Modern methods of modeling hydrodynamic processes in CCM tundish

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Abstract. A theoretical analysis of the motion of liquid metal in a tundish CCM during scavenging by an inert gas was carried out. The hydrodynamic parameters of the flow of liquid metal in the confined area of CCM under scavenging by argon are determined by methods of physical and mathematical modeling. Adjustable parameters of a purge are considered by lance distance from the center of a ladle and an angle of its slope to a vertical.

1. Introduction
Accurate knowledge of the parameters of the flow of liquid steel in the tundish (spatial distribution of the components of the velocity, turbulent and kinetic energy, etc.) is a necessary condition for the analysis of the efficiency of the refining process of the poured metal. At present, methods of physical and mathematical modeling are actively used for experimental research of complicated, high-velocity technological processes in multiphase systems, at extreme values of temperature and pressure [1 - 3].

2. Methodology
In our opinion, the most effective method for studying the hydrodynamic processes occurring inside the tundish of CCM is physical modeling. Therefore, a model stand, a simulating tundish of multi-strand CCM, was created for carrying out the relevant studies (Fig. 1). The chosen scale of modeling (1: 3) provided visual observation of all the processes taking place in the intermediate ladle, practically, in real time. A water heated up to a temperature of 20 +/− 2°C was used as the working medium simulating the molten steel. Table 1 gives the physical properties of water at a temperature of 20 °C and steel at 1600 °C [4, 5]. The table shows that the water at 20 °C and the molten steel at 1600 °C have almost the same kinematic viscosity; using reduced hydraulic models, this allows one to study various processes of mass transfer (flow regime, the nature of mixing, the motion of inclusions, the emergence of gas bubbles, etc.) in a tundish.

Table 1. Physical properties of the water and the steel

| Parameter                      | Water at 20 °C | Steel at 1600 °C |
|--------------------------------|----------------|-----------------|
| Molecular viscosity, $\mu$, kg/m·s | 0.001          | 0.0064          |
| Density, $\rho$, kg/m$^3$       | 1000           | 7014            |
| Kinematic viscosity, $v = \mu/\rho$, m$^2$/s | $10^6$        | $0.913 \cdot 10^{-6}$ |
| Surface tension, $\sigma$, N/m | 0.073          | 1.6             |
The method of inputting a colored liquid or light reflecting particles is used to visualize the flow of water with the possible determination of the matrix of its velocities. These methods provide for an experimental study of the hydrodynamics of processes with the provision of optical recording of the character of the flow in the tundish onto a video camera or camera. Imitation of the slag on the surface of the metal in the intermediate ladle is carried out with the aid of engine oil, which has a higher surface tension than water. This makes it possible to study the process of exit of bubbles gas blown onto the surface of the molten bath and evaluate the possibility of involving slag mixing in the top. Measurement of the residence time of the liquid in the tundish is carried out by a continuous control of the flow rate of water (l/min.) in relation to the volume of the ladle.

![Figure 1](image)

**Figure 1.** A model stand for studying the hydrodynamic characteristics of the molten metal in the tundish CCM: 1 - capacity simulating a steel-ladle; 2 - intermediate ladle; 3 - tank for collecting water leaking from the intermediate ladle with a pump to return it to the steel ladle; 4 - ladle nozzle; 5 - lance for purging the metal by argon; 6 - crucible of type “turbostop”.

### 3. Analysis of results

Existing ideas about the mechanism for removing nonmetallic inclusions (NI) from melted steel in the tundish of CCM are based on the model of "ideal" removal. Using time-tested formulas for calculating the ascent rate of non-metallic inclusions, one can argue that directly in the flow under the layer of refining slag with a high degree of probability, particles with a diameter of \((0.08-0.12) \times 10^{-3} \text{ m}\) will be completely removed [2, 3]. When a zone of reverse circulation is formed, the removal of NI is complicated due to the exchange processes between the forward and return flows.

The exchange ratio \(K\) between the flows is determined by the formula [6]:

\[
K = \frac{Q_{in} - q}{q},
\]  

(1)
where $Q_{tp}$ - flowrate of direct flow, m$^3$/s; $q$ - the flowrate that enters the tundish and leaves the mold, m$^3$/s.

In order to increase the degree of removal of non-metallic inclusions of smaller dimensions, bottom blowing by argon is usually used, and to calculate the degree of removal of NI one uses the basic laws of the interaction of two mutually neutral media, or more precisely, the formation and motion of gaseous spherical bodies in a multiphase fluid. At the time of the formation of gas bubbles, the liquid phase has inclusions forced out into the border area of the spherical body [7]. In our case, with the motion of bubbles with a diameter of $(0.5-1.0) \times 10^{-3}$ m, the velocity is 0.2-0.5 m/s, and the Reynolds number calculated from the formula

$$Re = \frac{V_d \cdot d}{\nu}$$

($d$ is the diameter of the bubble in the average section) is 1000 - 5000. At the same time, the exchange ratio $K$ with blowing is of an order of magnitude greater (10 to 20 times) than that for the version without blowing.

Behind a gas bubble that moves by a multiphase medium, the volume of liquid (the attached mass) is equal to 0.5 of the volume of the gas bubble and is enriched with nonmetallic inclusions, which are "drained" out of the spherical surface in the zone of separation of the boundary layer (Fig. 2) [8]. Then, to satisfy the condition that the entire volume of metal entering the tundish is transported to the zone marked under "slag-metal" as added mass, gas flow rate must be submitted as a plurality of separate bubbles, which is 2 times greater than the flow of metal.

**Figure 2.** Motion of a spherical body in a fluid under turbulent flow [8]: 1 - the "attached" mass of liquid which moves behind a spherical body; 2 - point of separation of the boundary layer from the spherical surface

When the "slag-metal" interface is reached, there is cavitations collapse of bubbles of argon; as a result, there is a crushing of micro volumes of liquid metal in the layer of refining slag, and this helps the assimilation (including physical and chemical absorption) of nonmetallic inclusions of a complex chemical composition.

The study of the peculiarities of the formation of a gas-liquid stream in the vertical supply of a gas phase under a flooded level, depending on the gas flow $Q_g$ and the pressure in the receiver $P$, has shown that at the entrance to the liquid, the gas phase forms bubbles in the form of a torch. The height of this zone ranges from $(0.20-0.25)$ H to $(0.20-0.45)$ N, depending on the pressure level (Figure 3).
Figure 3. Formation of gas-liquid streams at the initial stage of the introduction of gas jets

Modern ideas about the propagation of gas jets in a liquid show the existence of a flame of blasting (or “jet” outflow). Its length and subsequent decay by certain gas volume of different sizes (in the limiting description - gas bubbles) depend on the vertical velocity $V_0$ in the initial section. That is, the smaller the value of $V_0$, the less the jet torch length, and gas bubbles are affected by a larger volume of liquid [9]. The decrease of the vertical speed component $V_0$ can be achieved under the condition that the gas jet is directed at a certain angle $\alpha_v$ to the vertical. In our experiments, the angle of inclination of the gas jet $\alpha_v$ varied from 0 ° to 60 °.

The analysis of publications devoted to the study of hydrodynamic phenomena by the method of mathematical modeling shows that they are based mainly on the Navier-Stokes equations, including the indivisibility equation (the law of conservation of mass); a momentum equation (momentum conservation law); the equation of energy (the law of energy conservation) [1, 3, 10, 11].

For a stationary regime of motion of a liquid metal (a steady casting process), a series of experiments was carried out by blowing argon through a tuyere (with spatially oriented channels for supplying gas, which provides a bubbling blow down mode) installed at different distances from the center of the bucket. Figure 4 shows the structure of the currents in the longitudinal vertical cross section of the CCM tundish when using the FOSECO FTS 1890 A01 turbo stop and the different arrangement of the blowing lance. The presented results show that using the evaluation criterion $\alpha$ [12], it can be established that the lance should be installed at the optimal distance from the center of the bucket equal to 0.9 - 1.2 m.
Figure 4. The structure of eddy currents in the longitudinal vertical section of the tundish CCM using the turbocharger Foseco FTS 1890 A01 and different arrangements of the blowing tuyere L: 1 - the zone of direct flow; 2 - the zone of reverse circulation; 3 - the zone of feeding of the collector; L, m: a – 0.6; b – 0.8; c – 1.0; d – 1.2

Investigations of the flow structure at various levels of metal in the tundish showed that the impact by the argon purging on the kinetics of removal of NI at the nominal level is more significant than, for example, the installation receiver of a metal. When demotion is below rated, the efficiency of the refining process is reduced not only because of the reduction in the extent of the direct flow under the slag layer, but also because of possible re-engagement of previously assimilated particles from the slag layer. A similar situation is observed when using a receiver of metal with an inclined front edge. The obtained results show that during the transient operation of the tundish, inert gas purge reduces the efficiency of the process of continuous refining of liquid metal from NI and should be disconnected.

During the computational experiments, intermediate data were extracted, which made it possible to calculate the values by kinetic and turbulent energy discretely with a certain step. Below are the integral values of the average kinetic and turbulent energies over the three zones and in the entire space of the tundish CCM with various variants of its styling (Table 2). The considered variant corresponds to a standard two-arm tundish without internal structural elements for the installation of type of the Foseco "turbo-stop" metal receiver with a transverse inclined wall for two angles of inclination of 15 ° and 30 °.
Table 2. The ratio of kinetic energy and turbulent energy of flows in the various zones of the tundish CCM.

| Variant                  | B0  | D1 15° | D2 30° | B1  | D3 15° | D4 30° |
|--------------------------|-----|--------|--------|-----|--------|--------|
| 1– the zone of direct flow |     |        |        |     |        |        |
| S1/S                     | 0.54| 0.11   | 0.13   | 0.28| 0.26   | 0.25   |
| K_T/K                   | 0.62| 0.39   | 0.30   | 1.04| 2.78   | 2.88   |
| K/(K_T+K)               | 0.62| 0.72   | 0.77   | 0.49| 0.26   | 0.26   |
| K_T/(K_T+K)             | 0.38| 0.28   | 0.23   | 0.51| 0.74   | 0.74   |
| 2– the zone of reverse circulation |     |        |        |     |        |        |
| S2/S                     | 0.32| 0.67   | 0.69   | 0.58| 0.60   | 0.60   |
| K_T/K                   | 0.95| 1.29   | 1.24   | 2.52| 2.27   | 2.16   |
| K/(K_T+K)               | 0.51| 0.44   | 0.45   | 0.28| 0.31   | 0.32   |
| K_T/(K_T+K)             | 0.49| 0.56   | 0.55   | 0.72| 0.69   | 0.68   |
| 3 – the zone of feeding of the collector |     |        |        |     |        |        |
| S3/S                     | 0.14| 0.23   | 0.18   | 0.13| 0.14   | 0.15   |
| K_T/K                   | 1.05| 0.79   | 0.70   | 2.86| 4.66   | 4.41   |
| K/(K_T+K)               | 0.49| 0.56   | 0.59   | 0.26| 0.18   | 0.18   |
| K_T/(K_T+K)             | 0.51| 0.44   | 0.41   | 0.74| 0.82   | 0.82   |
| Entire tundish           |     |        |        |     |        |        |
| K_T/K                   | 0.61| 0.53   | 0.43   | 1.44| 2.52   | 2.42   |
| K/(K_T+K)               | 0.62| 0.65   | 0.70   | 0.41| 0.28   | 0.29   |
| K_T/(K_T+K)             | 0.38| 0.35   | 0.30   | 0.59| 0.72   | 0.71   |

For the convenience of analyzing the qualitative and quantitative features of the hydraulic gas dynamic flows under investigation, which affect the intensity of the turbulent processes occurring in them, the results obtained are given in relative form (as a ratio of the corresponding parameters for various variants of the experiments).

Analysis of these data shows that for a 40-ton tundish, the installation receivers of metal in the central part of the tundish lead to a decrease in turbulization of the volume of fraction of the metal by 7-16%, which is partly justified by the term "turbo-stop". The use of argon metal purge raises the level of turbulent energy in the entire volume by 29-33%. Generation of turbulent energy in the volume of liquid metal increases the degree of its mixing, which contributes to greater chemical and thermal uniformity of the medium and favorably affects the quality of metal products.

4. Conclusion

Thus, the conducted studies show that bottom-blowing with argon in a stabilized bubble regime creates the most favorable conditions for the continuous removal of nonmetallic inclusions in the process of pouring the metal. They make it possible to establish all the necessary constructive and regime parameters for the development of a special design of a tuyere, which provide the optimal mode for bottom blowing of steel by argon when it is refined in the CCM tundish. Analysis of kinetic and turbulent characteristics of the moving metal in the tundish showed that the selected regime and technological parameters ensure the efficiency of the continuous refining process of liquid steel from nonmetallic inclusions. Purge of liquid steel should be carried out in a bubbly mode with a total gas flow rate of 0.75-1.0 volumetric flow of metal supplied from the steel ladle, which corresponds to a gas flow rate of (5.4-7.5) m³/h. With the optimum gas flow rate set, the most effective solution is the
use of a tuyere with spatially oriented channels, which is installed at the bottom of the tundish at a distance of 0.9-1.2 m from its average cross-section.

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