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MODELING OF THE THERMOPHYSICAL PROCESSES IN SINTERING GLASSWARE

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A complex approach to the modeling of the thermophysical processes in glassware obtained by the sintering technique is proposed. A one-dimensional model of radiative-conductive heat exchange in a layer of a transparent scattering material formed from glass particles and a model of two-dimensional heat conductivity in a multilayer molding rig with an article are considered. The results of mathematical modeling are presented.

Introduction. Today the question of raw material resources is of great importance for all machine-building technologies. A powerful source of raw materials for making articles from glass is domestic and industrial glass waste (GW). In the composition of urban solid garbage, glass occupies the third place after paper and food refuse [1]. For large cities of Russia the yearly amount of GW reaches dozens of thousands of tons. A considerable part of such wastes is not recycled. Moreover, the irrevocable raw material loss of some glass works reaches 10% of their commercial output. This creates serious problems in the field of environmental protection since glass practically does not decompose and one cannot count on its natural reclamation. At the same time, glass is a high-quality and costly material. Therefore, GW recycling is justified not only for ecological reasons, but also from the viewpoint of saving energy and resources.

Glass container and sheet waste can immediately be processed into profile products. To this end, after collecting, sorting, and cleaning, broken glass is crushed and charged into a glassmaking furnace simultaneously with a mixture of raw materials. According to the data of [2], one ton of broken glass permits saving up to 1.2 tons of raw materials, and the replacement of 10% of the mixture of raw materials with broken glass decreases the power consumption in founding glass by 2%. In using GW for making glass containers the experience of European countries is significant. Due to the functioning in the majority of them of a closed cycle of glass circulation, the irrevocable losses are insignificant and the average level of GW recycling reaches 60%. In 1999, the total amount of collected and recycled GW in Europe exceeded 8 million tons [3].

There are a number of limitations influencing the efficiency of using GW for making glass containers. Among them are: the absence of a system of GW collection and preparation, the remoteness of collection points from the processing places, and the chemical composition of GW. In Russia, a system of GW collection and preparation analogous to the European one is absent so far. At a number of domestic enterprises, GW collecting firms have been set up recently. An example is the firm "MÉLZ Éko-steklo" organized at the Moscow Electric Lamp Plant for providing their own production of glass containers. With a considerable distance between the sources of formation and the processing places, GW transportation becomes unprofitable. Some kinds of GW, such as color container glass, fiber glass, picture tube breakage, and a number of others, have limitations on recycling volumes.

Promising technologies of processing free of the above limitation are known: the use of GW as asphalt and concrete fillers [4], in making foamglass [5], glass [6], microballs and microspheres [7], glasscrys-

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tallite plates and their analogs [8, 9]. Products of GW processing can be used as heat-insulating and building materials, fillers of paints and polymeric composite materials, protective coatings, fillers of medical antidecubitic beds, and abrasive materials.

The highest economic effect under the conditions of the general demand for inexpensive quality building materials can be attained by processing GW into building-purpose articles by the sintering technique [2, 8]. Sintering of glass particles in a mold under the action of thermal radiant fluxes provides the formation of a gradient structure of the article material. Such a structure arises at temperatures up to 1300 K, and its formation is accompanied by a decrease in the porosity from 40–60% to 1–2% and an increase in the degree of crystallinity from 0 to 30–100%. Building-purpose articles from GW exhibit valuable properties [2, 8, 9] and are superior to the widespread ceramic and natural materials in many respects.

Scientific Problems of Making Articles from Glass by the Sintering Technique. At the stage of developing a manufacturing technology, particular consideration should be given to the questions of justification of designs by using methods of mathematical and physical modeling. The central role in the traditional and novel technologies for manufacturing articles from glass is played by the thermal processes by means of which the shape, sizes, and structural characteristics of articles are controlled. Until recently, however, in choosing the conditions for manufacturing articles from glass, intuitive-empirical techniques prevailed and approximate mathematical models of heat exchange and data on the thermophysical and optical properties of materials were used. All this led to a low accuracy of design and the arising discrepancies between calculated and real characteristics had no strict scientific explanations. The experimental operational development entailed considerable material and time expenses. Moreover, the thermal, rheological, and physicochemical processes in the glass were considered separately.

The problem of modeling a technology for sintering glass particles is that it is necessary to take into account the structural transformation, the change in the porosity, the formation of a softened glass layer and the crystalline phase, the volumetric heating, the spatial inhomogeneity of the temperature fields, the nonlinearity of the physical properties of materials, and the differences in the rates of physicochemical and structural transformations in individual parts of an article.

Theoretical justification of thermal technologies of manufacturing articles from glass calls for specialized software based on mathematical models of radiative-conductive heat exchange (RCHE). The development of such models for solving applied problems of the glass industry has been carried out since the beginning of the 1950s and has made fairly good advances [10, 11]. At the same time, the real technological processes in glass exposed to intense heat are accompanied by physicochemical and structural-phase transformations and a change in the geometrical sizes, which calls for perfect models and new numerical algorithms. Taking into account that individual, special for a given case, problems were solved in growing crystals [11], investigating the crystallization of glasses [12, 13], sintering of metal powders [14], and analyzing the mechanisms of heat insulation [15, 16], it is expedient to turn to the synthesis of a generalized thermal model from compatible parts of special models.

Special Models of Thermophysical Processes in Sintered Glassware. In constructing a generalized thermal model and developing a calculation-theoretical technique, the necessity of estimating the significance of individual components of a complex process arises. At this stage, one can utilize methods of analysis and synthesis leading to the formation of a hierarchical family of special models. As applied to the problem under consideration, classified among such conventionally special models can be the model of one-dimensional RCHE in a layer of a partially transparent scattering material formed from sintering glass particles and the model of two-dimensional heat conductivity in a multilayer mold with an article.

Each of the above-mentioned models relies on particular special models of heat conductivity, radiation transfer, etc. which do not reach the limit of the depth of the phenomenon, but feature a satisfactory accuracy and are fast, acceptable as to the cost of the necessary resources, and practically useful at the same time. For example, the first of the models under consideration makes it possible to take a very precise ac-

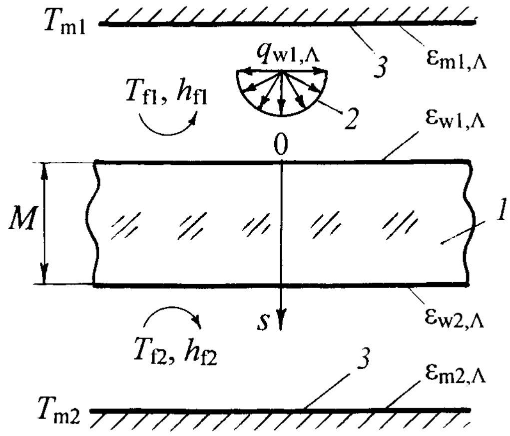

Fig. 1. On the model of radiative-conductive heat exchange in a layer of sintering glass particles: 1) layer of glass particles; 2) heater; 3) opaque surfaces.

count of the influence of the partial transparency of the glass particle layer on the temperature distribution in the article thickness in the course of sintering as well as such characteristics of the raw material as viscosity, particle size, etc. The second model takes into account the influence of the multilayer molding rig on the temperature gradients in the thickness and on the surface of the article being sintered at the heating and cooling stages and thus permits choosing the optimum design of the molding rig and the regimes of thermal treatment of the article.

We now turn to the first of the above-mentioned models (Fig. 1). Assume that the process of heat exchange is developing in a two-dimensional infinitely extended layer 1 with initial thickness L_0, density ρ_0, and temperature T_0. The material of the layer is a homogeneous material isotropic in the planes parallel to the boundary surfaces of the plate. A selective diffuse radiation flux of the heater 2 of density $q_{wt,\Lambda}$, uniformly distributed over the surface, is incident on one of the layer boundaries. In the region of partial transparency Λ_s the material absorbs and scatters thermal radiation in the bulk, and in the region of opacity Λ_0 radiation is absorbed on the surface. Heat is removed from the surfaces into the environment by means of emission and convection. Between the front and rear surfaces and the opaque surfaces 3 parallel to them a radiation heat exchange occurs. In the process of heating, shrinkage and partial crystallization of the material take place. The layer mass remains unchanged. The external force action and the release of gaseous products are absent. The thermophysical properties depend on the temperature and porosity, and the optical properties are also associated with the radiation wavelength.

To this physical model there corresponds the model of RCHE in the layer of the partially transparent scattering material of a variable density. The mathematical model of RCHE incorporates the radiant energy and radiation diffusion equations with the corresponding boundary conditions, the kinetic sintering and crystallization equations, and a number of additional relations:

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{\partial s}\left(\lambda \rho \frac{\partial T}{\partial s}\right) + q_v ; \tag{1}$$

$$T(s, 0) = T_0(s) , \quad 0 \le s \le M ; \tag{2}$$

$$s = 0 \quad -\lambda \rho \frac{\partial T}{\partial s} = \int_{\Lambda_o} \varepsilon_{ef1,\Lambda} (q_{w1,\Lambda} + B_{m1,\Lambda} - B_{w1,\Lambda}) \, d\Lambda + h_{f1} (T_{f1} - T) ; \tag{3}$$

$$s = M \qquad \lambda\rho \frac{\partial T}{\partial s} = \int\limits_{\Lambda_o} \varepsilon_{\mathrm{ef2},\Lambda} (B_{\mathrm{m2},\Lambda} - B_{\mathrm{w2},\Lambda})\, d\Lambda + h_{\mathrm{f2}} (T_{\mathrm{f2}} - T) ; \tag{4}$$

$$-\frac{\partial}{\partial s} D_\Lambda n_\Lambda^2 \rho \frac{\partial N_\Lambda}{\partial s} + \frac{k_\Lambda n_\Lambda^2}{\rho} N_\Lambda = \frac{k_\Lambda n_\Lambda^2}{\rho} B_\Lambda ; \tag{5}$$

$$s = 0 \qquad -D_\Lambda \rho n_\Lambda^2 \frac{\partial N_\Lambda}{\partial s} + \frac{1}{2} \frac{(1 - R_{\mathrm{ef1},\Lambda})}{(1 + R_{\mathrm{ef1},\Lambda})} n_\Lambda^2 N_\Lambda = 2 \frac{(1 - R_{\mathrm{ef1},\Lambda})}{(1 + R_{\mathrm{ef1},\Lambda})} n_\Lambda^2 (q_{\mathrm{w1},\Lambda} + B_{\mathrm{m1},\Lambda}) ; \tag{6}$$

$$s = M \qquad D_\Lambda \rho n_\Lambda^2 \frac{\partial N_\Lambda}{\partial s} + \frac{1}{2} \frac{(1 - R_{\mathrm{ef2},\Lambda})}{(1 + R_{\mathrm{ef2},\Lambda})} n_\Lambda^2 N_\Lambda = 2 \frac{(1 - R_{\mathrm{ef2},\Lambda})}{(1 + R_{\mathrm{ef2},\Lambda})} n_\Lambda^2 B_{\mathrm{m2},\Lambda} ; \tag{7}$$

$$q_{\mathrm{v}} = \int\limits_{\Lambda_s} \frac{k_\Lambda n_\Lambda^2}{\rho} (N_\Lambda - B_\Lambda)\, d\Lambda , \tag{8}$$

where

$$\varepsilon_{\mathrm{ef1(2)},\Lambda} = \frac{\varepsilon_{\mathrm{m1(2)},\Lambda}\, \varepsilon_{\mathrm{w1(2)},\Lambda}}{\varepsilon_{\mathrm{m1(2)},\Lambda} + \varepsilon_{\mathrm{w1(2)},\Lambda} - \varepsilon_{\mathrm{m1(2)},\Lambda} \varepsilon_{\mathrm{w1(2)},\Lambda}} ; \quad R_{\mathrm{ef1(2)},\Lambda} = 1 - \varepsilon_{\mathrm{ef1(2)},\Lambda} .$$

Equations (1)–(8) are written in the mass coordinate system. The total thickness of the layer is calculated by the formula

$$L = \int\limits_0^M \frac{ds}{\rho} . \tag{9}$$

The relation for calculating the material density is inferred from the mass conservation law:

$$\rho = \rho_0 (1 - \Pi) . \tag{10}$$

Glass is an amorphous material in which transitions from the solid state to the viscoelastic, plastic, and liquid states on heating and back on cooling occur smoothly and the boundaries of such states are identified with the vitrification and softening temperatures. On the other hand, at a certain chemical composition and in certain regimes of thermal treatment, in the glass the formation of a crystalline phase imparting new and higher, than in the initial glass, qualities to the article is possible. In the crystallization kinetics, one most commonly operates with the rate of formation of crystallization centers and with the crystal growth rate [12].

Integrating the models of [12, 13], we can give the kinetics of the volume crystallization process by the following relation:

$$X(s, \tau) = 1 - \exp\left(-g \left(\int\limits_0^\tau n^* \left(\int\limits_{\tau'}^\tau U d\tau'' + r_{\mathrm{c}} \right) d\tau' + \int\limits_0^\tau I \left(\int\limits_{\tau'}^\tau U d\tau'' + r_{\mathrm{c}} \right) d\tau' \right) \right). \tag{11}$$

For taking into account the amorphous-to-crystalline transition heat, the value of the specific enthalpy is calculated by the following formula:

$$H(s, \tau) = \int_0^{\tau} \frac{\partial T}{\partial \tau'} (c(T) - QX)\, d\tau' . \tag{12}$$

In (1)–(5), the data on the local porosity and size of the relative contact point of individual particles are used. These parameters are determined by means of the equations of the phenomenological theory of sintering.

In sintering a porous body with no action of external forces, the main compacting mechanism is likely to be the viscous flow of the substance under the action of capillary forces [14]. In this case, the body is compacted due to the reduction of the free surface energy. Using the statistical model of the porous body [14], we write the rheological compaction equation in the form

$$\Pi(\tau, s) = \Pi_0 \exp\left(-\frac{9}{4}\int_0^{\tau} \frac{\sigma d\tau'}{r_p \eta}\right). \tag{13}$$

In [14], it is shown that one and the same viscous flow mechanism determines both the local deformation of particles in the regions of contacts (growth of the contact sizes) and the macroscopic volume deformation of the porous body on the whole (shrinkage). This enables us to calculate the value of the relative contact point of individual particles by the formula

$$\xi^2 = 1 - \left(\frac{\Pi}{\Pi_0}\right)^{4/3} . \tag{14}$$

The considerable change in the structure of the material in the sintering process points to the fact that for calculating its heat conductivity coefficient it is expedient to use complex models. In the present paper, for describing the heat conductivity coefficient of a porous material, the relation based on the models of [17, 18] is used:

$$\lambda(\Pi) = \begin{cases} \Pi \geq 0.4 & \lambda_{\text{i.p}} ; \\ 0.3 < \Pi < 0.4 & 10(\Pi - 0.3)\lambda_{\text{i.p}} + 10(0.4 - \Pi)\lambda_{\text{i.v}} ; \\ \Pi \leq 0.3 & \lambda_{\text{i.v}} , \end{cases} \tag{15}$$

where

$$\lambda_{\text{i.p}} = \lambda_1 (\bar{L}^2 + \nu(1 - \bar{L})^2 + 2\nu\bar{L}(1 - \bar{L})(\nu\bar{L} + 1 - \bar{L})^{-1}) ;$$

$$\lambda_{\text{i.v}} = \lambda_1 (1 - \Pi/((1 - \nu)^{-1} - (1 - \Pi)/3)) ; \quad \nu = \lambda_2/\lambda_1 .$$

Equations (1)–(15) in the aggregate represent the problem of nonstationary RCHE in a layer of a partially transparent scattering material in a one-dimensional definition for modeling the thermophysical processes in sintering glassware.

We now turn to the consideration of the model of heat conductivity in the two-dimensional region combining the article and the multilayer molding rig (Fig. 2). At the boundaries of the region Γ_i, $i = \overline{1, 4}$, time-varying external thermal radiation fluxes of density q_{wi} act, and also a convective heat exchange with

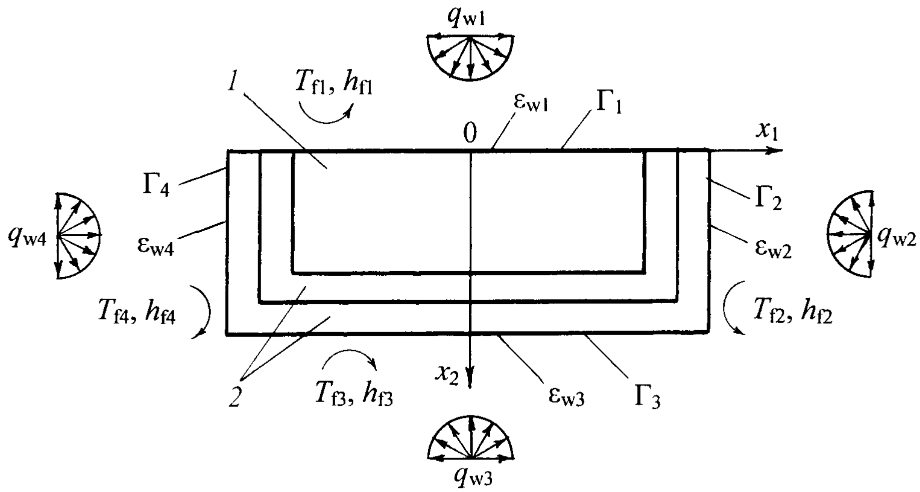

Fig. 2. On the model of two-dimensional heat conductivity in a multilayer molding rig with an article (a layer of glass particles): 1) article; 2) molding rig.

the environment and energy loss through intrinsic emission takes place. The materials of the article and of the mold are assumed to be homogeneous, orthotropic, opaque, gray, diffusely radiating, and absorbing. In the materials, no phase and structural deformation transformations take place. The thermophysical and optical properties of the materials are temperature dependent. The principal axes of the heat conductivity tensor coincide with the chosen axes of the coordinate system x_1 and x_2. The initial temperature distribution in the region as well as the ambient temperature and the heat-transfer coefficients in the vicinity of the boundary surfaces are known.

To the above-formulated physical model there corresponds the following system of equations: the heat conductivity equation

$$c\rho \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x_1}\left(\lambda_{x_1} \frac{\partial T}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\lambda_{x_2} \frac{\partial T}{\partial x_2}\right); \tag{16}$$

the initial condition

$$T = T_0\,; \tag{17}$$

the boundary conditions at Γ_i, $i = \overline{1, 4}$:

$$-\left(\lambda_{x_1} \frac{\partial T}{\partial x_1} l_i + \lambda_{x_2} \frac{\partial T}{\partial x_2} m_i\right) = \varepsilon_{wi}\,(q_{wi} - \sigma_0 T^4) + h_{fi}\,(T_{fi} - T)\,. \tag{18}$$

The solution algorithm for the nonlinear heat conductivity problem (16)–(18) is synthesized on the basis of the finite-element method.

Results of the Mathematical Modeling. GWs usually contain glasses of different brands with differing optical properties, which raises the question of sorting the raw materials. The influence of optical properties of glasses on the sintering process is still not clearly understood. In the present paper, an estimate of the influence of optical properties of GW on the temperature state of the article being sintered has been made.

In mathematical modeling, the raw material was endowed with the optical properties of clear, green, and brown glass. In the range of wavelengths from 0.1 to 1.0 μm, the absorption coefficients of the glasses were calculated by the transmission coefficients. The experimental data on transmission coefficients for the

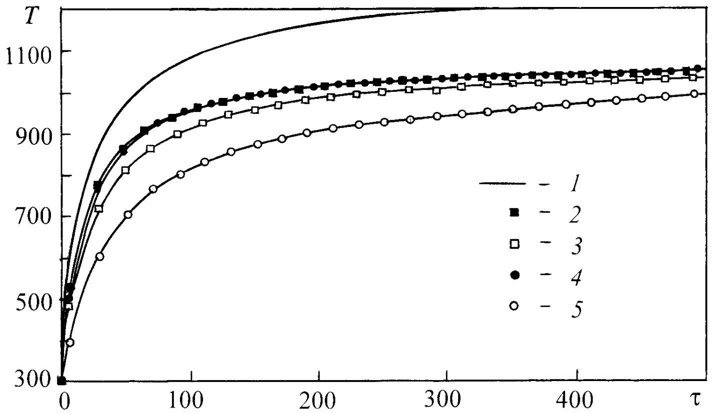

Fig. 3. Time change in the temperature on the front surface of the article being sintered depending on the brand of glasses and heat sources: 1) opaque material; 2 and 4) brown glass, T_h = 1373 and 3000 K; 3 and 5) clear glass, same T_h. T, K; τ, sec.

above types of container glass were supplied by the Moscow Electric Lamp Plant. For the 1.0–4.5-μm range of wavelengths, the absorption coefficients of the glasses were taken from [19]. The effective scattering coefficients of the layer of glass particles were calculated by the relations of [20]. The data on the thermophysical properties of glasses were supplied by the limited company of the Scientific-Research Institute of Glass. The temperature dependences of viscosity and surface tension corresponded to [21]. The charge thickness was assumed to be equal to 17.5 mm and the initial porosity was 42%. The front surface of the charge was assumed to be subjected to the action of a thermal radiation flux of density q_{w1} = 89 kW/m^2 and the convective exchange in it was absent. The front surface was assumed to be cooled due to the convection (heat-transfer coefficient h_{f2} = 4 W/(m^2·K), ambient temperature T_{f2} = 300 K) and the radiation. The optical properties of the surfaces were taken as follows: ε_{w1} = 0.9; ε_{w2} = 0.2; ε_{m1} = 1; ε_{m2} = 0.2.

Figure 3 shows the results of modeling the sintering of a glass particle charge exposed to the radiation of heat sources having the spectral distribution as in the blackbody at temperatures of 1373 and 3000 K. It is seen that the temperature state of the less transparent brown glasses with a high thermal radiation absorption coefficient is not influenced by the temperature of the heat source. The temperature state of the clear glass with a high thermal radiation transmission coefficient depends on the heat-source temperature and is most appreciable at the initial stage of heating (the first 500 sec). From Fig. 3 it follows that the rate of heating by a heat source with a temperature of 1373 K noticeably exceeds that with a temperature of 3000 K. This result is due to the maxima position of the radiation wavelengths of the heat sources, which coincide with the regions of the largest spectral absorption of the brown glass, and for the clear glass such a coincidence is absent. From this it can be concluded that it is necessary to match the optical properties of glass charges to the spectral characteristics of the heat source.

The central point in analyzing the temperature state is the question of temperature drops in the article being sintered. It is expedient to try to minimize the temperature drops in the direction coinciding with the front surface. The temperature field uniform over the surface determines the quality and the appearance of articles. At the same time, if the thickness temperature gradients are small and the final state is characterized by a high temperature level, then such an article will lose its gradient structure and, therefore, its main commercial qualities. Moreover, the temperature gradients directly influence the stress-deformation state of an article as well. In this respect, it is important to assess the influence of the intensity of heat removal from the front, rear, and lateral surfaces on the corresponding temperature gradients. In practice, this problem can be settled by selecting the material and design of the molding rig and the heat shield, by creating, in the space

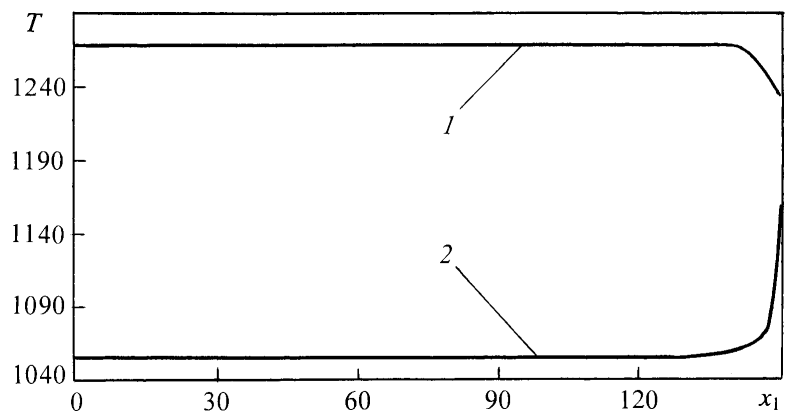

Fig. 4. The initial temperature distribution on cooling of the sintered article (two-dimensional model): 1) front surface; 2) rear surface.

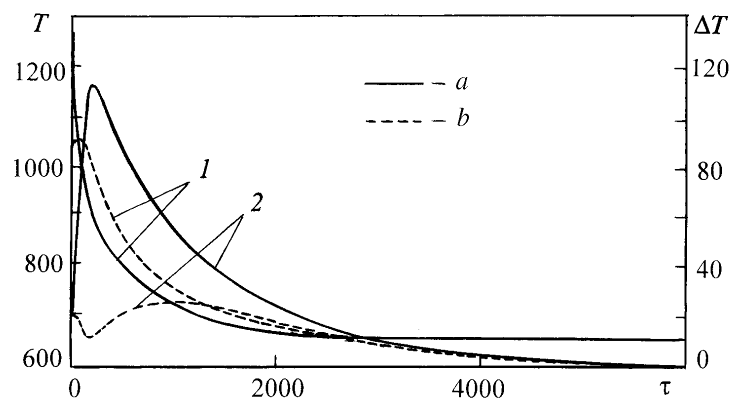

Fig. 5. Time change in the temperature state of the article at the cooling stage (two-dimensional model): 1) temperature in the center; 2) temperature drop (ΔT) from the edge to the center: (a) front surface; (b) rear surface. T, K; τ, sec.

of the technological facility, annealing sectors with intense convective or radiative heat removal, and by choosing the annealing time of an article.

In the present paper, the cooling of a sintered article 10 mm in thickness in a cermet mold was modeled. The modeling conditions were as follows: ambient temperature T_{fi} = 650 K; heat-removal coefficient h_{fi} = 5 W/(m^2·K); incident heat fluxes q_{wi} = 10 kW/m^2; emissivities ε_{w1} = 0.9; $\varepsilon_{w2} = \varepsilon_{w3} = \varepsilon_{w4}$ = 0.7. The initial temperature distribution of the article corresponded to the end of the sintering stage and is displayed in Fig. 4. As the model material, we took a sintered charge of brand BT-1 glass particles with a zero porosity and crystallinity. The data on the thermophysical properties of BT-1 were supplied by the limited company of the Scientific-Research Institute of Glass. The thermophysical properties of the mold materials were borrowed from [22, 23].

Figure 5 presents the results of modeling the radiation-convective cooling of a sintered article in a cermet molding rig. It is seen that after about 1 h the temperature on the rear and front surfaces of the article decreases to 650 K and then remains constant. It should be noted that on the rear surface the temperature gradient from the edge to the center is low, whereas on the front surface it is significant at the initial stage of cooling and reaches its maximum of 110 K at the 150th second. Further cooling leads to a decrease in the temperature drops on the article surfaces, and after 1.5 h they practically become equal to zero. Based on this

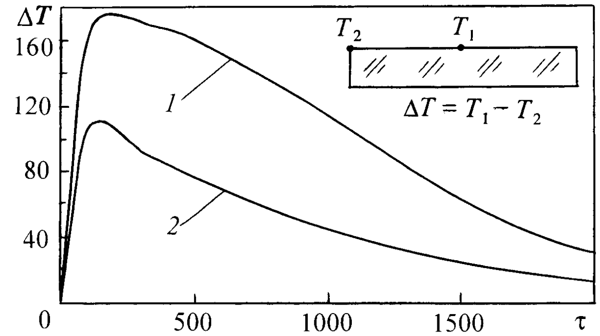

Fig. 6. Change in the temperature drop on the surface of the article being sintered (two-dimensional model): 1) metal molding rig; 2) cermet molding rig.

model problem, it may be concluded that on cooling of the article the thickness temperature gradient and the uniformity of the temperature fields over the surface given at the sintering stage can really be maintained.

It is known that in manufacturing glass articles by the sintering method the quality of finished products strongly depends on the molding rig and the output is directly associated with the duration of the stages of thermal treatment. The influence of materials and design of the molding rig on the quality of articles has been investigated. The main quality criteria were the uniformity of the temperature fields over the surface and the stability of the geometric dimensions of the article.

Calculations have shown that for the cermet mold the temperature drop on the surface of the article being sintered is half that for the metal one (Fig. 6). This is due to the small, compared to metal, heat conductivity coefficient of the ceramic material, which, in addition, has a low thermal coefficient of linear expansion, which provides stability of the geometrical dimensions and decreases the probability of article warpage.

CONCLUSIONS

1. In connection with the acute problems of energy saving and environmental protection, the prospects of developing a technology for manufacturing building-purpose articles from glass by the sintering technique is noted. A powerful source of raw materials for this and other technologies is domestic and industrial glass waste.

2. Ways of synthesing a generalized mathematical model corresponding to the technology for manufacturing articles from glass by the sintering technique have been mapped out. Models of the thermophysical processes in sintering glassware that permit taking into account the unsteadiness and multidimensionality of heat exchange, the partial transparency of the material, and the physicochemical and structural-phase transformations have been developed.

3. By means of mathematical modeling of the thermophysical processes the influence of certain important characteristics of the raw material and conditions of thermal treatment on the temperature state of articles manufactured by the sintering technique has been established.

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NOTATION

T, temperature; L, layer thickness; ρ, density; τ, time; q, heat flux density; q_v, internal heat sources; Λ, radiation wavelength; λ, heat-conduction coefficient; h_f, heat-transfer coefficient; c, specific heat; H, specific enthalpy; ε, emissive power; σ_0, Stefan–Boltzmann constant; B, Planck function; M, specific mass of a layer; s, mass coordinate; x_1 and x_2, Cartesian coordinates; D, radiation-diffusion coefficient; N, reduced spectral density of radiant energy; n, refractive index; k, radiation-absorption coefficient; R, hemispherical coefficient of surface reflection; Π, porosity; X, relative volume fraction of the crystalline phase; g, growing crystal form factor; I, rate of formation of crystallization centers; r_{cr}, critical radius of the crystallization center; n^*, number of critical-size crystallization centers; U, linear growth rate of a crystal; τ' and τ'', variables of time integration; Q, specific heat of the exothermal effect of crystallization; r_p, mean radius of particles; η, shear-viscosity coefficient of the particle material; σ, specific surface tension; ξ, relative linear size of contact of individual particles; $\lambda_{i.p}$ and $\lambda_{i.v}$, heat conductivity coefficients of structures with interpenetrating components and isolated inclusions; λ_1 and λ_2, heat-conduction coefficients of the particle material and gas in pores; $\overline{L}$, relative size of the bar of the structure framework with interpenetrating components; l and m, direction cosines; Γ, boundary of the region; λ_{x_1} and λ_{x_2}, heat-conduction coefficients in the direction of the axes of the coordinate system. Subscripts: 0, initial value; ef, effective characteristics; w, surface of the computational domain; m, opaque surfaces; f, environment; s, partially transparent; o, opaque; λ, dependence on the radiation wavelength; i, boundary number; h, heating.

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