Physical And Mathematical Description Of The Thin-Layer Crystallization Process Of Aluminate Melt On A Twin-Roll Crystallizer.

Dmitriy Aleksandrovich Bashmakov[1], Danis Irekovich Israphilov[2]

1 Kazan Federal University, Naberezhnye Chelny Institute ,e-mail:

BashmakovDA@yandex.ru

Tel.: +79274508511

2 Kazan Federal University, Naberezhnye Chelny Institute

ABSTRACT

The article considers the melt crystallization process in a twin-roll crystallizer. Resolved an important problem of heat conduction through the wall of variable thickness, using the Fourier method and theorem Duhamel. Obtain theoretical dependence of the frozen layer thickness on the melt physical parameters and technological parameters of the crystallization process. Calculation of the twin-roll crystallizer for aluminate freezing is given. The nomogram for determining the parameters crystallizer work was designed.

Key words: Liquid melt, crystallizer, heat flow, moving wall, drum.

1. INTRODUCTION

World metallurgical complex remains one of economy sectors that maintain confidence stability in global financial crisis. Metallurgical products traditionally are in demand. Against this background, mining of precious metals continues to show high activity and investment attractiveness. Gold and other precious metals price level allows to organize production on the resources that previously would have been assessed as unprofitable. Development and implementation of technologies for the processing of low-grade ores of nonferrous metals and extraction of precious metals from scrap and waste around the world is becoming an important area of activity of metallurgical companies. This makes it possible to improve production performance and extend life of mine.

[1]   Stable development of the industry provides growing demand for metals from China, also other Asian countries and South America with growing economy. (Letter of the Federal Tax Service of the Russian Federation of 21.08.2009 N ShS-22-3 / 655 @ "On the direction of materials "Research of the market for the extraction, production and sale of precious metals in Russia")

In connection with the above, an urgent task becomes optimizing production to reduce the cost of deeper extraction of precious metals from ores and waste.

The technology of extracting precious metals from ores in the final stage provides for depleted melt spilling into different flasks for further storage and processing, to further valuable impurities recover. Depleted melt according to the used extraction technology includes a variety of chemical impurities, including cyanide and toxic reagents, which imposes additional constraints on the melt cooling technology.

Further chilled ingot is ground in mills. Crushed fraction is sent to further processing.

2. METHODS

In order to exclude the long-term operation of cooling and energy-consuming step of crushing pigs, proposed to use modified twin roll crystallizer (Fig. 1). Initially, crystallizer (Dynin et al,1998) is designed to produce a fine-grained alloy structure throughout its volume, thus not provide complete cooling of the melt for the purpose of melt material removal capability like the tape. In this paper offered method of calculating crystallizer process with a complete cooling of the melt with simultaneous production of fine fraction.
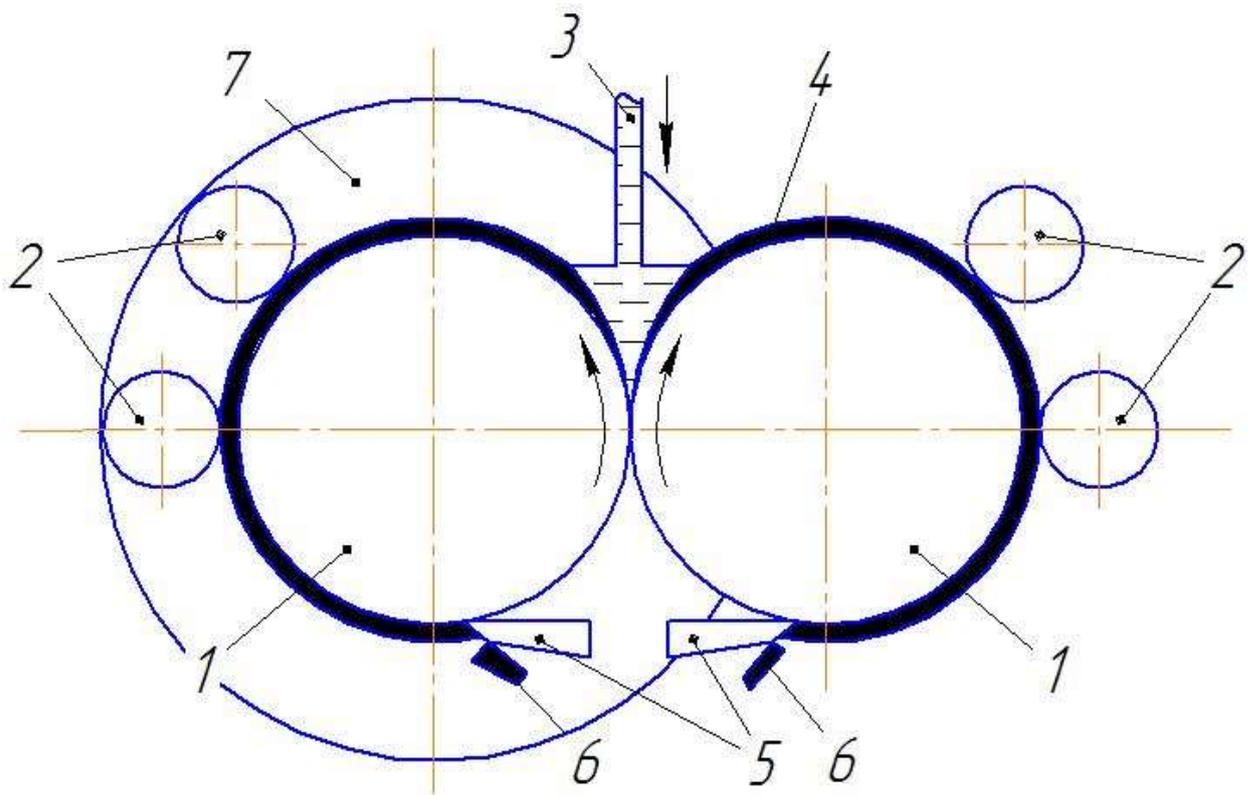
Picture 1. Scheme of a modified twin-roll crystallizer

1 – rolls; 2 – rollers; 3 – melt; 4 - crystallized layer; 5 – blades; 6 - fine crystallized fraction; 7 - roll flange.

Crystallizer works as follows: container-crystallizer volume, formed by two rotating rolls 1 with flanges 7, fed continuously with melt 3. In this surfaces of the crystallizer, rotating towards the feed melt carry out melt 3 crystallization continuously to form a crust of crystallized layer 4. Further, the crystallized layer cooled and crushed previously by rollers 2. Knives 5 cut fully chilled layer 4 of the rolls 1 to the form fine fraction 6.

For easy clarifying character of crystallization process, two-roll scheme during molding considered on example of the right roll (Figure 2). Second roll will be same in operating.
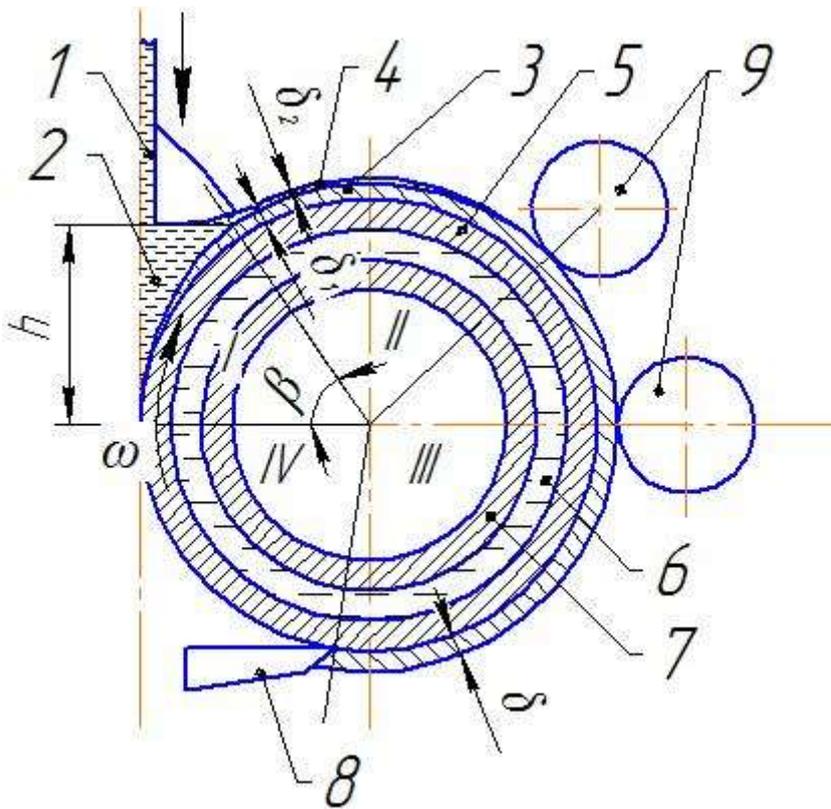
Figure 2. Scheme of continuous operation roll crystallizer.

1 - melt filing; 2 - container-crystallizer; 3 - crystallized layer; 4 - film liquid melt; 5 - drum, 6 - coolant, 7 - internal drum 8 - blade, I - first cooling zone, II - second cooling zone, III - third cooling zone IV - cooling zone of the roll, δ_1 - thickness of crystallized layer at the outlet of the first zone, δ_2 - layer thickness of liquid melt at the outlet from the first zone, δ - thickness cooled melt, ω - angular rotation velocity of the rolls, β - angle of the first zone, h - the depth of container - crystallizer

Full rotational cycle may be divided into four zones marked as I, II, III and IV.

First zone - crystallization time t_1 layer thickness δ_1. Second area - further crystallization time t_2. Third zone - cooling time of "rolls wall - hard layer" system till full crystallized layer at which the destruction of the material under a permanent load by shear knifes 8. In the fourth zone only wall of the roll is cooled till come to entrance of container-crystallizer zone 1.

Is necessary to mark that the process of melt crystallization and cooling liquid melt phase on the roll with δ thickness occurs at variable temperature of the rolls wall.

3. HEAT TRANSFER IN THIN-LAYER CRYSTALLIZATION ON THE ROLLS.

Considered adjoin problem of heat conduction through variable thickness of wall "rolls wall - hard layer" with a convective heat exchange from two sides, is solved using equations of thermal conductivity for rolls wall, solid layer with release heat of phase transition.

In practice, wall thickness of the roll is much smaller than roll radius of curvature, so rolls wall admitted as unlimited flat plate. Problem solved in a Cartesian coordinate system moving together with the wall of the roll.

Heat transfer problem for the drum wall comes to the solution of the heat equation:

$$\frac{\partial T_L}{\partial t} = \alpha_W \frac{\partial^2 T_L}{\partial x^2}, \ 0 \leq x \leq l;$$

where T_L - layer temperature, α_W - heat transfer coefficient from freezing layer to the rolls wall, x - coordinate of the rolls wall layer beginning from inside of rolls wall, washed by coolant, l - thickness of the rolls wall, t - contact time of cooled roll surface with the melt.

In boundary conditions:

$$\frac{\partial T_L}{\partial x} = \frac{\alpha_2}{\lambda_W} \left(T_W - T_2 \right), \ x = 0;$$

$T_W = T_0(t), \ x = l;$

$T_L = f(x), \ t = 0;$

where λ_W - rolls wall heat transfer coefficient, α_2 - rolls wall heat transfer coefficient to the coolant, T_2 - coolant temperature, T_W – outside rolls wall temperature.

Temperature profile T_M of solid layer of melt described by the heat equation.

$$\frac{\partial T_M}{\partial t} = a_1 \frac{\partial^2 T_M}{\partial \xi^2}, \ 0 \leq \xi \leq \delta_1;$$

where a_1 - thermal conductivity of liquid melt, ξ - (coordinate) freezed layer thickness at the beginning on outside rolls wall.

With in view of boundary and initial conditions.

$T_M = T_0(t), \ \xi = 0;$

$T_M = T_{Cr}, \ \xi = \delta_1;$

$$\lambda_1 \frac{\partial T_M}{\partial \xi} - c_{Cr} \rho_1 \frac{\partial \delta}{\partial t} = \alpha_1 (T_1 - T_{Cr}), \ \xi = \delta_1;$$

$$\delta_1 = 0, \ t = 0;$$

where T_{Cr} - melt crystallization temperature; λ_1 - melt coefficient of thermal conductivity, c_{Cr} - specific heat of melt crystallization, ρ_1 - melt density, T_1 - melt temperature, α_1 - coefficient of heat transfer from the melt to rolls wall.

Conjugation conditions include equality of temperatures and heat flux on the contact surface of wall with crystallized melt layer:

$$T_L\big|_{x=l} = T_M\big|_{\xi=0} = T_0(t);$$

$$\lambda_W \frac{\partial T_L}{\partial x}\bigg|_{x=l} = \lambda_2 \frac{\partial T_M}{\partial \xi}\bigg|_{\xi=0}.$$

where λ_2 - thermal conductivity of the coolant.

To solve this problem of the inhomogeneous heat on roller wall used Fourier method (Timmermans,1959) and Duhamel theorem.

The task of freezing melt layer in our formulation was solved by multivariable L.G. Loitsiansky, common to the heat conduction problem with moving boundary E.M. Smirnov (Smith,1932).

After the transformation equations to new dimensionless variables and then integrate a series expansion in powers of the parameters, we obtain a system of equations for the determination of $T = T_0 \ (t)$ and $\delta_1 = \delta(t)$, describing the process of freezing the liquid product on the surface of the roll wall.

Similarly, solve the problem of freeze imposed δ_2 layer (second zone), while in the equation instead of the coefficient of heat transfer to the liquid melt α_1, located in the tank-crystallizer, substituted the heat transfer coefficient from making films to the surrounding air α_{Sur} and of liquid melt temperature T_1, it is replaced by the ambient temperature T_{Sur}.

For the calculation of the melt film imposition δ_2 used dependence (Kuzmenko et al, 1984):

$$\delta_2 = 0,94 \left(\frac{\mu u}{\sigma} \right)^{\frac{1}{6}} \left(\frac{\mu u}{\rho g \sin \frac{\beta}{2}} \right)^{\frac{1}{2}} \frac{\rho}{\rho_S} \tag{1}$$

Where: μ - dynamic viscosity of the of liquid melt, u - linear outer surface of the rotational speed of the roll, σ - the surface tension of liquid melt, ρ - melt density at a temperature close to the temperature of crystallization, g - acceleration due to gravity, β - angle of first zone, ρ_S - frozen melt density.

Determination of the temperature field in the system of the roll wall - crystallized melt (the third zone) is the task of the composite body of transient heat conduction with boundary conditions of the third kind on the external surfaces. Solving these problems is also done with the help of the Fourier method and Duhamel theorem.

In the fourth area to solve the problem of non-stationary heat conduction, roll wall with boundary conditions of third kind with both sides. The final temperature distribution in the wall of the drum in this zone is the initial distribution of temperature condition for first zone.

As a result of solving the problems described above to determine the dependence of the film thickness, freezed on the surface of the roll, during his stay in container-crystallizer.

$$\delta_1 = 6{,}5 \cdot 10^{-5} \frac{\left(\lambda_M \dfrac{T_{Cr} - T_2}{c_{Cr} \rho a_M} \tau \right)^{\frac{2}{3}}}{\left(\lambda_M \left(\dfrac{1}{\alpha_2} + \dfrac{\delta_W}{\lambda_W} \right) \right)^{\frac{1}{2}} \left(\alpha_1 \dfrac{T_1 - T_{Cr}}{T_{Cr} - T_2} \right)^{\frac{1}{6}}}, \qquad (2)$$

where δ_W - the wall thickness of roll.

The experimental data of the experiments performed on a two-roll crystallizer (Figure 3) shows a good correlation with this formula.

Figure 3. Experimental two-roll crystallizer.

4. RESULTS AND DISCUSSION

As the input task of data accepted a requirement the cooling on the existing two-roll mold aluminate 0,034 m^3 during 120 seconds with the ability to specify the installation location of the shearing knife.

Speaking of the main mass melts, with high viscosity, which is typical for aluminate melts, it can be stated, the laminar flow of the melt (Israphilov et al, 2014), almost at all modes. So Nusselt number Nu including our case can be calculated by the followingformula (Bartel,1978; Dub et al, 2005):

$$Nu_M = 7{,}22 \operatorname{Re}_M^{0,33} \operatorname{Pr}_M^{0,33} \left(\frac{\operatorname{Pr}_M}{\operatorname{Pr}_{WM}} \right)^{0,25},$$

where Re_M - melt Reynolds number; Pr_M - melt Prandtl number; Pr_{WM} - melt Prandtl number near rolls wall.

In the case of the turbulent regime in the container-crystallizer at $\operatorname{Re}_M > 30000$, the number of Nu_M:

$$Nu_M = 0{,}052 \operatorname{Re}_M^{0,8} \operatorname{Pr}_M^{0,43} \left(\frac{\operatorname{Pr}_M}{\operatorname{Pr}_{WM}} \right)^{0,25}.$$

Further by formulas (Dub et al, 2005) determine the coefficient of heat transfer from the melt to a frozen layer in the container-crystallizer.

To determine α_2, heat transfer coefficient from the rolls wall to coolant calculated Reynolds number from the formula that takes into account the rotation of the roll:

$$\mathrm{Re}_R = \frac{\omega \cdot l_R^2}{v_R},$$

where ω - the angular velocity of rotation of the rolls; l_R - the width of the roll; v_R - the rate of coolant flow.

To calculate coolant flow rate in channels accepted the resulted diameter. Further calculations carried out according to formulas for cooling of the roll due to the circulation of coolant through annular channel in a turbulent flow regime, which provides a more efficient heat transfer.

$$\mathrm{Pr}_R = \frac{v_R \cdot \rho_2 \cdot c_2}{\lambda_2},$$

where ρ_2 - density of a cooling liquid; c_2 - the specific heat capacity of the coolant. When calculating the Prandtl number for wall flow of coolant should take into account that heat capacity, density and thermal conductivity depend on temperature of environment (Andrews,1972).

$$Nu_R = \frac{\alpha_2 d_r}{\lambda_2} = 0{,}021\,\mathrm{Re}_R^{0,8}\,\mathrm{Pr}_R^{0,43}\left(\frac{\mathrm{Pr}_R}{\mathrm{Pr}_{WR}}\right)^{0,025},$$

where: d_r - the resulted diameter of the part where the flowing coolant; Re_R - Reynolds number of coolant; Pr_R - Prandtl number in coolant; Pr_{WR} - Prandtl number near the wall of coolant.

When calculating thickness of melt adhering film layer used relation (1), and thickness of a freezed layer, directly after the tank-crystallizer dependence (2). Adding the values obtained, it is possible to calculate the total thickness of the crystallized layer δ. Based on the thickness of each layer, and knowing the density and melt the crystallized portion easily calculate mass.

Next determined minimum length of drum surface for cooling melt to a state of embrittlement, to this end, define the total thermal resistance in the first region:

$$R_1 = \frac{1}{\alpha_1} + R_{L1} + R_W + R_{RS} + \frac{1}{\alpha_2},$$

where: R_{L1} - thermal resistance freezes layers in the first zone in a certain area at (variable on the corner of the zone); R_W - thermal resistance of the walls of the roll; R_{RS} - thermal resistance of rust/scale on the roll surface.

Total thermal energy, which is necessary to withdraw from the first zone can be determined:

$$Q_1 = c_M m_{M1}(T_1 - T_{Cr}) + m_{M1}c_{Cr} + l_R l_1 t_1 \frac{T_1 - T_2}{R_1},$$

where: c_p - specific heat capacity of the melt; m_{p1} - the mass of the crystallized melt in the first zone; l_1 - roll wall length of the first zone.

Then flow of water, required providing a given amount of exhaust heat to one of the roll, calculated by the following formula:

$$G_R = \frac{\pi D Q_n}{c_R \Delta t_R l_1 t_1 \rho_R},$$

where: c_R - specific heat of the coolant; Δt_R - difference between initial and final temperatures of the coolant; ρ_R - coolant density; D - outer diameter of the roll.

It should to take into account that initial temperature of the coolant will depend on overall organization of cooling system, and final, highest possible temperature will depend on quality of coolant, to ensure no formation of scale inside the cooling duct (Gelperin , Nosov, 1975).

Thermal resistance of the second section:

$$R_2 = R_{M2} + R_{L2} + R_W + R_{RS} + \frac{1}{\alpha_2},$$

where: R_{L2} - thermal resistance freezes layers in a second zone at a certain point (variable on the corner of the zone); R_{M2} - thermal resistance of the liquid film in the second zone at a certain point (the angle variable area).

The amount of thermal energy for removing from the second region:

$$Q_2 = c_M m_{M2}(T_1 - T_{Cr}) + m_{M2}c_{Cr},$$

where m_{M2} - mass of the crystallized melt in the second zone (mass imposition of the melt film).

Then the length of the second section:

$$l_2 = \frac{Q_2 R_2}{(T_1 - T_2)l_R}.$$

In third section, it is necessary to remove heat from the crystallized layer only, for cooling it to a state of fragility. The calculation is carried out in a similar manner. The total length of the roll surface to remove heat from the melt summed lengths of sections each zone.

To determine specific values of crystallized layer thickness, angular roll speed and coolant flow rate following initial data (Israphilov et al, 2015; Dub et al ,1990; Babichev et al, 1991 ; Andrews,1972; Lebedev ,2014; Skuratov et al, 1964; Israphilov ,2014) have been taken to aluminate aluminate viscosity of the melt at a temperature close to the temperature freezing $\mu_{Cr} = 0.65$ Pa·s; melt viscosity at 1700 °C $\mu = 0,18$ Pa·s; $D = 0,48$ m; the surface tension of the melt at temperatures close to the crystallization temperature $\sigma = 0,47 \frac{N}{m}$; $\rho = 2031 \frac{kg}{m^3}$; $\rho_S = 3385 \frac{kg}{m^3}$; $\lambda_M = 5,54 \frac{W}{m \cdot K}$; aluminate melt crystallization temperature corresponding to the point solidus workover $T_{CrS} = 1375$ °C; aluminate melt crystallization temperature corresponding to the point of liquidus $T_{CrL} = 1465$ °C; $c_{Cr} = 10^6 \frac{W}{m \cdot K}$; specific heat of a frozen melt $c_S = 1233 \frac{J}{kg \cdot K}$; $T_1 = 1700$ °C; temperature brittleness $T_{FR} = 309$ °C; a melt flow rate $G = 0,017 \frac{m^3}{min}$; $c_M = 1387 \frac{J}{kg \cdot K}$; the initial temperature of the coolant (water) $t_{WP} = 5$ °C; the final temperature of the coolant (water), $t_{WF} = 55$ °C; $\lambda_1 = 4,85 \frac{W}{m \cdot K}$; $R_{RS} = 8,6 \cdot 10^{-4} \frac{m^2 \cdot K}{W}$; $1 = 0,01$ m; $l_1 = 0,5$ m.

Results of calculations presented in graphical form in Figures 4 and 5.
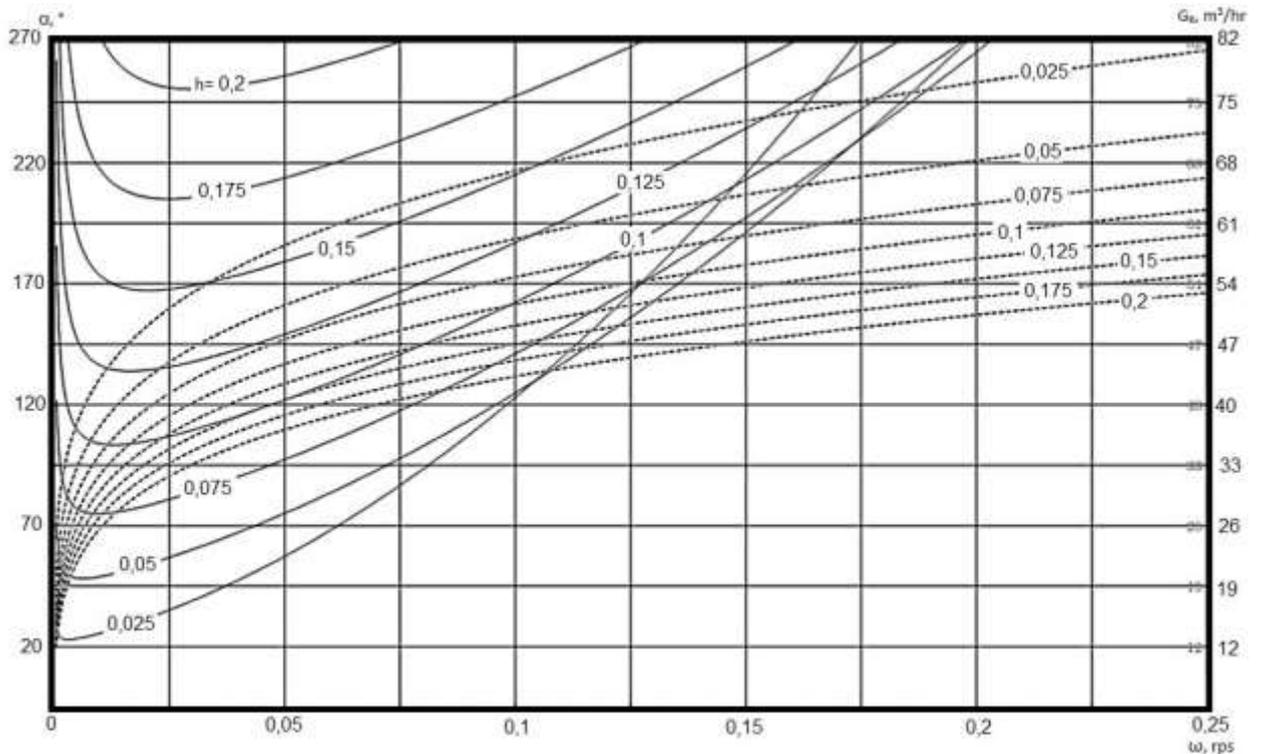
Figure 4. The nomogram for determining the parameters crystallizer work.

- The installation angle of the blades, α°; --- Coolant flow in m³/h; h - depth container-crystallizer, m.

Nomogram (Fig. 5), based on the depth h container-crystallizer supported by a twin roll crystallizer selected allowable rotational frequency ω of the rolls. For the selected rolls wall speed within defined and implemented mold angle of the blades α chosen, with the definition of the necessary flow of coolant (water) G_R.
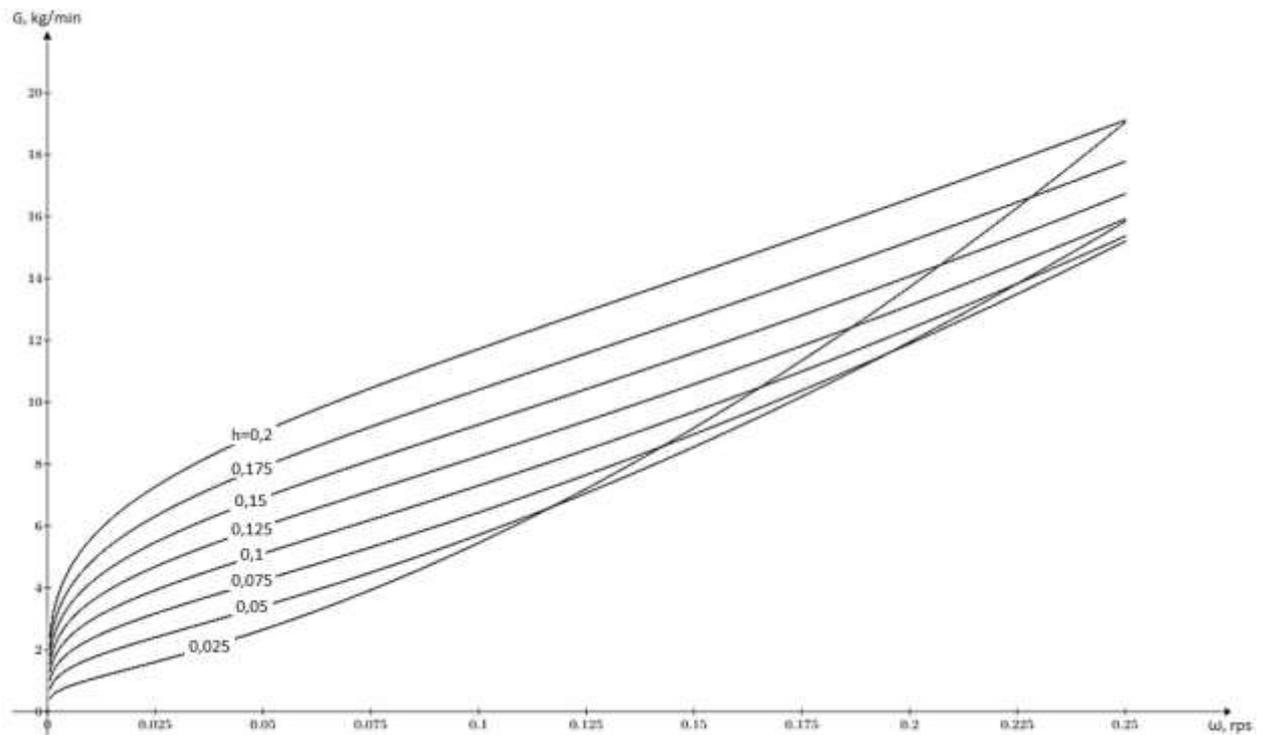
Figure 5. Capacity of the crystallizer.

Further, according to the diagram depicted in Figure 6 may identify crystallizer performance liquid melt in kg / min.

The result of tests carried out at the facility, with the parameters selected by nomogram and diagram (Figure 5, 6), $\omega = 0,75$ 1/s; $h = 0,2$ m, the installation angle of the blades 270 °, the water flow rate of 40.8 m^3/h was stable operation crystallizer to obtain a shredded fraction.

5. CONCLUSIONS

The result of this work is a method of calculating the two-roll crystallizer, allowing to select appropriate modes of operation depending on the crystallizing melt. All this allows choosing the optimal operating conditions crystallizer work mode for the specific requirements of the final product.

6. ACKNOWLEDGEMENTS

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