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MATHEMATIC SIMULATION OF GLASS MELTING PROCESS IN GLASS PRODUCTION

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***Abstract**: A systematic analysis of the technological process of glass melting as an object of automatic control and management has been carried out. As an object of automatic control with distributed parameters, the mathematical description of the glassmaking furnace operation has been developed (considering the main phenomenological features of the technological mode of glassmaking).In this paper, a mathematical description of charge melting process, additional heating by electric current, bubbling, thermal conductivity and heat fluxes during the processing of molten glass have been generated. Initial conditions and simplifying assumptions have been derived. The model is based on the equations of continuity, momentum and energy, as well as kinetic turbulent energy, dissipation of kinetic turbulent energy. An experiment has been conducted on the proposed in order to check for its adequacy to real glass-making processes.*

***Key words**: glass furnace; thermal regime, technological process, glassmaking, mathematical description and optimization of the glassmaking process, energy and resource saving, quality of glass mass.*

***Аннотация:** Шиша эритиш технологик жараёнини автоматик назорат қилиш ва бошқариш объекти сифатидаги тизимли таҳлили амалга оширилган. Шиша эритиш печи тақсимланган параметрли автоматик бошқариш объекти сифатида қаралиб, унинг ишини математик тавсифи тузилган. Модель шиша эритишнинг технологик режимини асосий феноменологик хусусиятларини эътиборга олади. Ишда шихтани эритиш жараёнининг математик тавсифи олинган, шиша массасига ишлов беришда электр токи билан қўшимча қиздириш, барботаж, иссиқлик ўтказувчанлик ва иссиқлик оқимлари кўриб чиқилган. Бошланғич шартлар аниқланган ва соддалаштирувчи таклифлар шакллантирилган. Моделларнинг асосида бузилмаслик, ҳаракат ва энергия миқдорини тенгламалари, шунингдек кинетик турбулент энергия ва кинетик турбулент энергия диссипацияси ифодалари ётибди. Моделларни реал шиша эритиш жараёнига монандлиги текширилган.*

***Таянч сўзлар:** шиша эритиш печи; иссиқлик режими; технологик жараён; шиша эритиш; шиша эритиш жараёнини математик тавсифлаш ва оптималлаштириш; энергия ва ресурс тежамкорлик; шиша массасининг миқдори.*

***Аннотация:** Выполнен системный анализ технологического процесса варки стекла как объекта автоматического контроля и управления. Составлено математическое описание работы печи стекловарения как объекта автоматического управления с распределенными параметрами. Модель учитывает основные феноменологические особенности технологического режима стекловарения. В работе получено математическое описание процессов плавления шихты, дополнительного нагрева электрическим током, барботажа, теплопроводности и тепловых потоков при обработке стекломассы. Определены начальные условия и сформулированы упрощающие предположения. В основу модели положены уравнения неразрывности, количества движения и энергии, а также выражения кинетической турбулентной энергии, диссипации кинетической турбулентной энергии. Осуществлена проверка модели на адекватность реальным процессам стекловарения.*

***Ключевые слова:** стекловаренная печы; тепловой режим, технологического процесса, стекловарение, математическое описание и оптимизация процесса стекловарении, энерго- и ресурсосбережение, качество стекломассы.*

Introduction

The main technological process in the industrial production of glass products for any purpose consists of the implementation of complex technological methods of glass-making, proceeding in glass-melting furnaces, which are the determining consumer of material and energy resources in the entire technological chain of production. In modern conditions of technology, the energy and resource saving issues are very important, which should find its immediate solution in glassmaking industry. One of possible methods to solve these problems is to create a control system that would ensure the functioning of the glass furnace in optimal technological modes. According to the testimony of many researchers, the optimization of the technological mode of a glass furnace operation, is primarily associated with the optimization of the thermal mode of controlling system [1,5]. Modern development of information technologies and computer control systems contributes to solving this problem at a new, more efficient technical level, namely: increasing the efficiency of the main technological method in the production of glass products of the glassmaking process by automating the control of the process of thermal operation that meets the strict requirements of energy and resource conservation [6,8]. A glass furnace is a complex technological object in which physical and chemical transformations, all types of heat exchange (both in a gas environment and in liquid glass mass) take place simultaneously and in parallel. The glassmaking process is characterized by many mutually related parameters that affect both each other and the quantity and quality of the finished product as a whole [8,11]. To ensure the continuous operation of the glass furnace in the resource - and energy-saving mode, which would simultaneously ensure high quality of finished products, an effective control system for the glassmaking process is necessary. The development of such a management system is associated with considerable difficulties, caused by the need to conduct experimental studies on a working furnace, which, as a rule, leads to a deviation of the technological mode from the routine one and, as a result, can lead to the production of defective products and, as an extreme case, the occurrence of accidents, and consequently, significant production losses, which is by no means acceptable. The only alternative to avoiding this is to study the glass furnace and control system.

Mathematical modeling of the glass-making process in industrial furnaces

A mathematical model of charge melting, additional electric heating, bubbling, thermal conductivity, and heat fluxes during the processing of glass mass is obtained. Taking into account that any mathematical description reflects only a certain part of the properties of the object of modeling, simplifying assumptions used in mathematical modeling of the glassmaking process are formulated [7].

In accordance with the considered physical concepts of the processes occurring in a glass furnace, the mathematical modeling is based on the following equations:

continuity features

$$\nabla \cdot \triangledown = 0 \tag{1}$$

traffic volumes

$$\rho_0\left[\frac{\partial \triangledown}{\partial \tau} + (\triangledown \cdot \nabla)\triangledown\right] = -\nabla\overline{p} + \nabla \cdot \hat{\overline{\tau}} + \rho_0\beta(\overline{T} - T_0)\,g, \tag{2}$$

energy sources

$$\rho_0 c_p\left[\frac{\partial \overline{T}}{\partial \tau} + \nabla \cdot (\triangledown \overline{T})\right] = \nabla\left[(\lambda + c_p\eta_t)\nabla\overline{T}\right] - \nabla \cdot \overline{q}_r + \hat{\overline{\tau}} : \nabla \triangledown + \overline{q}_v, \tag{3}$$

kinetic turbulent energy

$$\rho_0\left[\frac{\partial k}{\partial \tau} + \nabla \cdot (\triangledown k)\right] = \nabla \cdot \left[(\eta + \frac{\eta_t}{\sigma_k})\nabla k\right] + \eta_t G - \overline{\rho}\varepsilon, \tag{4}$$

kinetic turbulent energy dissipation

$$\rho_0\left[\frac{\partial \varepsilon}{\partial \tau} + \nabla \cdot (\triangledown \varepsilon)\right] = \nabla \cdot \left[(\eta + \frac{\eta_t}{\sigma_\varepsilon})\nabla \varepsilon\right] + \frac{\varepsilon}{k}(C_1 G - C_2\rho\varepsilon), \tag{5}$$

where ∇ - Hamilton operator, m^{-1}; $\cdot\overline{\nabla}$ – Reynolds-averaged velocity vector of the medium, m/c; ρ_0 – density at temperature, T_0, $кг/м^3$; T_0 - absolute reference temperature, K; τ -time, c; $\overline{T}$ - centered absolute temperature, k; $\overline{p}$ - centered pressure, $Па$; $\hat{\overline{\tau}} = (\eta+\eta_t)\left[\nabla\overline{\nabla}+\overline{\nabla}\nabla\right]-\frac{2}{3}\rho_0 k$ or $\hat{\overline{\tau}} = (\eta+\eta_t)\hat{\overline{D}}-\frac{2}{3}\rho_0 k$ – tensor of the 2nd rank of focal effective stresses, $Па$; η - dynamic viscosity, $Па\cdot c$; $\eta_t = C_\eta \rho \frac{k^2}{\varepsilon}$ - turbulent viscosity, $Па\cdot c$; k - turbulent kinetic energy, $Дж/кг$; ε - dissipation of turbulent kinetic energy, $Дж/(кг\cdot c)$; $\hat{\overline{D}} = \frac{1}{2}(\nabla\overline{\nabla}+\overline{\nabla}\nabla)$ tensor of the 2nd rank of the averaged strain rate, c^{-1}; $C_П = 0{,}09$ – empirical constant; β – coefficient of linear temperature expansion, K^{-1}; c_p - mass Isobaric heat capacity, $Дж/(кг\cdot к)$; λ -thermal conductivity, $Вт/(мК)$; $\nabla\cdot\overline{q}_r = k\left[\int_{\Omega=4\pi} I(s)d\Omega - 4n^2\sigma\overline{T}^4\right]$ divergence of the radiative heat flux density or bulk density; $Дж/м^3$; q_r - vector of radiation heat flux density, $Вт/(м^2)$; k and n -absorption coefficient ($м^{-1}$) and refractive index, respectively; Ω - solid angle, c_p; σ - Stefan's constant - Boltzmann's, $Вт/(м^2K^4)$; $I(s)$ – radiation intensity $(Вт\cdot c/(м^2 c_p))$ go to directions $S(м)$ in solid angle $d\Omega$ it is determined from the solution of the transfer equation in the form $\nabla\cdot\left[I(s)s\right]+kI(s)=kn^2\frac{\sigma\overline{T}^4}{\pi}$; $\overline{q}_v$ - the volume density of the internal heat source, which may be due to chemical reactions or Joule heat $(\overline{q}_v)=\chi\left|\nabla\phi\right|^2)$, $Вт/(м^3)$; χ -electrical conductivity, $(Ом\cdot м)^{-1}$; φ - electrical potential, $В$; $G=\eta_t\dot{\gamma}^2$ source of turbulent kinetic energy due to the average velocity gradient or strain rate, $Вт/(м^3)$; $\dot{\gamma}=\sqrt{2\hat{\overline{D}}:\hat{\overline{D}}}$ d is the modulus of the average strain rate tensor, c^{-1}; (:) - is the double scalar product operator; $\sigma_k = 1{,}0$; $\sigma_k = 1{,}0$; $C_1 = 1{,}44$; $C_2 = 1{,}92$ σ_k =1,0; – constants $k-\varepsilon$ of the turbulence model [12-13].

In addition, the initial and final words have been indicated.

To test the considered mathematical model for its adequacy to real processes, the vector of output variables directly measured in the furnace for 100 hours was observed, and corresponding calculations were performed using the given model.

The study of the adequacy of the proposed model to the existing ones was carried out according to the well-known statistical criteria of student and Fisher. Comparison of calculated and tabular values of the adequacy criteria for all initial variables confirms the main hypothesis about the adequacy of the model, and therefore the mathematical model under study can be considered to adequately describe the glassmaking process [14,15].

Conclusion

The above mathematical model was implemented as a 3D computer model. The results of modeling using this model made it possible to obtain a spatial distribution of temperatures in any plane of the investigated glass furnace.

Modern computer control systems, as a rule, are built on the basis of mathematical models of controlled processes. Therefore, when creating a glass furnace control system, you need a mathematical model of this control object.

The mathematical model proposed above is a system of partial differential equations of a rather complex form. Solving such a system requires considerable time, which actually limits the practical application of such mathematical models in computer control systems.

The above-mentioned circumstances make it necessary to develop a simplified mathematical model of a glass furnace that would describe its behavior with the necessary accuracy.

In this regard, the work was developed bythaton a simplified mathematical model of the glassmaking process. This model is constructed using the method of separation of variables (Fourier method), according to which it is assumed that a function of several variables (time and spatial coordinates) is represented in the form of a series, each term of which is a product of two functions of one variable-time and spatial coordinates

$$T(\xi,t)=\sum_{i=1}^{n} a_i(t)\varphi_i(\xi), \tag{6}$$

where the functions are unknown a priori $a_i(t)$ and $\varphi_i(\xi)$ must be selected so that the variable $T(\xi,t)$ met the limit conditions of the problem.

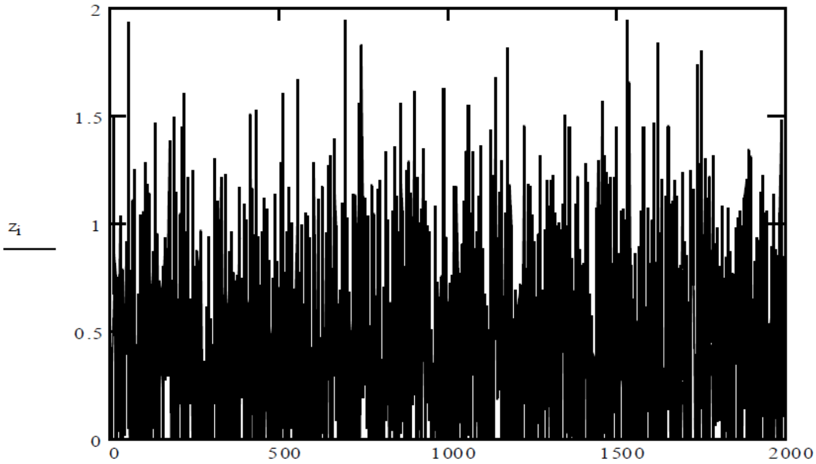

*Fig 1***. Graph of changes in absolute errors.**

Basis vectors $\varphi_i(\xi)$ calculated from the data contained in the matrix values of temperature samples calculated from the initial model. To define $\{a_i(t)\}_{i=1}^{n}$ Fourier coefficients you can use system identification methods using a mathematical model in the state space.

In order to study the quality of a simplified mathematical model of a glass furnace, simulation modeling was carried out.

As can be seen from the graph of changes in absolute errors at one of the studied points shown in figure 1, the simplified model approximates the original mathematical model quite accurately. The greatest approximation errors occur at relatively high rates of temperature change.

The temperature of glass mass is the most important technological parameter that determines the processes of melting, cleaning, homogenization, re-cleaning and thermal homogeneity of glass. This makes it necessary to create a perfect system for monitoring and controlling the temperatures of glass mass and gas medium in a glass furnace.

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