ABSTRACT

The most complex task is the description of non-metallic inclusions behaviour in various zones of the tundish molten bath. In this case the most important feature of simulation is the prediction of conditions, under which large-sized non-metallic inclusions of 20-100 μm and over, are captured by convective flows and transferred to the liquid steel surface. Mathematical and physical modelling has demonstrated that the upfloating of large-sized non-metallic inclusions is substantially enhanced with argon purging into a molten bath via a dedicated plug placed at the tundish bottom. The blowing efficiency through this plug depends heavily on the argon flow rate, bubbles diameter, steel residence time in the tundish, etc. It was proved that the main constraint for gas flow rate amount blown into a tundish molten bath, is the swirling of steel and slag in the area of argon bubbles ingress into the air. At the same time, small-sized particles of the covering slag are entrapped into the liquid bath by downward convective flows.

Keywords: mathematical FEM modeling; physical modelling; caster tundish; vector component; steel flows; gas purging; mass- and heat-transfer processes.

INTRODUCTION

Continuous casting processes enjoy immense potential in terms of casters’ efficiency and productivity increase, as well as in meeting high requirements to the blanks’ quality. Concurrently, a special emphasis is laid on the blanks’ pollution with non-metallic inclusions, which enter the molten bath at process over-flows, and are also resultant from the destruction of the working lining in steel ladles, tundishes and other refractory equipment. A tundish placed between a steel-teeming ladle and a CCM mold, is a key element specifically pertaining to support of quasi-continuous casting process and steel pollution by non-metallic inclusions.

Meanwhile, the specific feature of the tundish operation is its long-standing operation mode (10 - 15 hours and over), in the course of which steel enters the tundish from steel ladles, and outflows to CCM molds.
Steel specific flow-rate during casting, can range up to 3 - 5 tons and above. Thus, high-intensive mass transfer stipulates formation of convective flows that can markedly affect casting process and steel homogenization.

Most of the basic phenomena proceeding in the tundish can be fairly well described by means of mathematical models. These models enable performance of quantity and quality assessment of mass- and heat-transfer processes in the tundish with respect to the specific design of the tundish and casting parameters. This is appropriately confirmed by various studies undertaken by a number of researchers [1 - 4]. However, the combination of several solutions on the hydrodynamics of the tundish’s different zones aimed at the performance of the numerical analysis of non-metallic inclusions behaviour during casting, is yet left a topical issue. The most important aspect in this context, can appear the simulation of non-metallic inclusions flotation to the slag, as well as penetration of Al\textsubscript{2}O\textsubscript{3} inclusions into the nozzle.

Computer-based mathematical modelling is becoming more and more efficient tool of researchers and engineers, and frequently appears to be a key element of computer-aided design systems. Furthermore, numerical solution can be obtained for actual conditions of the studied process, which is by any means not always the case with experimental research [5 - 7].

The analysis of known articles dedicated to fluid-and-gas dynamics phenomena, has proved that the mathematical models are mostly based on Navier-Stokes equations, including continuity equation (mass conservation law); momentum conservation (momentum conservation law); energy equation (energy conservation law). These laws represented as partial differential equations, are solved by finite element method with employment of standard packages for computer-aided modelling of liquid motion (PHOENICS, FLOW, CFX, ANSYS), or with self-developed software implementing the said method [1, 8 - 10].

EXPERIMENTAL

The mathematical model development is accomplished by us based on ANSYS application package, the one implementing finite element method (FEM) within Flotran module framework, which reflects CFD (Computerized Fluid Dynamics) modelling technology. The model was considered as non-stable, turbulent, with single-phase representation of the steel melt.

Basic phenomena to be reasonably described by mathematical models, can be rated as follows:

- introduction of the falling jet into the tundish liquid bath, and its interaction with the tundish bottom;
- development of convective flows motion areas and generation of “dead” zones, where steel motion is essentially non-existent;
- evaluation of the steel residence time in the tundish pursuant to the tundish box design and baffles arrangement;
- tundish filling by steel at initial casting steps, as well as drop and recovery of the steel level in the tundish at the steel-teeming ladle replacement;
- mixing of the slag overlaying the liquid steel in the tundish, and identification of lining areas those susceptible to erosion, affected by steel moving flows;
- steel flows motion in the tundish in the course of the inert gas purging into the liquid bath;
- steel outflow from the tundish nozzle to the CCM mold;
- motion of non-metallic inclusions in the steel molten bath influenced by convective flows, and their flotation to the slag.

Meanwhile, the simulation of the abovementioned phenomena employs different approaches for tasks statement, and consequently, different mathematical models, which to a variable degree account for the impact of associated phenomena on the process under investigation. Moreover, these models differ in the accuracy of the calculations performed, which considerably hampers integration of several models into a comprehensive model.

SIMULATION RESULTS AND DISCUSSION

The calculation results are values of velocity vectors and total velocity, temperature, thermal flow at each nodal point of the calculation domain for each time step, which can be represented in tabular and graphical format (Fig. 1 and Fig. 2). The model also offers a possibility to evaluate kinetic energy and its dissipation, laminar and effective viscosity of the steel melt, shear stress and turbulence in the near-wall area, etc.
To assess the pattern of convective flows motion in the tundish, a great importance is attached to the information on the known behaviour of horizontal and vertical component of the molten flow motion velocity. As an example, Fig. 2 illustrates results of the mentioned computations performed with regard to the tundish of a six-strand billet continuous caster with an installed tundish box of well-shape. The most representative result of the modelling, is the identification of steel areas with heavy motion of convective flows. This is of particular importance for casting of extra-long series in the tundish’s near-wall areas.

The data resultant from computations, provide an opportunity of quality and quantity assessment of the tundish box and baffles performance with respect to the specific conditions and adjust the tundish box design, where required. Thus, Fig. 3 presents mathematical modelling results of particular features of steel flows motion in the tundish of a one-strand billet continuous casting machine. These results are essentially consistent with results obtained by physical modelling. First of all, it relates to the motion direction of main convective flows and their behaviour in the tundish’s near-wall areas. At the same time, it was established that of considerable importance to secure optimum pattern of convective flows motion, is the location and height of the tundish.
box walls in relation to the falling jet axis. As such, the displacement of windows location (or tundish-box location) just by 20 - 30 mm (in the tundish cross-section), can lead to high turbulence in areas adjacent to the tundish and tundish-box walls, which is regarded as an adverse phenomenon accounted for high wear-rate of the tundish lining.

The geometric parameters of the tundish box can be optimized by means of mathematical modelling of steel flows in the tundish molten bath. The basic criteria used for the optimization are as follows: absence of high turbulent areas in the vicinity of the tundish lining, reduction in number and spread of the so-called “dead” zones, and approximately equal time of steel travel from the tundish box to the tundish nozzle, as well. The most complicated, as the research has shown, is to comply with the latter requirement.

The development of the simulation system of convective flows motion in the tundish, implies topping up the liquid slag layer - as the simulation entity - on the steel surface. The behaviour of this slag substantially influences the erosion of the refractories working lining in the tundish, as well as the entrapment of slag inclusions by steel convective flows.

Concurrently, steel flows motion along the steel surface, is characterized by high velocity, which affects development of the circulation flows in the slag layer (Fig. 4). Slag flows motion on the steel surface is of strongly pronounced circulation nature. Meanwhile, peripheral areas of these flows come into contact with the tundish’s working lining and bring about its high wear rate. Hence, the simulation of slag flows motion is of great applied relevance in terms of consistent operation of the tundish lining. This can be reached by the adequate design of the tundish box and optimum location of the baffle plate that governs steel flows motion.

However, the analysis of convective flows development conditions in the tundish liquid bath, should also consider various process settings, which among others include steel level drop under steel ladle replacement, reduction of the casting speed (e.g., in the presence of breakout risks), loss or damage of 1 or 2 strands in multi-strand billet casters, etc.

The information on the dynamics of the tundish filling during initial casting time is deemed as essential for the optimization of convective flows development.
and motion processes (Fig. 5). At an initial stage, at casting of the first heat of the series, the tundish box exhibits non-homogenous structure of the molten steel flows motion. In this respect, the velocity horizontal component changes only slightly, and is at the level of $0.025 \text{ m s}^{-1}$, while the vertical component changes both the direction and value (within the range of $0.5 - 0.9 \text{ m s}^{-1}$), engaging increasingly larger steel volumes into mixing. Another important feature of this casting stage, is that the tundish filling is accompanied with steel swirling, splashing, and spattering. Simulation of these processes appears quite practicable. At this stage, due to non-homogenous nature of hydrodynamic development of the molten steel flows in the tundish box (especially for the velocity vertical component), the entrapment of additional amount of non-metallic inclusions from the tundish to CCM molds, becomes possible. Nevertheless, major difficulties arise when this model is coupled with the model of steel mixing in the tundish within a single comprehensive model.

Of utmost importance for the modelling of process in the tundish, is the research of non-metallic inclusions behaviour in the molten bath, and the determination of conditions for their flotation to the slag layer. This task is of immediate concern in terms of billets quality assurance, specifically, contamination with non-metallic inclusions. Consolidating data from published studies, it should be emphasized that this task is the most complex one, for it requires tracking of inclusions dimensions, their density, geometric shape, aggregate state, conditions of inclusions wetting by steel, inclusions residence time in the molten steel, direction and travel velocity of convective flows \cite{11, 12}. The assignment of this task involves certain challenges related to the setting-up of dimensions, geometric shape, density and number of inclusions. This is even more crucial since subject to the liquid bath status (velocity and direction of convective flows motion) one can observe processes like non-metallic inclusions upfloating, and their immersion depthward in the tundish. The works performed within the present study, have corroborated that the same conditions can trigger entrapment of certain inclusions by convective flows and their transfer depthward into the liquid bath, and flotation of other inclusions to the surface.

The most important feature of simulation, in our opinion, is the prediction of conditions, under which large-sized non-metallic inclusions of 20-100 mcm and over, are captured by convective flows and transferred to the liquid steel surface. This is still more significant for quality steel grades, for the number of such inclusions is relatively small, and this hinders evaluation of their
distribution by traditional methods.

The mathematical and physical modelling have demonstrated that the upfloating of large-sized non-metallic inclusions is substantially enhanced with argon purging into a molten bath via a dedicated plug placed at the tundish bottom (Figure 6). The blow-off performance through this plug depends heavily on the argon flow-rate, bubbles diameter, steel residence time in the tundish, etc. It was demonstrated that the main constraint for gas flow-rate amount blown into a tundish molten bath, is the swirling of steel and slag in the area of argon bubbles ingress into the air. At the same time, small-sized particles of the covering slag are entrapped into the liquid bath by downward convective flows.

It follows that the development of modelling technique of various physical phenomena in the tundish, calls for the elaboration of new approaches that enable to solve coupled tasks in the integrated simulation complex.

CONCLUSIONS

The research performed with mathematical models, have shown high efficiency of numerical simulation methods. As of today, a great number of mathematical models to consider various aspects of the tundish metallurgy: hydrodynamics, residence time, non-metallic inclusions behaviour and thermal energy transfer, electromagnetic stirring, turbulent processes, etc., have been developed and implemented.

Alongside with that, special interest for the development of simulation methods, is gained by the issue of models coupling that describe mass- and heat-transfer in the tundish liquid bath. This would secure far more accurate forecasts of non-metallic inclusions behaviour, and recommendations of scientifically proven procedures aimed at the liquid steel efficient refining in the tundish.

REFERENCES

Oleksiy Smirnov, Yevgen Smyrnov, Seppo Louhenkilpi, Oleg Smyrnov


