Applications of Numerical Simulation to Continuous Casting Technology

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The continuous casting process in steel production is a highly efficient and productive process. Since this process was first applied to steel foundations, rapid progress has been made. Recently, trends in continuous casting have been focused on near net shape casting, high speed casting and the adoption of electromagnetic processes. These systems involve many coupled phenomena such as fluid flow, heat and mass transfer, solidification and electromagnetic phenomena. Because of the interplay between the underlying phenomena, it is very difficult to understand these systems systematically. Consequently there are many unresolved technical problems. In order to analyze fluid flow, heat and mass transfer and solidification simultaneously, the finite volume method (FVM) with body fitted coordinate (BFC) is first used. The finite element method (FEM) code is applied to the analysis of the deformation of solid shell and mold, and electromagnetic fields. Some groups are trying to couple microsegregation with macrosegregation, and develop algorithms that can be applied to multicomponent solidification. In addition, a combined analysis of all the above-mentioned phenomena is being developed. In the future, caster design and on-line control of continuous casting processes based on numerical simulation will be even more important.

KEY WORDS: continuous casting; near net shape casting; electromagnetic processing; process optimization; numerical simulation; coupled analysis.

1. Introduction

The continuous casting technologies in recent decades have been developed toward the near-net-shape casting and the adoption of electromagnetic processing such as electro-magnetic stirring (EMS), electro-magnetic casting (EMC), electro-magnetic braking (EMBR), electro-magnetic level accelerator (EMLA) etc. for quality and productivity improvements.

The continuous casting process and the digital computer appeared at about the same time. As casting technology and the striving for better quality have advanced together, there have been large improvements in computational models for the continuous casting processes. This paper overviews the applications of computational models to the continuous casting technologies. As the space is limited, only a few examples, especially developed by our group, will be covered among the various computational models to illustrate the role of modeling in continuous casting processes and compared with early and recent contributions. These examples include the shape optimization of submerged entry nozzle, the near-net-shape casting, electromagnetic processes in application to the continuous casting, and the coupled analysis of fluid flow, heat and mass transfer, and deformation behavior of solidifying shell and mold.

2. Near-net-shape Casting

The near-net-shape casting is an emerging technology offering many economic benefits such as reduction of production cost and increase of the productivity. Beam blank casting, strip casting and thin slab casting are typical examples of near-net-shape casting in steel industry. While many numerical models have been developed to understand the physical phenomena in the cast strand of the simple geometry such as billet, bloom and slab, analysis of the transport phenomena in near-net-shape casting are still challenging problems mainly due to the complex geometry of the system. One of the approaches to overcome the treatment of complex geometry is the adoption of the general curvilinear coordinate system. This makes it possible to describe exactly the boundary of the complex shaped system without additional grids and computational resources at the expense of complexity in transforming of the governing equations for fluid flow, heat transfer, and solidification and imposing of the boundary conditions, which allow the general computational code of the FDM based on the finite control volume to widen its capability of application.

2.1. Beam Blank Casting

The cast beam blank is used for a starting material of hot rolled H-beam and has the complex geometry of dog-bone type as shown in Fig. 1(a). Yoon and his group have developed the computational models to describe fluid flow in
beam blank casting using body-fitted-coordinate (BFC) system\textsuperscript{12)} The grid system generated by elliptic method was used for the calculation. Figure 1(b) shows the 3-dimensional characteristic patterns of fluid flow at the several regions in the mold of beam blank caster.

2.2. Thin Slab Casting with Funnel Type Mold

In the thin slab casting process, the small thickness of the slab usually ranging from 50 to 100 mm, allows extraction at high speeds. The casting speed is much faster than that in the conventional slab caster (typically about 4–6 m/min), which compensates for the small cross-section area. Until now, there were about five main types of mold in the thin slab casting process (funnel type and parallel type). In the case of the CSP (Compact Strip Production)-process, the vertical type mold has a funnel-shaped bulge in the upper mold region, which facilitates the introduction of the casting nozzle in the meniscus to provide more space for fluid flow motion. The mold is presented in the schematic diagram in Fig. 2(a). Yoon and his group have analyzed the effects of the funnel shape of the mold on the characteristics of fluid flow and heat transfer\textsuperscript{16)} with the non-orthogonal grid system as shown in Fig. 2(b). As a result, the basic flow pattern was characterized by four recirculations and two small eddies near the narrow face of the mold as shown in Fig. 2(c). The fluid flow motion is different from that of a conventional slab caster presumably due to the funnel shape of mold and a flattened bifurcated SEN. They also find that the region where the funnel shape ends shows a very high temperature, which affects the mechanical strength of the copper material mold. This shows good agreements with the observation that mold scratch often occurs as a result of thermal stress during the casting operation and that internal cracks occurs when the copper plate structure is examined.

3. Electromagnetic Processing of Materials

In the past few decades, the continuous casting process has made remarkable progress, solved many technical problems, and spreaded over the world. While its technology now appears to be matured, the work is still being conducted to pursue the excellence of continuous casting process. Among these activities, the application of electromagnetic force to the process has aroused keen interest. This can be explained by the fact that various effects can be achieved with an electromagnetic field such as heating, stirring, confining, pressurizing depending on the specific design. In addition to these, the possibility of remote action is also considered as very attractive characteristic. At present,
the electromagnetic technologies are mainly being utilized to control the flow pattern of molten steel including several kinds of EMBR process. Electromagnetic contactless shaping technologies including EMC process have been proposed as new applications of electromagnetic technologies. This paper deals with the above-mentioned two important electromagnetic technologies; EMBR and EMC.

3.1. EMBR (Electro Magnetic BrAke)

In the numerical analysis of the fluid flow of EMBR, BFC (Body Fitted Coordinate) was implemented into FVM (Finite Volume Method) to consider complex geometry of the SEN (Submerged Entry Nozzle) and irregular shape of the meniscus. In investigation on the influence of important operating parameters on the effect of EMBR, several useful standards were used such as evaluation of velocities of each grid plane along the casting direction. In spite of general stabilizing effect of EMBR, it was found that the molten steel stream spouted from the SEN makes bypasses to avoid strong magnetic field region under particular conditions: such bypasses act as channels and prevent uniform distribution of the flow.

FC-mold is an equipment to control the molten steel flow in a mold of continuous casting process using two-level static magnetic field. Yoon and his group developed a mathematical model for the coupled analysis of fluid flow, heat transfer and induced current in FC-mold. In order to evaluate the electromagnetic braking force, magnetic field was analyzed with finite element method using A-\(\phi\) method. Fluid flow, heat transfer, induced current and meniscus shape were analyzed with 3-dimensional finite volume method based on body fitted coordinate. The influences of some operating parameters such as magnetic flux density, core position, casting speed, and inlet angle on fluid flow, heat transfer and distribution of solidifying shell were investigated. According to Yoon et al., in FC-mold, the flow velocity at meniscus was somewhat reduced and inclusion behavior pattern was improved in comparison with no magnetic field. Besides, the flow pattern was less sensitive to different casting conditions in comparison with conventional one-level field EMBR. This is not because the upper magnetic field acts as the braking force to the meniscus flow directly but because it creates a flow-guide region of no magnetic field in the middle of mold and the magnetic field imposed on upper part of mold suppresses the flow to the meniscus. Figure 3 shows the fluid flow without the EMBR force (a), fluid flow with 0.1 T of one-level magnetic field (b) and fluid flow with same strength of two-level magnetic field in FC-mold (c). Heat transfer and distribution of solidified shell were also simulated and this shows that the EMBR effects result in the rise of the meniscus temperature and uniform distribution of solidifying shell.

3.2. EMC (Electro Magnetic Casting)

EMC is a technology which has several beneficial effects such as reduction or elimination of oscillation mark by reducing contact pressure between mold and strand with the strong electromagnetic pressure on the surface of the strand. The interaction among electromagnetic, hydrodynamic and metallurgical phenomena in this process is too complicate to understand quantitatively. In addition, due to high temperature, strong electromagnetic force and dynamic movement of the system, observations and measurements during operations are difficult. Therefore, numerical analysis is a very important tool to understand this complex system.

In the research of Cha et al., a mathematical model was developed, which can simulate electromagnetic field and fluid flow of magneto-hydrodynamic (MHD) system, as a fundamental research for analyzing the MHD phenomena in the electromagnetic mold. The electromagnetic induction, the deformation of the surface of the strand and the characteristics of fluid flow due to electromagnetic force in a laboratory scale electromagnetic mold were calculated using this mathematical model. Figure 4 shows the simulation results on fluid flow and solidified shell thickness with/without magnetic force. Through this study, the following results were obtained in EMC. There exist upward flows covering the surfaces of the slab. This is due to the concentration of electromagnetic force on the upper part of the slab. These flows join together and form a downward flow near the SEN. The flow velocity on the meniscus increases because the flows by two driving forces (electromagnetic force and inertia force) have the same direction under the meniscus.

4. Coupled Analysis

One of the important features in the mathematical model for the analysis of the continuous casting is the fully coupled analysis of fluid flow, heat transfer and deformation behavior of solidifying shell. It has been reported that most
of the primary causes of defects in the cast strand result from the inhomogeneous solidification in the mold region, which may be affected by the fluid flow of molten steel, the formation of air gap due to the deformation behaviors of the mold and the strand and other casting variables such as casting speed, mold taper, mold flux and mold oscillation. Most of the developed mathematical models in the literature have been focused on heat transfer analysis, fluid flow-heat transfer analysis and heat transfer-stress analysis. Fluid flow, heat transfer and deformation behavior in continuous casting have mutual interaction with each other. In order to obtain more accurate analysis results, hence, the fully coupled analysis of fluid flow, heat transfer and deformation behavior is required.

A numerical model has been developed for the coupled analysis of fluid flow, heat transfer and deformation behavior of solidifying shell in continuous casting process by Lee et al. and was applied to the continuously casting round billet and to the beam blank.

In the simulation of beam blank, fluid flow, heat transfer and solidification in the strand and the mold were analyzed with 3-dimensional finite difference method (FDM) based on control volume method. A body fitted coordinate system was employed for the complex geometry of the beam blank. The effects of turbulence and natural convection of molten steel were taken into account in determining the fluid flow in the strand. The thermo-elasto-plastic deformation behavior in the cast strand and the evolution of air gap between the solidifying shell and the mold were analyzed by the finite element method (FEM) based on 2-dimensional slice model using the calculated temperature of the strand by the FDM. The heat transfer coefficient between the strand and the mold was iteratively determined with the coupling analysis of the fluid flow-heat transfer analysis by the FDM and the thermo-elasto-plastic stress analysis by the FEM. In order to determine the solid fraction, \( \delta \)-Fe fraction and \( \gamma \)-Fe fraction with the variation of temperature and to obtain the characteristic temperatures such as liquidus temperature, zero strength temperature, liquid impenetrable temperature, and zero ductility temperature, the microsegregation model of solute element was used. Based on this model, Lee et al. studied the pattern of fluid flow and its effect on the heat transfer, the solidification of steel and the distribution of shell thickness during the casting of beam blank. In their study, the deformation behavior of the solidifying shell and the possibility of cracking of the strand were also investigated. As shown in Fig. 1(b), the recirculating flows in the mold were developed in the regions of the web and the flange tip. The impinging of the inlet flow from the nozzle on the shell in the regions of the fillet and the flange center retarded the development of the solidifying shell. The air gap between the strand and the mold wall was concentrated near the region of the corner of the flange tip (see Fig. 5). Figure 6 shows the crack susceptibility of the strand at several stages of casting. At the initial stage of casting (near the meniscus), the probability of the surface cracking was predicted to be high in the regions of the web, the fillet and the flange center. At the middle stage, the internal cracking in the regions of the web and the fillet and the surface cracking in the corner region of the flange tip were likely to occur. After the middle stage, the internal cracking in the

corner region of the flange tip could be found. As shown in Fig. 7, the shell thickness in the mold region shows good agreements with the experimental observations and the shape of the solidified shell in the mold exit are well consistent with that of the real product.

5. Shape Optimization of Submerged Entry Nozzle

In metallurgical processes, especially in the continuous casting process, engineering design process is a vital component of industry. Recent efforts to improve competitiveness have brought the caster design to the fore. The design processes have so far been developed by a trial and error process or by experiments. However, owing to the high cost
of building prototypes in metallurgical processes, especially, continuous casting processes, numerical optimal analysis becomes an important tool and can be used to evaluate and improve designs in the preliminary stages.

A numerically optimal design can be defined as the process of finding the minimum or maximum of certain criterion function which is the 'objective function'. This function usually represents the deviation of the solution from some ideal. If the deviation is large, modification of the simulation parameters (design variables) should be made to reduce the disparity.

The use of the numerical optimization in engineering design was popularized in 1960 when Schmit\textsuperscript{19} applied nonlinear optimization techniques to structural design. While his work was restricted to structural optimization, the presented concepts offered a fundamentally new approach to engineering design which is applicable to a wide spectrum of design problems. Tortorelli and Dantzig’s group\textsuperscript{20,21} extensively has studied the numerical optimization for the system with coupled complex transport phenomena.

As an example of the numerical optimization in the continuous casting, here, we introduce the shape optimization of bifurcated submerged entry nozzle used in the continuous slab caster.\textsuperscript{22} (1+1)-Evolution Strategy method (a kind of Genetic Algorithm)\textsuperscript{23} was used as an optimization tool. The SEN (Submerged Entry Nozzle) has an important influence on steel quality through its effect on the flow pattern in the mold. The SEN should deliver molten steel uniformly into the mold while preventing problems such as surface waves, meniscus freezing, and crack formation. Impingement of the hot molten steel with a high momentum against the solidifying shell can cause shell thinning and costly “breakouts”.\textsuperscript{24} In addition, the SEN should be designed to deliver molten steel with the optimum level of superheat to the meniscus while preventing the detrimental surface turbulence, shell erosion or thinning due to excessive impingement of the hot molten steel jets, and the penetration of non-metallic inclusions. In some operations, it is also important for the flow pattern to assist in the flotation of detrimental inclusions into the protective molten slag layer.

For simplicity, the nozzle shape was assumed to be 2-dimensional. Considering the symmetry of the system, only a half of the bifurcated nozzle was used as the calculation domain, the effect of the scalar field such as temperature field was excluded, and only two design parameters were adopted though this method is general and can be extended to 3D complex systems. Figure 8 shows the schematic nozzle shape for optimization. The left nozzle shape is the conventional bifurcated nozzle and the right one is the one in the optimization sequences. For simplicity, two changing design variables were selected. Point A can move freely in 3D space while Point B can move only along the $z$-direction as shown in Fig. 8. The effective area fraction, which is defined as the fraction of the outlet port area where the flow has a positive $x$-directional velocity component, so it exits the nozzle domain, is set up. This was adopted as the objective function for optimization. Najjar, Thomas, and Hershey\textsuperscript{23} pointed out that the temporal variation and spatial inhomogeneity of the flow exiting the port may cause surface turbulence, rapid surface level fluctuations, sloshing, the entrainment of the mold slag into the liquid steel and that a high turbulence intensity and a large recirculation zone in the top portion of the nozzle (small effective area fraction) are two strong indicators of turbulent fluctuations. Therefore, if the effective area fraction is maximized, the high turbulence intensity and a large recirculation zone in the top portion of the nozzle (small effective area fraction) can be minimized. Thus, we selected the effective area fraction as the standard for optimization.

Figure 8 shows the flow pattern and the inner shapes of (a) before-optimized and (b) after-optimized SEN.

Fig. 8. Inner shapes and grid systems of the bifurcated nozzle (a) before and (b) after the optimization process.
6. Further Study

Now we need to focus on implementation of our results into plant or online control of the whole casting process. The best way to utilize modeling results is to let the model itself control the process by running online. Such a model would simultaneously manage the operational variables in order to minimize defects. By responding to sensor feedback, such a model could also identify impending problems and take immediate corrective action.

We also need to apply the numerical optimization methods to the optimization of the operation conditions and caster designs in the continuous casting processes. As introduced in Sec. 5, the numerical optimization method is very helpful to change the small parts of the caster design to achieve our object. In addition, the optimization method can be also applied to the optimization of the operation conditions in the continuous casting processes, for example, the determination of the optimal distribution of the magnetic field in EMBR.

Offline models are still needed to improve understanding of process. Faster computers will enable existing models to perform large parametric studies for true optimization, rather than to simply demonstrate their capability, as is often done today. There should be more comprehensive studies with advanced models, followed by reduction to simple empirical equations that can be applied in process design. The same modeling effort that has gone into bulging for roll-system design should be applied to other areas.

Future models will need to combine even more various phenomena together. For example, adding deformation to the solidification models would help one to understand and improve thin-slab and strip casters. Prediction of internal cracks, for example, will eventually benefit from microstructural prediction and thermodynamic models which track the formation of harmful embrittle precipitates together with temperature gradient and the tensile stresses that cause cracks. Controlled laboratory experiments of mechanical properties, precipitation, and microstructures are needed to develop the fundamental knowledge for these models.

7. Summary

The surface and internal defects in continuously cast slab are closely related to the fluid flow and heat transfer condition of the liquid steel and deformation behavior of solid shell in the continuous casting mold. Therefore, understanding of transport phenomena as well as deformation behavior in mold is regarded as the most important information in control of the process for quality and productivity improvements. Combined with physical models and experiments, numerical modeling plays an important role in understanding of continuous casting process and future work will be continued focusing on implementation of mathematical models in the development of new casting process and fully coupled analysis of complex phenomena and finding optimum conditions of process through better understanding of the physical phenomena.

REFERENCES