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INFLUENCE OF VARIOUS COOLING CONDITIONS AND HEAT TRANSFER COEFFICIENTS ON SOLIDIFICATION DURING THE FORMATION OF BERYLLIUM CERAMIC PRODUCTS

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Abstract. The article presents the results of a parametric study of the solidification process of a thermoplastic beryllium oxide (BeO) suspension in the cavity of a ring mold. The primary aim of the study is to ensure uniform structure formation in cast products and to address the issue of preventing technological defects. To this end, the spatial-phase characteristics of beryllium oxide suspensions were comprehensively analyzed, and their dependence on casting properties, phase composition, rheological characteristics, and technological parameters was scientifically assessed. It was shown that the solidification process of cast products is determined by a complex set of hydrodynamic, thermal, and crystallization phenomena that develop during solidification. It was established that these phenomena directly depend on the suspension flow rate, temperature regime, ratio of liquid to solid phases, particle distribution, and the intensity of heat removal from the mold. The mathematical models presented in this work provide a practical and experimental scientific tool to predict the nonuniform distribution of suspension structure and physico-mechanical properties across the cross-section of castings. It was determined that during solidification, the heat removal rate from the normal state depends on the suspension flow rate, the thermal conductivity of the mold material, and the temperature field characterized by the width of the transition zone. The solidification process of the suspension mass was evaluated through the analysis of heat flux distribution, viscosity changes, and density variations along the concentric channel. Hydrodynamic and heat transfer modeling results, carried out considering the crystallization of the thermoplastic beryllium oxide suspension, showed good agreement with experimental data. The obtained results enable efficient control of the casting process, reduce energy consumption, and consequently produce homogeneous, high-quality castings in terms of texture.

Keywords. Beryllium oxide, continuous casting, Bingham liquid, rheological parameters, heat transfer, solidification

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БЕРИЛЛИЙ КЕРАМИКАЛЫҚ БҰЙЫМДАРЫН ҚАЛЫПТАСТЫРУ КЕЗІНДЕ ӘР ТҮРЛІ САЛҚЫНДАТУ ЖАҒДАЙЛАРЫ МЕН ЖЫЛУ БЕРУ КОЭФФИЦИЕНТТЕРІНІҢ ҚАТАЮҒА ӘСЕРІ

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Аннотация. Мақалада сақиналы қалыптау қуысында бериллий оксидінің (BeO) термопластикалық суспензиясының қатаю процесін параметрлік зерттеу нәтижелері баяндалған. Зерттеудің негізгі мақсаты – құйма бұйымдарда құрылымның біркелкі қалыптасуын қамтамасыз ету және технологиялық ақаулардың алдын алу мәселесін шешу болып табылады. Осы мақсатта бериллий оксиді суспензиясының кеңістіктік-фазалық сипаттамалары жан-жақты қарастырылып, олардың құю қасиеттеріне, фазалық құрамына, реологиялық сипаттамасына және технологиялық параметрлерге тәуелділігі ғылыми тұрғыдан бағаланды. Құйма өнімдердің қатаю процесі қатаю кезінде дамитын гидродинамикалық, термиялық және кристалдану құбылыстарының күрделі жиынтығымен анықталатыны көрсетілді. Бұл құбылыстар суспензияның қозғалу жылдамдығына, температуралық режимге, сұйық және қатты фазалардың арақатынасына, бөлшектердің таралуына, сондай-ақ қалыптан жылуды әкету интенсивтілігіне тікелей байланысты екені айқындалды. Жұмыста ұсынылған математикалық модельдер құймалардың көлденең қимасы бойынша суспензия құрылымы мен физика-механикалық қасиеттерінің біркелкі емес таралуын болжауға нақты тәжірибелік және қолданбалы ғылыми мүмкіндік береді. Қатаю кезеңінде қалыпты жағдайдан жылуды кетіру жылдамдығы суспензия қозғалысының жылдамдығына, қалып материалының жылу өткізгіштігіне және өтпелі аймақтың енімен сипатталатын температуралық өріске тәуелді екені анықталды. Суспензия массасының қатаю процесі жылу ағынының таралуын, тұтқырлық өзгерісін және концентрлік арна бойындағы тығыздықтың өзгеруін талдау арқылы бағаланды. Бериллий оксиді термопластикалық суспензиясының кристалдануын ескере отырып, жүргізілген гидродинамика мен жылу алмасуды модельдеу нәтижелері эксперименттік деректермен жақсы сәйкестік көрсетті. Алынған нәтижелер құю процесін тиімді басқаруға, энергия шығынын азайтуға және нәтижесінде біркелкі құрылымды, жоғары сапалы құймалар алуға мүмкіндік береді.

Түйін сөздер: Бериллий оксиді, үздіксіз құю, Бингем сұйықтығы, реологиялық параметрлер, жылу беру, қатаю

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ВЛИЯНИЕ РАЗЛИЧНЫХ УСЛОВИЙ ОХЛАЖДЕНИЯ И КОЭФФИЦИЕНТОВ ТЕПЛОПЕРЕДАЧИ НА ЗАТВЕРДЕВАНИЕ ПРИ ФОРМИРОВАНИИ БЕРИЛЛИЕВЫХ КЕРАМИЧЕСКИХ ИЗДЕЛИЙ

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Аннотация. В статье представлены результаты параметрического исследования процесса затвердевания термопластичной суспензии оксида бериллия (BeO) в полости кольцевой формы. Основной целью исследования является обеспечение равномерного формирования структуры в литых изделиях и предотвращение технологических дефектов. Для достижения этой цели были всесторонне рассмотрены пространственно-фазовые характеристики суспензий оксида бериллия, а также дана научная оценка их зависимости от литейных свойств, фазового состава, реологических характеристик и технологических параметров. Показано, что процесс затвердевания литых изделий определяется сложным комплексом гидродинамических, тепловых и кристаллизационных явлений, развивающихся в ходе затвердевания. Установлено, что эти явления напрямую зависят от скорости движения суспензии, температурного режима, соотношения жидкой и твердой фаз, распределения частиц, а также интенсивности отвода тепла из формы. Представленные в работе математические модели обеспечивают возможность прогнозирования неравномерности распределения структуры суспензии и физико-механических свойств по поперечному сечению отливок, что имеет как экспериментальное, так и прикладное значение. Установлено, что в период затвердевания скорость отвода тепла из расплава зависит от скорости движения суспензии, теплопроводности материала пресс-формы и температурного поля, характеризуемого шириной переходной зоны. Процесс затвердевания суспензионной массы оценивали путем анализа распределения теплового потока, изменения вязкости и плотности вдоль концентрического канала. Результаты гидродинамического моделирования и моделирования теплообмена, выполненные с учетом кристаллизации термопластичной суспензии оксида бериллия, показали хорошее согласование с экспериментальными данными. Полученные результаты позволяют эффективно управлять процессом литья, снижать энергозатраты и, как следствие, получать высококачественные отливки с однородной структурой.

Ключевые слова: Оксид бериллия, непрерывная разливка, жидкость Бингема, реологические параметры, теплопередача, затвердевание

Introduction. Products made of thermoplastic beryllium oxide slip have become widely used in various industries over the past decades, primarily as a thermal insulation material for equipment operating at high temperatures (Walsh, 2020). Using the hot casting method in an industrial injection molding plant with preset dimensions, ceramic products of a predetermined shape with an adjustable density can be obtained

(Wei, et al., 2019), the high thermal conductivity of beryllium oxide during casting in the temperature range of 40-55°C causes difficulty in controlling structure formation (Shakhov, 2008). The mechanism of solidification, as well as the mechanical behavior of the casting mass during the casting process, the rheological and thermophysical properties of a thermoplastic beryllium oxide slip due to exposure to ultrasound are poorly understood. The experimental study of physical-chemical properties and phase transformation, while taking into account all factors affecting the quality of products in the continuous casting process, is laborious. Therefore, an effective way to control the physical processes occurring during the formation of products with specified properties and shapes is to model the process and determine its main characteristics. The main purpose of the article is to determine the influence of cooling and heat transfer conditions on the solidification of the slip, while the rheological properties of the thermoplastic slip during its flow are an important factor. According to experimental data (Zhapbasbayev, et al., 2016), the Bingham-Papanastasiou model with a control parameter is used to validate experimental curves and describe the behavior of a viscoplastic slip before and after yield strength and viscosity during ultrasonic treatment (Papanastasiou, et al., 1997), (Jabbari, et al., 2016), (Mehmood, et al., 2020). The high thermal conductivity of beryllium oxide has a significant effect on the increase in the volume of the liquid phase and the rheology of the viscoplastic slip during preparation and molding (Shakhov, et al., 2008). The thermal conductivity of beryllium oxide with a relative density of 99% is 220-230 (W/m*S) at a temperature of 100□ (Walsh, 2020). However, with an increase in shrinkage friability to 5-10% and zonal liquation, the thermal conductivity of ceramics at low temperatures decreases by 10-13%. As the temperature increases, the thermal conductivity decreases and reaches a value of 15.4 W/m×From (Shakhov, et al., 2008). Therefore, when considering the object under study, factors such as the dependence of thermophysical properties on temperature, phase transformations of liquid suspensions into a solid state, heat of crystallization, and a sharp change in temperature boundary conditions on cooling circuits should be taken into account. As mentioned in other articles on MIM technology, increasing the volume of the liquid phase to impart the necessary casting properties to the slip does not allow achieving the desired effect, since during firing an «additional» amount of binder leads to the appearance of structural defects and deformations of products. (Sattinova, et al., 2022). When forming products in the forming cavity, it is of great importance to control the cooling of the slip mass, since the solidification process inside the mass depends on the temperature distribution (Zhao-Hui, al., 2021). Also, the change in the temperature field during the cooling process depends on the heat release in the phase transition region and the determination of boundary conditions. Experimentally determined temperatures of the liquidus and solidus of the slip make it possible to identify the nature of the phase distribution at different stages of crystallization, calculate the rate of solid phase separation necessary for studying thermal processes and analyzing the formation of shrinkage defects (Zhapbasbayev, et al., 2016), (Weiß, et al., 2019).

The comparative analysis of the rheological and thermal characteristics of the slip in the range of phase transformations, combined with experimental data, allows us to identify a detailed method of physico-chemical analysis of the solidification of the slip depending on the cooling rate and the change in the position of the crystallization interval of the slip in the forming cavity of the casting installation.

Materials and methods. Rheological characteristics of the thermoplastic slip. Thermoplastic slips based on beryllium oxide (BeO) with a binder content of 9.5, 10.7 and 11.7% were used to produce ceramic products. The molding compound, a thermoplastic slip, is a highly viscous suspension in which one of the phases is a solid – beryllium oxide powder, and the second is a liquid - organic binder. The organic binder includes three components: paraffin, beeswax, and oleic acid in a ratio of (82; 15 and 3%) (Sattinova, et al., 2022).

The slip mass is characterized by a certain ratio of the concentration of solid C_v, liquid C_w phases, the critical concentration of the solid phase in the cv_crit system, the proportion of kinetically free C_V and kinetically bound C_W liquids. The critical concentration of [Cv]_crit is considered an important criterion for objectively characterizing the state of a slip when determining its properties and structure (Shakhov and Bitsoev, 1999). (Shakhov, et al., 2002), (Pivinskii, et al., 1983). Its proportion in the slurry is equal to the relative density of the solid phase in the sediment obtained after 60 minutes of centrifugation at a temperature of 90 ° C.:

For the BeO slip, the technologically permissible concentration of the solid phase is 75-78% (Shakhov, Bitsoev, 1999). (Sattinova, et al., 2024). High-quality molding of ceramic products with homogeneous properties is achieved by increasing the fluidity of the slip due to intensive ultrasonic treatment with a frequency of 16-18 kHz. As a result, the technological properties increase and at the same time the slip changes its structure under the influence of the forces of molecular attraction, forming conglomerates of particles (Fig.1). An increase in the fluidity of the suspension is accompanied by a decrease in the thickness of the solvated shell and an increase for ligament (Kiiko V.S., et al., 2015). The amount of kinetically bound ligament in a slip with different volume concentrations is Cw_f2=0.252. Improving the fluidity of the slip leads to a decrease in viscosity, which is one of the main indicators of the relationship between the concentration of the slip and its rheological properties (Shakhov and Bitsoev, 1999).

The rheological parameters of the slip, such as yield strength, plastic viscosity and shear rate, were determined experimentally in the studied temperature range of 80-40°C in the production conditions of ceramic products of Keramika LLP (Shakhov, Bitsoev, 1999). Along with rheological properties, thermal conductivity, heat capacity and heat of melting are the main elements for calculating technical parameters and play an important role in the manufacture of products by injection molding (Dvinskikh, et al., 1976). Based on experimental data, empirical dependences of the rheological and thermophysical properties of a thermoplastic slip on temperature have been established, which make it possible to describe the movement and heat exchange during the molding of beryllium ceramics, taking into account changes in its state of aggregation (Sattinova , et al., 2022). In scientific literature, data on the thermophysical properties of a dispersed system are limited, and they theoretically confirm that mechanical damage to the structure of a dispersed system does not affect the thermophysical properties, i.e., the value of heat capacity c_p and thermal conductivity λ (Makurin , et al., 2006). To confirm which, graphs of changes in thermal conductivity are given before (1) and after (2) ultrasonic treatment with the action of a slip (BeO batch No. 3) in the temperature range of 20-80 °C (Fig.1).

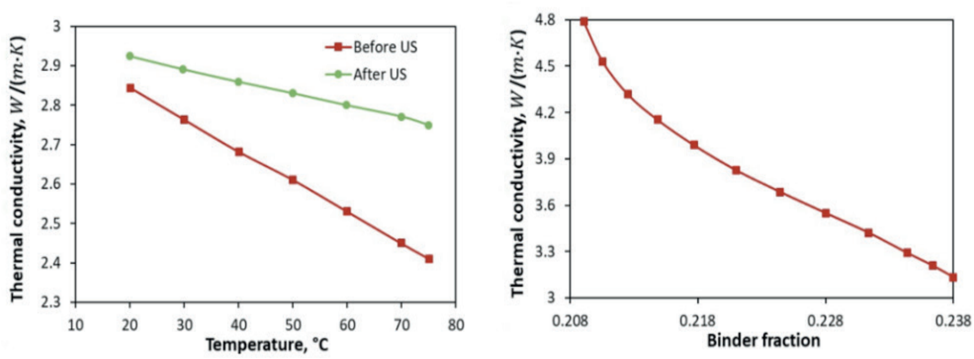

Figure 1- Thermal conductivity of the slurry versus liquid phase concentration (a) and thermoplastic slurry before/after ultrasonic treatment (b)

The effect of ultrasonic vibrations on the thermophysical properties of a dispersed system is related to the anisotropy of thermal conductivity, i.e., the direction of heat flow. This means that heat transfer is mainly due to a molecular mechanism, unlike momentum transfer, where deformations of the structural framework are of decisive importance (Makurin, et al., 2006).

A comparison of the high thermal conductivity of pure beryllium oxide with the low thermal conductivity of the binder indicates that when considering a thermoplastic slip as a structured dispersed system, its thermal conductivity depends primarily on the thermal conductivity of the binder, especially free, undissolved, since the particles of the dispersed phase practically do not interact with each other. They are in contact with each other and cannot significantly affect the thermal conductivity of the system. This phenomenon is noticeable when considering the dependence of thermal conductivity on the volume fraction of the bundle content in the slips (Fig.1).

The specific heat capacity of beryllium oxide has been widely studied experimentally and theoretically (Dong Hou, et al., 2022); Yamamoto, et al., 2021). The heat capacity of the beryllium oxide slip increases naturally with increasing temperature and binder content. The graphs show that the heat capacity of the slip depends only on the density and does not depend on the viscosity and shear stress (Fig.2).

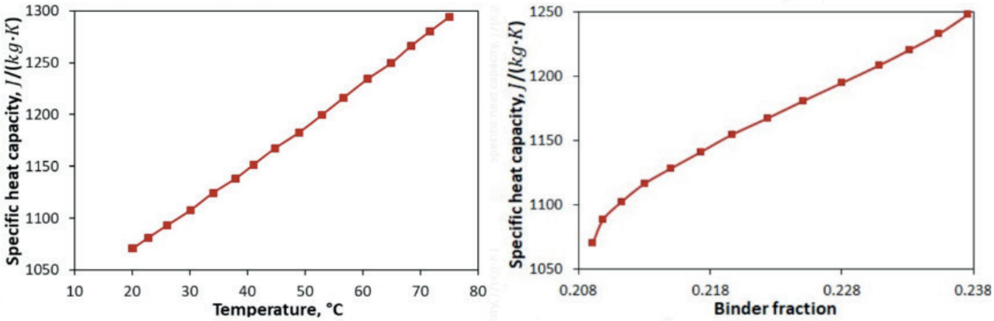

Figure 2- Heat capacity versus liquid phase concentration (a) и temperature slurry (b)

The melting heat of the slip strongly depends on the structure of the dispersed system (Theodore, et al., 2011). In the structure of the slip on the surface of solid particles, some physical properties of adsorbed liquid molecules change significantly, in particular, the melting point and density increase

During the melting process, the solvated bond in the slip will not significantly change its structure. This is equivalent to the absence of the latent heat of melting of the solvated bond, i.e. the heat spent on the destruction of the structure to change the state of aggregation at the melting temperatures of the free bond.

Flow of beryllium oxide (BeO) slurry considered between two concentric cylinders with the length of 108 mm as shown in Fig. 3(a). This approach considers damping source in the Navier-Stokes equation to force calculated velocity to equal zero when BeO slurry becomes fully solid. Damping coefficient is introduced similar with the permeability of porous medium, which depends on BeO slurry liquid fraction. As BeO slurry enters the cavity between concentric cylinders, it begins to be cooled by external circulating water in three cooling zones with the lengths of L_1=22, L_2=45 and L_3=41 mm, respectively, and cooling temperature of T_1=73^{0}C, T_2=59^{0}C and T_3=45^{0}C mm, respectively (see Fig. 3(b)). Outer radius of inner cylinder, inner radius of outer cylinder and outer radius of outer cylinder is r_1=20, r_2=25 and r_3=26, and r_3=26 mm, respectively. The thickness of outer cylinders (crystallizer) wall is mm. the material of inner and outer cylinders is made from steel of grade 12X18H10T. Inner radius of water circulation zones is r_w=36 mm. The model equations are derived under the following assumptions that BeO slurry:

- Flow is laminar due to the low casting velocity.
- Flow is steady-state
- Behaves as Bingham liquid
- Flow is axisymmetric
- Thermophysical and rheology properties are functions of temperature.

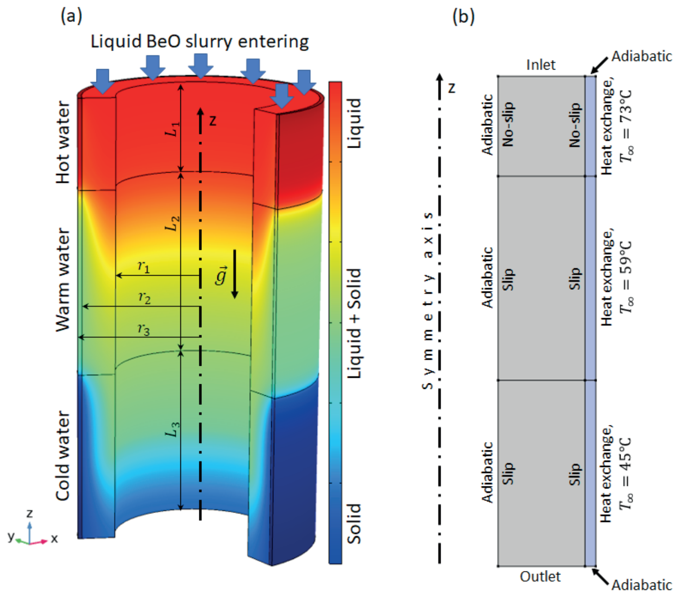

Figure 3- (a) 3D schematic of BeO slurry flow and solidification and (b) 2D domain with an imposed boundary conditions

Under the above assumptions flow equation for BeO slurry, energy equation for BeO slurry and crystallizer are described as following.

Fluid flow equations

$$\rho(\vec{u}\cdot\nabla)u = \nabla\cdot(-pI + K) + \rho\vec{g} - A(\vec{u} - \vec{u}_{cast}) \quad (1)$$

$$\nabla\cdot(\rho\vec{u}) = 0 \quad (2)$$

where $\vec{u}$ is the BeO slurry velocity (m/s), ρ is the BeO slurry density (kg/m3), $K=\mu_{app}(\nabla\vec{u} + (\nabla\vec{u})^T) - \frac{2}{3}\mu_{app}(\nabla\cdot\vec{u})I$ and I denote the viscous stress and identity tensor, respectively, p is the pressure (Pa), μ_{app} is the apparent dynamic viscosity (Pa·s), $\vec{u}_{cast} = (0, u_{cast})$ is the casting velocity.

Energy equation for BeO slurry

$$\rho C_{p,app}\vec{u}\cdot\nabla T = \nabla\cdot(\lambda\nabla T) \quad (3)$$

where $C_{p,app} = C_p + L_H D(T)$ is the apparent specific heat capacity $(J/(kg\cdot K))$, C_p, and $L_H = 7800 J/kg$ are specific heat capacity $(J/(kg\cdot K))$ and latent heat of solidification, respectively, T is temperature (K), λ, is thermal conductivity $(W/(m\cdot K))$ and

$$D(T) = \frac{2}{\Delta T\sqrt{\pi}} e^{-\left(\frac{2(T-T_m)}{\Delta T}\right)^2}$$

where $\Delta T = T_l - T_s = 2\ (K)$ denotes transition zone temperature range (K), $T_m = 59°C$ is the crystallization temperature (K), $T_l = T_m + \Delta T$ and $T_s = T_m - \Delta T$ are liquidus and solidus temperatures (K), respectively.

Energy equation for the crystallizer

$$\rho_s C_{p,s} \frac{\partial T_s}{\partial t} = \nabla \cdot (\lambda_s \nabla T_s) \quad (14)$$

where $\rho_s = 7900\ kg/m^3$, $C_{p,s} = 500\ J/(kg \cdot K)$ and $k_s = 15\ W/(m \cdot K)$ and [14].

Boundary conditions. Hot BeO slurry enters the cavity between two concentric cylinders (gray domain in Fig. 3(b)) at a constant casting velocity $u_{cast} = 20 mm/min$ and temperature $T_{cast} = 75°C$. The surface of the mandrel is assumed to be adiabatic and partly no-slip (Fig. 3(a)). BeO slurry leaves the cavity with uniform outlet pressure and zero gradient of temperature. On the inner surface of the crystallizer there is conjugate condition between energy equations for the BeO slurry and crystallizer. On this surface, no-slip and slip conditions are applied to the momentum conservation equation. Slip condition allows the movement of the thermoplastic slurry near the wall when it starts to be cooled. COMSOL Multiphysics software automatically calculates slip velocity based on the yield stress value and velocity profile at the wall. Convective heat transfer occurs between the outer surface of the crystallizer and the cooling water. Adiabatic boundary condition is imposed to the energy equation for the crystallizer at the top and bottom surfaces of the crystallizer.

Convective heat transfer coefficient h_i on each part of outer boundary with height L_i is calculated from the Nusselt number using Churchill and Bernstein correlation for the external forced convection which is valid for $RePr \gtrsim 0.2$.

$$Nu = \frac{2r_3 h}{\lambda_w} = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5}$$

where $Re = \frac{2r_3 Q_w}{\nu_w (r_w - r_3) L}$ and $Pr = \frac{\mu_w c_{p,w}}{\lambda_w}$ are Reynolds and Prandtl numbers, respectively, r_w is the inner radius of cooling zone, Q_w is the flow rate of circulating water in the cooling zone, μ_w, $c_{p,w}$ and λ_w are dynamic viscosity $(Pa \cdot s)$, specific heat capacity $(J/(kg \cdot K))$ and thermal conductivity $(W/(m \cdot K))$ of circulating water.

Results and discussion. Isothermal temperature distribution lines at different casting speeds are shown in Fig.5. The correspondences of the above-shown phase transition intervals (liquidus isotherm AB-54^{0}C, solidus isotherm CD-45^{0}C) established experimentally are confirmed by temperature profiles that coincide with the intverals along the length of the annular cavity. For example, at u=20 mm/min and u=100 mm/min, the phase transition temperatures correspond to the following channel length ranges H=0.008-0.010 and H=0.011-0.015, respectively (Fig.4).

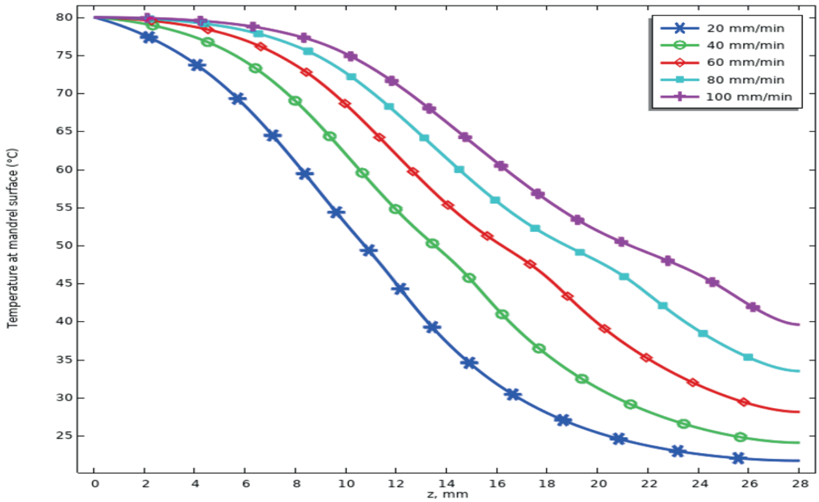

Figure 4- Casting velocity effect.

Estimates of the effect of cooling conditions on the hardening process of beryllium ceramics are achieved by a detailed study of the profiles of casting speed, shear rate and temperature along the annular cavity. The evolutions of the transient temperature contours at different casting speeds are presented (Fig.5, 6). From the graphs shown, it can be seen that with increasing casting speed, the solidification front becomes steeper starting at u=70 mm/min. The zones of liquid, viscoplastic, and solid-plastic slips are represented by red, green, and blue colors, and it can be seen that the red area increases in proportion to the increase in casting speed. The reason for this phenomenon is that as the casting speed increases, more slip mass enters the annular cavity, which in turn increases the flow of thermal convection. Another reason for such phenomena is that as the casting speed increases, the residence time of the liquid slip decreases, and the heat generated also decreases. In all the figures below, the isotherm of the parabolic liquidus changes to an almost horizontal front in the central zone of the cavity. In this part, the conductive mode of heat transfer mainly operates, which, in turn, leads to an increase in the horizontal length of the solidus isotherm. In the phase transition interval, the process proceeds at negligible speeds. According to the phase rule and experimental data, the casting system, i.e. the solid and liquid phases are in an equilibrium state at a temperature of T = 59 ° C, the zone of which is represented by a bright blue area.

At the end of the thermal circuit, it is observed that the sliding effect has a strong effect on the velocity profiles of the cold circuit. The change in the direction of velocity in the transition interval from the warm contour (green) to the cold contour (blue) occurs due to the force of viscous friction associated with an increase in the casting speed from u=40 mm/min to u=100 mm/min, which leads to uneven cooling and zonal liquation. The dynamics of solidification of a thermoplastic slip depending on the casting speed shows when, at a casting speed below u=30 mm/min, the temperature pressure gradient effectively affects the heat transfer coefficient, similar to the effect of the flow velocity gradient on the sliding coefficient. The intensity of free convection, which occurs in the presence of a temperature gradient in the flow, leads to a significant increase in heat transfer from the non-isothermal surface, i.e. from the slip to the coolant.

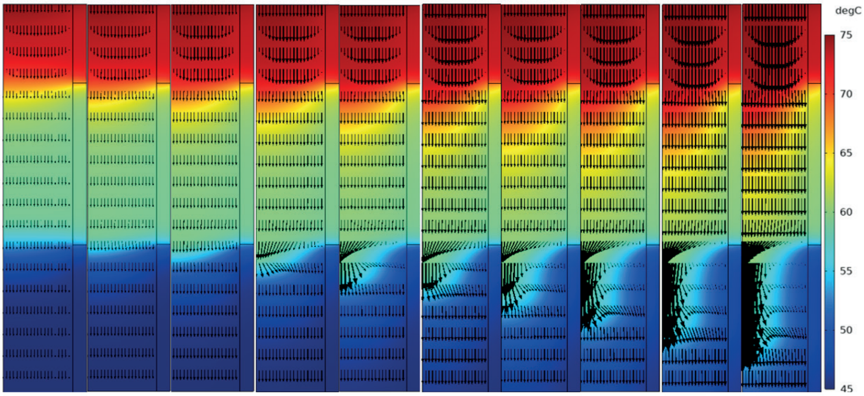

Figure 5- Temperature distribution in $BeO\&$ crystallizer domain for $\frac{D2}{D1} = 1.25$ and casting velocity of 10-100 mm/min

Graphical dependences show that with increasing velocity, the depth of the viscoplastic core zone stretches, forming a curved contour upon contact with the cooling wall.

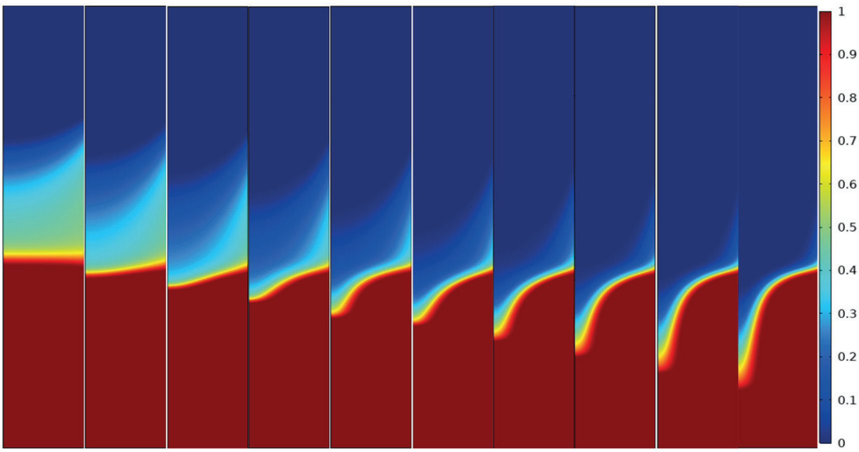

Figure 6- Solid phase fraction for and casting velocity of 10-100 mm/min

In Fig.7 shows the change in heat flow on the inner (discontinuous lines) and outer (solid lines) walls of the mold along the length of the annular cavity at D_2/D_1=1.25 and different casting speeds. Obviously, the heat flux density does not change significantly along the length of the hot circuit. This is because the temperature of the coolant T_0=73°C is almost equal to the initial temperature T_0=75°C of the slip. At a distance of z=22 mm, a warm circuit begins, the coolant temperature will become T_0=59°C and the heat exchange on the inner wall will increase sharply to q_(u=10) =5089; q_(u=30) =8832; q_(u=50) =11458; q_(u=70) =13368; [q]_(u=100) =15525 W⁄m^2.

The temperature gradient, having reached its maximum, begins to decrease sharply due to the alignment of the temperature plot near the wall. At a distance of z = 67 mm, a cold contour is marked, where the temperature of the coolant is T_0 = 45°C. A decrease in the temperature of the slip to the crystallization temperature causes the solidification of the slip mass.

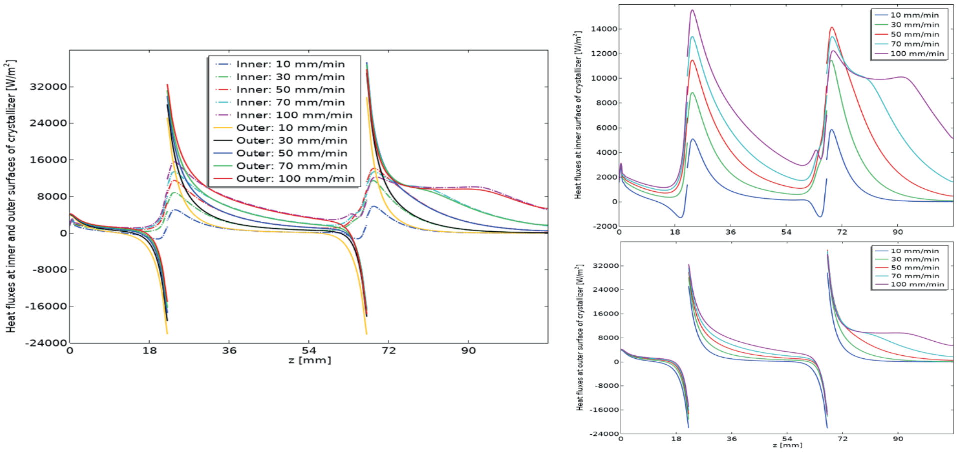

Figure 7- The change in heat flow on the inner (discontinuous lines) and outer (solid lines) walls of the mold along the length of the annular cavity at $D_2/D_1 = 1.25$

The effect of the circulating water layer on the gradual cooling of the slip during product molding is very important, since to calculate the total heat transfer coefficient, it is necessary to determine the coefficients of convective heat transfer. In this case, the hot slide transfers its heat to the inner wall of the die due to internal convection, then it is transferred to the outer wall of the die, only then it enters the cooling water. It is considered that there is no thermal contact layer with a certain thermal resistance between the slip, the inner wall, the outer wall and the water. The influence of the Bi criterion, which characterizes the boundary conditions on the inner wall along the three contours of the annular forming cavity, is shown (Fig.8). Changes in the velocity and temperature profiles determine the patterns of changes in the Bi criterion.

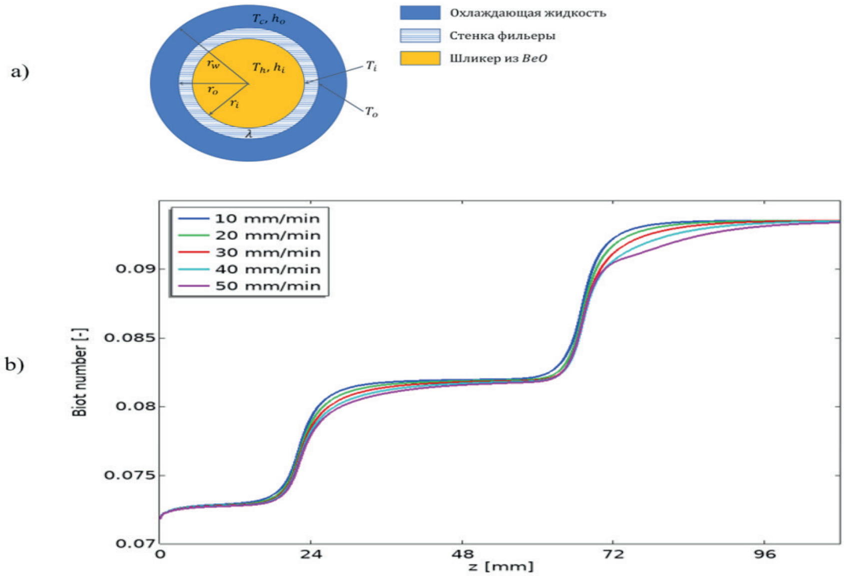

Figure 8- a) the scheme of heat transfer from the slip to the cooling water; b) the effect of the Bi criterion on the inner surface of the annular cavity along three contours.

When the slip moves along the annular channel, an increase in the Bi criterion leads to a decrease in the intensity of heat exchange, and a decrease leads to an increase in the intensity of heat exchange (Fig.8).

The coefficient of external convective heat transfer is calculated from the condition of the cooling water flow through the outer casing of the die, which is the external flow for the die. To explain this, we will use the well-known empirical Nusselt formulas for cooling a cylinder with an external stream of water.

Conclusions. Simulation of the solidification process of beryllium oxide ceramic articles with regard to phase transitions and optimization of casting technology have been performed using COMSOL Multiphysics software. The goal was to improve the quality of products by determining the optimal geometric and technological parameters of the casting process. To obtain articles with uniform properties, the space-phase characteristics of the thermoplastic beryllium oxide slurry are studied in detail, which make it possible to reasonably assess their effects on the property and composition of the casting. Prior to performing numerical calculations of the beryllium ceramic solidification process model in a concentric cylinder with three cooling circuits, the results of the rheological and hydrodynamic model with experimental data have been validated.

Based on the results of the study of the influence of the optimal control parameters of the solidification process on the homogeneity of the product, the following conclusions can be drawn:

- mathematical models of non-isothermal flow and heat exchange taking into account the phase transformation, as well as the results of calculations of the solidification of the slurry depending on the cooling rate and the change in the position of the crystallization interval of the slurry in the concentric cylinder;

- distribution of heat flows on the inner, outer walls and changes in the density of the slurry along the length of the concentric cylinder at different casting speeds are installed;

The numerical results carried out show adequate agreement with the available experimental data. The results obtained in the work and the quantitative values given for the different casting parameters can be useful in the production process in evaluating possible solidification conditions to obtain castings of higher quality.

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