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STUDY OF JET FOUNTAINING AND LIQUID STEEL SPREADING DURING THE INITIAL STAGE OF LARGE HORIZONTAL INGOT CASTING

The search for ways to improve large ingot casting technology to enhance quality and reduce production costs is ongoing. Horizontal ingot casting (LH-ingots) is an effective method for producing high-quality billets for large slabs, thick sheets, and other heavy products requiring high isotropy of properties [1, 2]. The horizontal position of the ingot, when its height is significantly less than its length and width, enables unidirectional solidification of the metal from bottom to top. Consequently, such ingots exhibit increased physical and chemical homogeneity compared to products obtained by traditional casting methods. Notably, shrinkage defects and signs of liquidation are absent in the central part of the ingot, which are common in large ingots of traditional design.

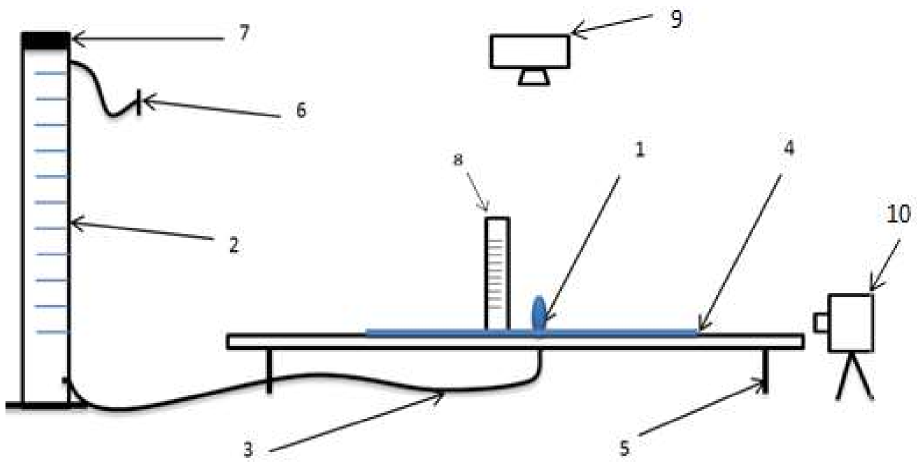
Some enterprises developed and implemented the technology for casting large-scale LH ingots with unidirectional solidification for heavy plates in the 1980s and

1990s [1, 3]. Although this method has not become widely used, it is still effective for producing high-quality cast plates. Therefore, improving the technology remains relevant. Specifically, the goal is to develop measures to produce ingots without surface defects to minimize or eliminate the need for preparation before further use.

It should be noted that the upper and lower surfaces of such ingots form under fundamentally different physical conditions [2]. The lower surface forms during the initial stage of casting when the molten metal spreads across the bottom of the mold. Analysis of defects on the lower surface of ingots and research into the conditions under which they occur have shown that the gating system design should prevent metal splashing at the beginning of casting and ensure rapid, uniform coverage of the mold's bottom surface with liquid metal. The casting process must also be carried out quickly, which is determined by the gating system design. Critical parameters affecting the formation of the bottom surface of the ingot include the location of the feeders, the geometry of the feeder outlet openings, and the flow rate.

This study aims to determine the flow and spreading patterns of liquid metal on a horizontal surface when entering a mold from a pouring system through cold modeling of the process. Specifically, the study examines how the pouring speed and the outlet shape of the pouring system influence the fountain's height and the fluid's movement across the surface. Particular attention is paid to determining the parameters under which the fluid is uniformly distributed across the surface with maximum steel flow and a minimum fountain height at the feeder outlet.

For the experiments, a laboratory setup was assembled that simulated the flow of liquid steel from the pouring system onto the flat bottom surface of the mold. The setup diagram is shown in Fig. 1.



1 – spout outlet; 2 – measuring vessel; 3 – transparent hose; 4 – working surface of the setup; 5 – screw for adjusting the horizon; 6 – air supply tap; 7 – airtight cover; 8 – ruler; 9, 10 – video cameras

Fig. 1. Diagram of the laboratory setup

Water was used to simulate liquid steel. Galileo's criterion (Ga), which indicates the ratio between gravitational and viscous forces in a liquid, was chosen as the similarity criterion [4]. Ga is a combination of two other similarity criteria: the Reynolds criterion, which applies to viscous fluid flow, and the Froude criterion, which applies to fluid and gas motion under the influence of external forces. To comply with the conditions of hydrodynamic similarity between water and liquid steel, water at 35 °C was used. At this temperature, Galileo's similarity criteria (Ga) values for water and liquid steel at a temperature of 1 600°C, with a density of 7 000 kg/m^3 and a dynamic viscosity of 0.005 Pa·s, are close.

The level was used to ensure the working surface of the installation was horizontal. During one experiment, the water flow rate was kept constant. Video camera 9 recorded the spread of liquid over the surface, and video camera 10 recorded the height of the fountain. The experiment was conducted at various flow rates, and the flow duration was measured with a stopwatch. To study how the shape of the feeder outlet affects the flow of liquid from the drainage system channel, a cylindrical nozzle (d = 0.006 m) and a diffuser (d_1 = 0.006 m, d_2 = 0.013 m, opening angle β = 20°) were used.

To evaluate uniform liquid spreading, concentric circles were marked on the laboratory setup's working surface at 1-cm intervals, with the center located on the feeder outlet's axis. Ideal spreading was defined as the formation of a round liquid spot. The quantitative characteristic was the radius of the circle that was covered with liquid by at least 90 %.

Measurements of the height of the liquid fountain as it exits the feeder outlet at different flow rates showed the expected increase in fountain height with increasing flow rate (Fig. 2).

The height of the fountain is determined by the speed of the liquid flow at the outlet of a hole of a certain diameter. As the liquid moves upward, the force of gravity gradually reduces its vertical speed, which becomes zero at the highest point of the trajectory. Based on the energy ratio $1/2mv^2 = mgh$, the calculated height of the fountain from a cylindrical opening H_{calc} can be determined by the formula, m:

$$H_{calc} = v^2 \cdot \frac{sin^2\alpha}{2 \cdot g} \tag{1}$$

where α is the angle of inclination of the jet relative to the horizon; v is the flow velocity at the outlet of the feeder opening, m/s; g is the acceleration due to gravity, m/s^2.

If the jet flows vertically upward, i.e., α = 90°, formula (1) is simplified because sin α equals one. The velocity of the fluid flow at the outlet of the feeder opening is determined by the fluid flow rate and the diameter of the outlet opening, m/s:

$$v = \frac{10^{-6} \cdot Q}{\pi \cdot (d/2)^2}, \tag{2}$$

where d is the diameter of the outlet, m; Q is the fluid flow rate, ml/s.

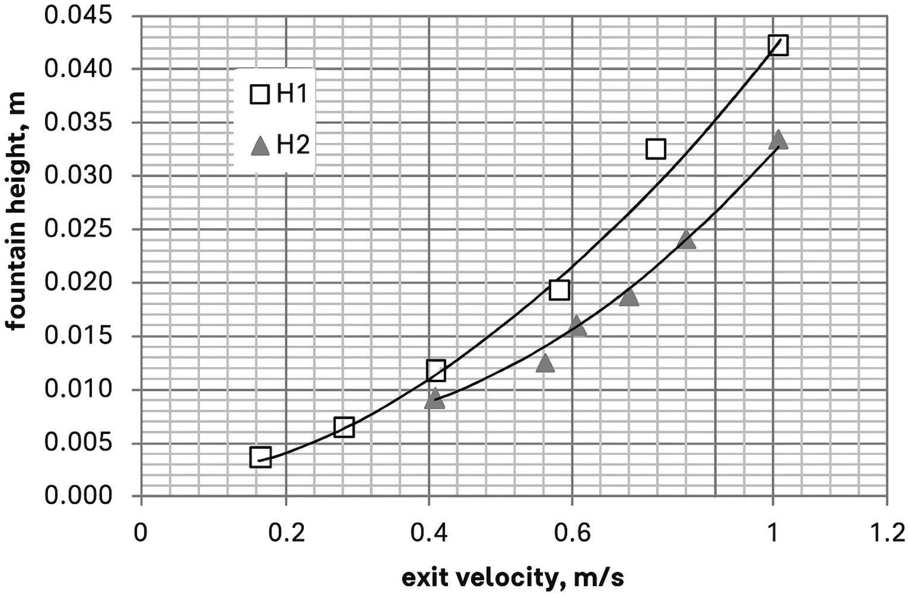


Fig. 2. Dependence of the height of the liquid fountain on the initial velocity of the jet (H1 – measured values for a cylindrical opening; H2 – measured values for an opening with a diffuser)

For an opening with a diffuser, a lower height of liquid fountain at the feeder's outlet was observed at the same liquid flow rate (Fig. 2). Conversely, as the liquid flow rate increases, so does the outlet flow velocity and the difference in height. The fountain height value for an opening with a diffuser can be represented by the ratio m:

$$H_{calc.dif} = H_{calc} - \Delta H, \tag{3}$$

where ΔH is the change in jet height when using a diffuser, m.

The loss of jet height caused by decreased flow pressure due to diffuser geometry [4] can be calculated using the following formula:

$$\Delta H = \left(1 - \frac{A_1}{A_2}\right)^2 \cdot k\,\frac{v^2}{2g} \tag{4}$$

where A_1 is the area of the inlet opening, m^2; A_2 is the area of the outlet opening, m^2; υ is the flow velocity at the inlet, m/s; k is the attenuation coefficient, where $k = \sin\beta$ and β = 5-25°.

Calculations using formulas (1) and (2) were highly consistent with the results of cold modeling. These results are presented in the form of corresponding curves in Fig. 2. These results support the recommendation to use these formulas in calculations when developing steel casting technology.

The results shown in the figure clearly illustrate the effect of using a diffuser compared to a conventional cylindrical opening. Thus, the height of the liquid fountain can be adjusted through the geometric parameters of the feeder outlet and minimized without reducing the metal flow during pouring. This will prevent metal from splashing on the surface of the mold and reduce the intensity of secondary oxidation. In addition, reducing the outlet velocity slows down the circulation flows in the molten metal volume and reduces the disturbance of the bath surface.

Additionally, the geometric parameters of the sprue system feeder's outlet opening affect the dynamics of liquid metal flow and determine how it spreads over the horizontal mold surface. To identify the patterns of this process during the initial stage of filling, we investigated the influence of pouring speed and opening shape on liquid distribution. The conditions under which the surface is covered most uniformly with metal at the minimum fountain height were determined. The optimal mode is when the liquid metal coming out of the feeder spreads into a uniform circle. This type of spreading ensures the formation of a defect-free bottom surface of the ingot.

The results of the experiments show that in both cases there are no fundamental differences in liquid spreading over the surface. The uniformity of the spreading front depends mainly on the flow rate: the higher it is, the closer the shape of the spot is to a circle.

The growth rate of the area occupied by liquid metal increases with the flow rate, though not directly proportionally. Figure 3 shows a graph characterizing the size of the liquid spot at a given moment for different flow rates. This graph is based on experimental results. The experimental dependence obtained can be described by the following approximation equation:

$$R = 0.0514 \cdot ln(Q) + 0.3209. \tag{5}$$

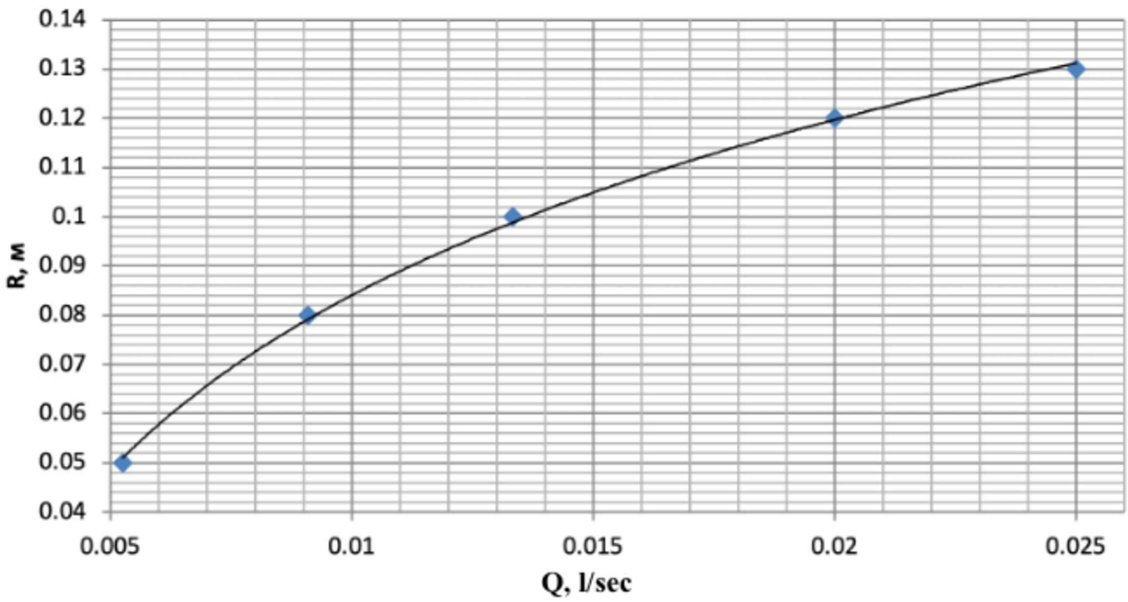


Fig. 3. Dependence of the radius of the liquid spot at the same specific moment in time on the liquid flow rate

This ratio enables you to estimate the size of stains at higher flow rates, which is useful for designing drainage systems.

In summary, using an opening with a diffuser increases fluid flow and reduces splashing. This speeds up mold filling without compromising the quality of the bottom surface of the casting. Accelerating the steel pouring process minimizes metal contact with the refractories of the pouring system and interaction with atmospheric air. This prevents secondary oxidation and reduces the number of non-metallic inclusions in the metal casting. Additionally, reducing the total time required to fill the mold minimizes heat loss, enabling a slight reduction in the steel pouring temperature without compromising product quality.

Laboratory investigations using cold modeling were carried out to study the formation of the liquid metal bath during the initial stage of mold filling in ingot casting with a height-to-width ratio below unity. The results show that the fountain height at the feeder outlet increases proportionally to the square of the jet velocity as the flow rate rises. Introducing a diffuser decreases the fountain height compared to a cylindrical opening at the same flow rate, thereby enabling faster mold filling while preserving the quality of the ingot’s bottom surface. The proposed correlations for estimating fountain height demonstrate good agreement with the experimental data and can be applied in the design of pouring systems and in developing casting regimes for molds with low height-to-width ratios.

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METHODOLOGY FOR DETERMINING THE COST OF PRODUCTS MADE FROM NEW COMPOSITE MATERIALS

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A significant number of studies in the field of materials science has led to the development and investigation of properties of new materials. However, the implementation of these materials is often hindered by the resource intensity of the composition, the energy consumption or labor intensity of the proposed technology, and the poor operational performance of the finished products. Considering the clear research gap in the field of technical and economic justification for the feasibility of using new polymer composite materials, which is underscored by the absence of such justification