SELECTION OF APPLICABILITY LIMITS OF A MATHEMATICAL MODEL OF TURBULENCE IN FORMATION OF A STEEL INGOT

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Rational applicability limits of a turbulent model of momentum and heat transfer in a solidifying melt in an enclosure are determined based on multivariant calculations of hydrodynamic and thermophysical processes during casting and solidification of steel ingots.

Hydrodynamic processes determine the thermal and physicochemical situations in a solidifying steel ingot. Calculation of velocity fields is a laborious problem requiring substantial computer time. Thus, calculation of velocity fields in a liquid core of a crystallizing melt takes 60% of computer time, and the remaining 40% is required for determination of the temperature field and the concentration and amount of the solid phase. If the process has a turbulent character, then 62-80% of computer time is spent in calculation of the hydrodynamic part of the problem. The percentage depends on the selected model of turbulence closure. Therefore, the choice of a mathematical model is a complex process: on the one hand, neglect of turbulent transfer of substances can lead to considerable distortion of results, and on the other hand, unsubstantiated allowance for turbulence considerably increases the time of computer calculation.

This paper is aimed at determination of the rational applicability limits of a turbulent model of momentum and heat transfer in a solidifying melt in an enclosure, since for enclosures this problem is still unsolved.

Experimental measurements in high-temperature melts are difficult; therefore, mathematical simulation of hydrodynamic processes and of heat and mass transfer using the $k$-$\varepsilon$ model of turbulence in casting and solidification of a steel ingot is chosen as the method for investigation [1-3]. The adequacy of the mathematical model was confirmed earlier [4] in modeling of processes of momentum, heat, and mass transfer in solidifying ingots.

The studies were conducted for two stages of ingot formation: casting into the mould and solidification. There is an alternative to the first stage, viz., to calculate the hydrodynamics in either a laminar or turbulent approximation. Figure 1 presents the dependence of the thickness of the hard skin averaged over the ingot height on the ingot tonnage in casting from above and through a bottom gate (from below). The effect of the casting method on the behavior of the melt was estimated for equal technological parameters (superheating and velocity of melt inflow to the mould) both in casting from above and through a bottom gate.

In casting from above, starting from a 1-ton ingot, allowance for turbulence noticeably affects the thickness of the hard skin. An increase in mass intensifies these differences. In casting through a bottom gate the effect of turbulence manifests itself starting from an 8-ton ingot (Fig. 1).

The difference in melt behavior, depending on the method of casting, is explained as follows. During casting the intensity of melt mixing is characterized by two factors: the mechanical action of the jet and heat convection. They govern the development of mixed convection in a melt, which determines the hydrodynamic situation in the melt and, as consequence, heat and mass transfer. In casting from above there are two zones. The first exists during the entire process of casting and is characterized by the presence of descending flows in the center of the mould that are caused by jet divergence. As the mould becomes filled (50%) the second zone forms, in which a reverse flow is observed, i.e., in the center there are ascending flows and in the near-wall region descending flows occur.
over the entire height of the mould [1]. This zone is caused, first of all, by a thermal gradient. The intensity of agitation in the second zone is by an order of magnitude smaller than in the first zone. As the region becomes filled the dimensions of the first zone do not change, and the second zone occupies an even larger volume.

Eddy viscosity $\nu_t$ substantially affects the thickness of the hard skin over the ingot height. By preventing jet propagation inside the melt [2], it facilitates the early formation of the second, more quiet, zone. While on the upper horizons the jet-induced flows transfer heat, thus melting the hard-skin, on the lower horizons descending flows take heat from near-wall layers and carry it away to the ingot center, thus facilitating hard skin growth.

In casting through a bottom gate, we observe three flow zones: central, represented by ascending flows caused by jet divergence; peripheral, formed by descending flows induced by jet ejection and heat convection; and a zone of ascending flows localized at the upper angle, which is formed by the melt level and the side wall. As in casting from above, the highest velocities (up to 60 cm/sec at a flow rate of 1000 kg/min) occur in the first zone. However, while in casting from above this zone moves as the mould becomes filled, in casting through a bottom gate it is motionless. The height of the jet plume does not exceed 70–100 cm, and eddy viscosity has practically no effect on its height.

The second zone is more quiet (maximum velocity attains 20 cm/sec) and localizes in the bottom portion of the mould. At the beginning of filling, melt agitation is caused by jet ejection. With the loss of heat equilibrium in the melt, the intensity of mixed convection increases due to convective heat transfer. It should be noted that the effect of turbulence is higher in the second zone. This is manifested by a more intense hard-skin growth. Apparently, ascending flows, having transferred heat at a height of 1–1.2 m, become cooled and descend to the mould bottom, thus facilitating hard-skin growth. It is clear that with turbulent heat removal the process of heat transfer is more intense.

The third zone is the most quiet (maximum velocity is 1.5–2 cm/sec); the jet is not active here and temperature, which is uniformly distributed over the ingot cross-section, does not promote heat convection. This zone is formed after 50% filling of the mould; therefore, the hard skin is the thinnest. The effect of turbulence virtually is not expressed.

With an increase in the mould dimensions the greatest effect is exerted by the mould width: growth of the second zone and of the thickness of the hard skin is observed.

It is shown by the examples of two types of casting that the value of eddy viscosity makes substantial amendments to the thermal and hydrodynamic situations. Therefore, to estimate the rational applicability limits of the turbulent model it is suggested to use similarity criteria $Re$ and $Gr$: the first characterizes the outer situation, which is determined by the jet, and the second characterizes inner situation caused by natural heat convection. It makes sense to introduce the complex $ReGr_*$, where $Re = \frac{Vd}{\nu}$, $Gr_* = \frac{g\Delta T x_{red}^3}{\nu^2}$. The choice of $x_{red}$ makes it possible to allow for different geometric ratios of the ingot [5].

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Fig. 1. Dependence of hard-skin thickness averaged over ingot tonnage in casting from above (without (1) and with (2) allowance for turbulence) and in casting from below (without (3) and with (4) allowance for turbulence). $\varepsilon$, mm; $m$, ton.