating and operational properties (durability, inertness to the effects of the environment and pests, complete fire safety, etc.). The main disadvantage of foam glass is its relatively high price, due to the use of scarce glass breakage as the main raw material, as well as the raw material mixture’s heat treatment energy-intensive stage presence [4].

The high price of foam glass is determined by the high costs of raw materials and heat treatment. In this regard, the urgent issue is the foam glass heat treatment processes’ improvement. Knowing the features of the processes of heating, foaming and annealing of the foam glass charge will make it possible to adjust the quality of the material, energy consumption and production space by adjusting the heat treatment modes and the processing equipment size [5].

Here are the most common foam glass technologies:

1. Powder technology. A mixture of powdered glass, together with gas, is placed in heat-resistant metal molds and subjected to heat treatment.

2. Cold technology. Foaming of ground glass with foaming agents in the cold followed by fixing the sintering structure of the glass particles.

3. Saturation of molten glass under vacuum.

4. Foaming softened glass under vacuum.

The most rational and popular way of producing foam glass in blocks is the powder method. The powder method makes it possible to obtain foam glass with a different structure and properties depending on the powders’ grain composition, the type and quantity of blowing agent, the temperature and the duration of the sintering process [4].

![Figure 1. Scheme of foam glass production using two-stage powder technology](image-url)
Powder technology foam glass can be produced in several ways [6]:
1. One-stage;
2. Two-stage;
3. By the method of foam glass tape continuous foaming;
4. Formless;
5. Hydrothermal;
6. The method of producing granular foam glass.

Despite the apparent ease of implementation, powder technology has a number of disadvantages. The main reason stopping the foam glass production in Russia is the technology imperfection, and in particular, the high energy production consumption [7, 8].

The theoretical basis for the research in this direction is the theory of heat and mass transfer and its logical expression in the form of a system of partial differential equations describing the phenomena of heat, mass and bar transfer in the solids under various boundary conditions that characterize the substance transfer at the boundaries of bodies with the surrounding their gas (liquid) medium:

\[
\frac{\partial t}{\partial \tau} = a_q \nabla^2 t + cr \frac{c_m}{c_q} \frac{\partial \Theta}{\partial \tau} + \frac{c_p k}{c_q' \rho_0} \nabla P \nabla t; \tag{1}
\]

\[
\frac{\partial \Theta}{\partial \tau} = a_m \nabla^2 \Theta + a_m \delta_T \nabla^2 t + a_m \delta_T \nabla^2 P; \tag{2}
\]

\[
\frac{\partial P}{\partial \tau} = a_p \nabla^2 P - \varepsilon \frac{c_m}{c_a} \frac{\partial \Theta}{\partial \tau}. \tag{3}
\]

where \(t, \Theta, P\) – are the functions determining the values of transport potentials (heat, mass, pressure) in the space of coordinates of a solid at arbitrary points in time; \(a_q, a_m, a_p\) – are the transfer coefficients, respectively, temperature-, mass- and bar conductivity; \(C_q, C_m\) – are the heat and mass intensity factors; \(r\) – is the latent heat of vaporization (heat of phase transition); \(\varepsilon\) – is the degree of phase transition; \(\delta_m\) – is the thermal diffusion coefficient (thermogradient coefficient); \(C_p, C_a\) – define the specific heat; \(\lambda_q, \lambda_m\) – show the heat factors and mass conductivity; \(q_q, q_m\) – show the the density of heat fluxes and masses of matter that determine the interfacial transfer between a denser (solid) and less dense (liquid, gas) phases.

The most important, energy-consuming and poorly studied stage of foam glass production is the thermal treatment stage (TT), including the steps of heating the foam glass mixture, foaming the softened glass mass and annealing the foam glass [9].

The importance of the stage TT lies in the fact that the basic properties and operational characteristics of foam glass are formed during it. The ability to control and manage the process depends on the knowledge degree of this TT stage, and therefore the properties of the future material.

Also, TT stage is the most energy-consuming production stage. For the block foam glass obtained in the classical way using the heat-resistant molds, the energy consumption for heat treatment is more than 6 times higher than the process cost of preparing the charge and reaches 500-600 kW·h per cubic meter of the manufactured product, for the granular foam glass energy consumption is 200-250 kW·h/m³. Reducing energy costs is possible in two directions: reducing the material consumption of the forms or completely abandoning them; selection of optimal (in terms of energy consumption) temperature conditions of the furnace. The effectiveness of the first option is clearly demonstrated by the above-mentioned example with the cost of producing granulated foam glass. The second direction is more knowledge-intensive, since the optimization of the TT maintenance process requires a comprehensive study of it and the creation of a theoretical base.

The theoretical basis for research and TT process optimization, according to Demidovich B.K., is the determination of temperature fields in the zone of forming the devices and in the product itself. To date, this task at all stages of the process has not been received. About the need to study TT at least the fact...
that researchers still do not have a single opinion on the simplest stage duration in terms of the combination of processes TT - charge heating.

For a complete picture of the entire TT cycle completeness the raw material mixture for the foam glass production it is necessary to analyze the physical and chemical characteristics of the phenomena inherent in the individual phases of the raw mixture transition from heating, foaming and annealing to the finished material (foam glass).

**The stage of heating (foaming) of the raw material mixture to obtain foam glass**

The raw mixture in the form has low thermal conductivity, so heating to sintering temperature continues for a relatively long time. Once the raw mix reaches a temperature near 600 °C, it starts sintering and decreasing in volume. At the same time, cracks form in the sintering mass. Shrinkage can be noticed in the places of maximum temperatures, that is, in the direction from the metal faces of the form [10]. Further, the entire glass layer in a metal form is cracked into pieces of irregular shape and size, which after sintering begin to sinter on their own. The more unequal in their shape and size these pieces are, the more uneven the formation of foam glass cells occurs. Since foaming occurs after complete glass sintering, it is advisable to maintain the sintering temperature below the foaming temperature until the entire mass in the mold is completely sintered. With the temperature stabilization within the limits of foaming of the glass melt, the porosity process will continue. The particles of the crushed blowing agent react with glass and emit gas, as a result of which the individual cells are connected to each other, which leads to the large cells’ emergence. At the initial stages of foaming, the process of the cells’ interaction with each other dominates, after which they start expanding and form the final material volume. At the end of the foaming process, the evolution of the gas phase ends because the blowing agent is completely burned out and the process of interconnecting the cells is activated. At this stage, it is necessary to take into account the factors of gas evolution, in which, in cases of excess concentration of the blowing agent in the raw material charge, can lead to the large pores’ formation, which leads to a decrease in the strength characteristics of the final material.

**Foam glass annealing**

Despite the very insignificant wall thickness of individual cells, the foam glass block should be considered from a technological point of view as a compact whole. The temperature differences that occur during cooling between the surface and internal parts of the block cause the appearance of stresses of the same kind that occur in the block of ordinary glass. Therefore, there is no fundamental difference between the method of annealing foam glass and bulk ordinary glass, since the change in the temperature gradient during annealing, and thereby the stress distribution, should be qualitatively the same for the foam glass block as for a similar-sized bulk glass block [11].

As follows from the glass transition kinetic theory basics, with a sufficiently long isothermal exposure, the glass structure can be brought to an equilibrium state at any temperature. However, the lower this temperature, the longer it takes. The process of achieving the structural equilibrium in the isothermal mode, fixed by approximating the properties of glass to their equilibrium values, is called the glass stabilization.

Let the glass be stabilized at a certain temperature T1, then its temperature was abruptly changed to T2 and then kept constant. If the temperature changed quickly enough, then at the beginning of exposure its structure corresponds to T1. In the end, it naturally comes into equilibrium with temperature T2. A change in structure leads to a change in properties, which can be recorded by the measuring equipment. Here a typical relaxation process takes place (the process of asymptotic approximation to the equilibrium state of a system removed from equilibrium).

All this is even more relevant for foam glass due to low thermal conductivity. In addition, the so-called second-type stresses associated with the appearance of the crystalline phase can occur in the glass matrix of the foam glass.

Stresses of the second kind include those, the emergence of which depends on the presence of a crystallization process in the glass. The resulting crystalline phase has a thermal expansion coefficient
different from glass. Due to this, there will be a difference between the compression values of the crystal and the glass matrix, which will lead to the stresses at the contact boundary.

The combined influence of both types of stresses is the destruction cause of the resulting block. Moreover, with improper cooling of the foam glass, the so-called residual stresses can appear, which reduce the strength of the finished product and lead to its subsequent destruction (possibly after a long period of time).

Summary

As a scientific problem, it should be noted that the contradiction, which consists, on the one hand, in the prospects of heat-insulating foam glass as a building material, and, on the other hand, its high cost, is due to the energy-intensive technological process of its production. Currently available possible solutions to the presented problem can be classified into two types:

1. Development of the raw material mixture optimal composition for foam glass using the local raw materials (blowing agent and cullet);
2. Development of a mathematical apparatus capable of taking into account the whole range of physicochemical features of the foam glass production process.

Taking the complexity of the mechanisms that occur at all stages of the production of foam glass into consideration, it is necessary to develop the scientific foundations for modeling the high-temperature processes raw mix TT for foam glass, as the most energy-intensive stage of the process. This includes the development of a common methodological approach to the study and modeling of high-temperature modes the raw mix TT for producing foam glass, creating the rational technological approaches to the process for producing block foam glass as the concept part of its production, determining and studying the laws of high TT temperature conditions for such models and the finished material’s final operational properties prediction.

At the same time, already developed mathematical models of various stages can be adapted into the general modeling TT methodology taking into account the technological cycle features. Of no less importance is the fact that it is necessary to take into account not only the dynamics of thermal TT processes, as well as the material porous structure formation kinetics at all the stages of the technological cycle.

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