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Fundamentals

Recent advances in the phase-field model for solidification (Review)

M.ODE et al.

The recent development of the phase-field models for solidification and their application examples are briefly reviewed. The phase-field model is firstly proposed for pure material systems and then extended to binary alloy, multi-phase and multi-component systems theoretically. Though the calculation conditions are limited due to the sharp interface limit parameters in the early stage, it is widened in the thin interface limit model. The development of the phase-field model is summarized from a viewpoint of the formulation of phase-field equation and parameters. The important studies and the latest results such as application examples of free dendrite growth, directional solidification, Ostwald ripening, interface-particle interaction and multi-phase simulation are mentioned. Finally future works of the phase-field model are prospected.

(cf. *ISIJ Int.*, **41** (2001), 1076)

Modelling of kinetics of isothermal allotriomorphic and idiomorphic ferrite formation in medium carbon vanadium–titanium microalloyed steel

C.CAPDEVILA et al.

A theoretical model is presented in this work to calculate the evolution of austenite-to-allotriomorphic and idiomorphic ferrite transformation as a function of time in medium carbon vanadium–titanium microalloyed steel. At temperatures above the eutectoid temperature where allotriomorphic ferrite is the only austenite transformation product, the soft-impingement effect should be taken into account in the modelling. By contrast, at temperatures below the eutectoid temperature, the formation of pearlite avoids the carbon enrichment of austenite due to the previous ferrite formation, and therefore carbon concentration in austenite far from the α/γ interface remains the same as the overall carbon content of the steel. Hence, the soft-impingement effect should be neglected, and allotriomorphic and idiomorphic ferrite is considered to grow under a parabolic law. The nature, size and distribution of the inclusions which are responsible of the intragranular nucleation of idiomorphic ferrite have been considered in this study. An excellent agreement has been obtained between experimental and predicted values of volume fraction of ferrite in all the studied range of temperature.

(cf. *ISIJ Int.*, **41** (2001), 1083)

Modelling of kinetics of austenite formation in steels with different initial microstructures

F.G.CABALLERO et al.

The main aim of this work is to study the mechanisms that control the austenitisation process in steels with different initial microstructures. The compiled knowledge in literature regarding the isothermal formation of austenite from different initial microstructures (pure and mixed microstructures), has been used in this work to develop a model for non-isothermal austenite formation in steels with initial microstructure consisting of ferrite and/or pearlite. The microstructural parameters that affect the nucleation and growth kinetics of austenite, and the influence of the heating rate have been considered in the modelling. Moreover, since dilatometric analysis is a technique very often employed to study phase transformations in steels, a second model to describe the dilatometric behaviour of the steel and calculate the relative change in length which occurs during the austenite formation has been developed. Both kinetics and dilatometric models have been validated. Experimental kinetic transformation, critical temperatures as well as the magnitude of the overall contraction due to austenite formation are in good agreement with calculations.

(cf. *ISIJ Int.*, **41** (2001), 1093)

Particle-size-grouping method of inclusion agglomeration and its application to water model experiments

T.NAKAOKA et al.

Agglomeration of inclusions in liquid steel causes not only the enhancement of inclusion removal by flotation but also the increase in the number of large inclusions in final products. To clarify agglomeration behavior theoretically, a lot of studies have been made until now. However, the behavior is not clearly understood yet. In this study, a new particle-size-grouping (PSG) method has been established, which enables a simple calculation of the agglomeration by a small number of size groups with complete conservation in total particle volume. This method has been verified by the comparison with the exact solution of a revised population-balance equation. An experimental study of the agglomeration of polyvinyl-toluene latex (PVTL) in a stirred electrolyte solution has been made in an agitated vessel under a rapid agglomeration condition. An effective Hamaker constant of PVTL in water, A_{131}, has been obtained by adjusting the measured agglomeration curve with the curve calculated by the PSG method. Good agreement has been obtained between observed and calculated agglomeration curves for $A_{131}=0.8\times10^{-20}$ J under a wide range of initial particle concentrations and agitation speeds. Numerical simulations of the fluid flow and particle transport in the vessel have been made to confirm the applicability of the PSG method. Computed agglomeration curves agree well with the theoretical curve if the energy dissipation rate averaged with the residence time of liquid in computational cells is used to calculate the dimensionless agglomeration time.

(cf. *ISIJ Int.*, **41** (2001), 1103)

Ironmaking

Modelling of liquid flow in the blast furnace. Theoretical analysis of the effects of fas, liquid and packing properties

S.J.CHEW et al.

Molten iron and slag flows play a critical role in the blast furnace lower zone, transporting mass and energy, whilst impairing and redistributing gas flow. In turn, molten iron and slag undergo physical and chemical changes, and are redistributed radially during descent to the hearth. Using a 'force-balance' approach, the flows of liquid in the blast furnace were characterised. A consistent set of equations describing liquid holdup, gas–liquid interaction and solid–liquid interaction was developed with reference to previous experimental studies and furnace conditions. The model accounts for the effect of gas, liquid and packing properties on liquid flow, as well as the effect of liquid on gas flow. Interaction between metal and slag phases occurs via a shared gas flow field. Importantly, the model can be applied under both countercurrent and non-countercurrent conditions, where gas can either hinder or enhance liquid flow.

(cf. *ISIJ Int.*, **41** (2001), 1112)

Modelling of liquid flow in the blast furnace. Application in a comprehensive blast furnace model

S.J.CHEW et al.

In Part 1 of this report, the flows of molten iron and slag in the blast furnace were characterised using a 'force-balance' approach. In this paper, the incorporation of a molten iron and slag flow submodel into a comprehensive numerical model of the blast furnace is discussed. Liquids are generated from ore during descent through the cohesive zone and their flow calculated according to the prevailing gas, liquid and packing properties. Predicted information for molten iron and slag includes holdup, velocity, accumulation and flooding distributions, as well as areas of interaction between gas and liquid, and solid and liquid. Liquid flow is most strongly influenced by the radial variation in ore volume fraction entering the furnace, gas flow in the vicinity of the raceway and the furnace profile. Liquids, in turn, significantly increase the gas pressure gradient in the lower furnace. The flow of slag is more sensitive to operating conditions than molten iron.

(cf. *ISIJ Int.*, **41** (2001), 1122)

Modeling the liquid levels in the blast furnace hearth

J.BRÄNNBACKA et al.

The drainage of a blast furnace hearth is analyzed on the basis of measurements of the instantaneous mass flow rates of tapped iron and slag, obtained from radar level measurements in the iron ladles and a pressure signal from the slag granulation drum. The measurements are used in a model estimating the levels of liquids in the blast furnace hearth, where correction terms have been introduced to prevent the level estimates from excessive drift. When applying the model on data from two Finnish blast furnaces, it was found that the estimated iron level exhibited strong correlation with the electromotive force (emf) measured between two electrodes at the furnace shell. The results of the model are in general agreement with results reported by other investigators. The performance of the model is illustrated by some examples, and a procedure for considering the case of a floating dead man is proposed.

(cf. *ISIJ Int.*, **41** (2001), 1131)

Mathematical model for transient erosion process of blast furnace hearth

K.TAKATANI et al.

A mathematical model that can estimate the transient erosion process of the blast furnace hearth has been developed. This mathematical model can treat the molten iron flow, heat transfer and the brick/refractory erosion at the hearth. To verify the availability of the mathematical model, comparisons of computational final erosion profile of the hearth were made with the investigation results of the dissection blast furnace and computational results gave good agreement with the measured one. The effects of the distribution profile of the dripping molten iron flow rate into the hearth, the coke free layer size, production rate of the molten iron, thermal conductivity of the carbon brick and the fluid flow resistance through the coke packed bed were examined by using this mathematical model.

(cf. *ISIJ Int.*, **41** (2001), 1139)

Steelmaking

Modeling of a DC electric arc furnace—Mixing in the bath

M.RAMÍREZ et al.

A mathematical model was developed to describe fluid flow, heat transfer and electromagnetic phenomena in the bath region of a Direct Current Electric Arc Furnace (DC-EAF). The different effects on the steel bath from the arc, a layer of slag on the top of the steel, and the injection of argon gas from the bottom, are represented using three different numeric approaches and analyzed in terms of fluid flow, heat transfer, and temperature stratification in the steel bath. Additionally, a sensitivity analysis was performed to explore the effect of the main process parameters and design variables of the process, such as furnace dimensions, arc conditions, and anode configurations. It was found that in the absence of gas injection, the electromagnetic body forces dominate the fluid flow in the bath region overcoming the opposite effects of buoyancy and shear from the arc. Injection of gases homogenizes the melt improving mixing, while the effect of the slag is to decrease mixing in the bath. Regarding the process analysis, the model showed that the best mixing and the best energy optimization from the arc are achieved when the geometry of the furnace presents the highest aspect ratio. Similarly, short arc lengths and high arc currents are beneficial for mixing. However, these improvements in mixing could be detrimental for the bottom refractory of the furnace because of the direct exposure of the hot metal coming from the arc attachment zone at the bottom wall. Then, the anode configuration can be designed to avoid excessive damage to the refractory.

(cf. *ISIJ Int.*, **41** (2001), 1146)

A mathematical model of the heat transfer and fluid flow in AOD nozzles and its use to study the conditions at the gas/steel interface

A.TILLIANDER et al.

Knowledge of process gas parameters in the area where the gas leaves the nozzle and then enters the molten steel in AOD converters is necessary in order to determine the boundary conditions needed to model the converter process. Using a newly developed mathematical model for an AOD nozzle verified by comparison against laser Doppler anemometer measurements, the objective of this study was to predict characteristics of non-isothermal heat transfer and fluid flow at the nozzle for pure oxygen gas injected into an AOD converter. The inlet boundary conditions for the nozzle simulation were taken from plant data. The investigation showed that the thermodynamic and physical phenomena in the region where the gas enters the steel melt cannot be determined if the transformation of kinetic energy of gas into heat is not considered because this would amount to oversight of the influences of bubble frequency, temperature, etc. on the process. The possible ranges of bubble frequency and temperature for the nozzle conditions in the study were also determined.

(cf. *ISIJ Int.*, **41** (2001), 1156)

Transient fluid flow phenomena in a gas stirred liquid bath with top oil layer—Approach by numerical simulation and water model experiments

J.W.HAN et al.

The flow characteristics in a gas stirred ladle with oil layer were investigated with the help of water model experiments and numerical simulation. The oil layer has a great influence on the fluid flow and mixing behavior in the ladle. While the mixing time decreased with the increase of the gas flow rates, the oil layer over the top of the bath extended the mixing time in the whole range of gas flow rates, and at constant gas flow rate, the mixing time was extended with the increase of oil thickness. From the results of water model experiments and numerical simulations, transient formation of plume eye from the start of gas bubbling was matched well each other. Based on water model experiment the plume eye size was found to increase with the increase of gas flow rates and to decrease with the increase of the oil thickness. These were precisely confirmed with numerical simulated results. From the results of numerical simulation flow pattern without oil layer showed that bubbles rising eventually made a recirculation loop at the central area of the bath forming uniformly distributed velocity vectors in the bath. This flow pattern regarded as a good flow pattern for the better mixing behavior. However, flow pattern with oil layer showed distorted and localized recirculating loop near side wall below oil layer. This eventually gave extended mixing time in the bath with oil layer.

(cf. *ISIJ Int.*, **41** (2001), 1164)

Mathematical modeling of flow and inclusion motion in vessel with natural convection

T.ISHII et al.

In a steel making process, the fine molten steel slab is required to make high quality sheet. From this point of view, it is very important to remove inclusions in molten steel. So a mathematical model, to predict the behavior of various sizes of aluminum inclusions in a molten steel flow, has been developed. In this model, three kinds of collision terms are considered: the first one is due to the flow field acceleration, the second one is due to the gravity acceleration, and the third one is due to the effect of the turbulent eddies. In the process of the collision, total 1 025 particle sizes are taken into consideration. In each particle size, number density should be calculated. But only 13 particles among 1 025 are selected to solve the number density conservation equation. For the rest of the particle sizes, the number density is evaluated by linear interpolation based on selected 13 particles in order to save the computational time.

Using this model, the behavior of aluminum inclusions in molten steel, which is dominated by the natural convection, has been simulated. The mechanism of the aluminum collision and coagulation has been studied.

(cf. *ISIJ Int.*, **41** (2001), 1174)

Casting and Solidification

Mathematical modeling of fluid flow in continuous casting (Review)

B.G.THOMAS et al.

Fluid flow is very important to quality in the continuous casting of steel. With the high cost of empirical investigation and the increasing power of computer hardware and software, mathematical modeling is becoming an important tool to understand fluid flow phenomena. This paper reviews recent developments in modeling phenomena related to fluid flow in the continuous casting mold region, and the resulting implications for improving the process. These phenomena include turbulent flow in the nozzle and mold, the transport of bubbles and inclusion particles, multi-phase flow phenomena, the effect of electromagnetic forces, heat transfer, interfacial phenomena and interactions between the steel surface and the slag layers, the transport of solute elements and segregation. The work summarized in this paper can help to provide direction for further modeling investigation of the continuous casting mold, and to improve understanding of this important process.

(cf. *ISIJ Int.*, **41** (2001), 1181)

Design optimization of a single-strand continuous caster tundish using residence time distribution data

K.J.CRAIG et al.

This paper contains the results of a design optimization study performed on the steady-casting operation of the Columbus Stainless single-strand stainless steel caster tundish. Residence Time Distribution (RTD) data such as minimum residence time (or plug flow volume fraction) and dead volume are used as objective functions in the mathematical optimization process. Water is used in the first two case studies as modeling fluid to allow for comparison with water model results. Liquid steel is used in the last case study to investigate the effect of temperature and buoyancy on the resulting flow patterns and the optimum design. Two separate tundish configurations are considered. The first has one dam and

one weir, while the second comprises a baffle with angled holes and an impact pad. Significant improvements of up to 34% in minimum residence time are obtained for the second configuration.

(cf. *ISIJ Int.*, **41** (2001), 1194)

Swirling flow effect in bottomless immersion nozzle on bulk flow in high throughput slab continuous casting mold

S. YOKOYA et al.

Swirling flow effectiveness on controlling the bulk mold flow has been acknowledged recently, concerning the productivity and its quality of continuous casting process. In this study, simple immersion nozzle without opposite face on the end of the nozzle is proposed. From the practical viewpoint, relationship between the throughput and bulk mold flow is investigated. Following results are obtained:

1) Numerical analysis fairly coincide with the experimental results for the cases: nozzle outlet, surface flow and velocity distributions along the narrow face.

2) Surface velocity decreases with increasing the axial length of the nozzle outlet, particularly in length from 20 to 60 mm.

3) For the high throughput case, considerably stable bulk mold flow can be obtained.

4) Bulk mold flows under different throughputs are similar with each other if (tangential velocity W in nozzle/axial velocity Vz in nozzle) of those have same magnitude with each other.

(cf. *ISIJ Int.*, **41** (2001), 1201)

Swirling flow effect in submerged entry nozzle on bulk flow in high throughput slab continuous casting mold

S. YOKOYA et al.

Swirling flow effectiveness on controlling the bulk mold flow has been acknowledged recently, concerning the productivity of continuous casting process and its quality. From the practical viewpoint, relationship between the throughput and bulk mold flow is investigated. Following results are obtained:

1) Numerical analysis fairly coincide with the experimental results for the cases: nozzle outlet, surface flow and velocity distributions along the narrow face.

2) Surface velocity decreases with increasing the axial length of the nozzle outlet, particularly in length from 20 to 60 mm.

3) For the high throughput case, considerable stable bulk mold flow can be obtained.

4) Bulk mold flows under different throughputs are similar with each other if (tangential velocity W in nozzle/axial velocity Vz in nozzle) of those have same magnitude with each other.

(cf. *ISIJ Int.*, **41** (2001), 1208)

Swirling flow effect in off-center immersion nozzle on bulk flow in billet continuous casting mold

S. YOKOYA et al.

It often occurs that setting up an immersion nozzle on the mold, nozzle axis does not coincide with the mold-axis. In this study, under the off-center nozzle with the mold-axis, bulk mold flow was investigated, and following issues were obtained:

1) For the case without swirl, the peak of the flow moves near the mold-wall with flowing down from the outlet of the nozzle due to the Coanda effect (shown in Appendix).[1] On the other hand, peak of the flow moves near the mold-axis with flowing down from the nozzle-outlet within considerable short distance, namely axisymmetric velocity distribution can be obtained within very short distance from the nozzle-outlet.

2) The surface flow patterns between coaxial and off-center nozzles are quite different. The flow pattern with coaxial nozzle is axisymmetric and simple, while the flow from one side to other side can be observed, with off-center nozzle.

(cf. *ISIJ Int.*, **41** (2001), 1215)

Simulation of sliding nozzle gate movements for steel continuous casting

N. KUBO et al.

The slab surface quality is generally known to deteriorate when the casting speed fluctuates during the continuous casting of steel. The mold powder on the meniscus is more likely to be entrapped in the molten steel undergoing molten steel flow fluctuations due to a casting speed change. As the casting speed is controlled by the sliding nozzle (SN) gate movement, an investigation into the effect of such SN gate movement on the molten steel flow would be useful. In this study, the molten steel flow in a mold was numerically simulated during partial opening/closing of the SN gate by a certain distance at a constant speed. The deforming mesh model was used to consider the geometry change in the simulation. The validity of this model was confirmed by comparison with the results of a water model simulation experiment.

When the SN gate is partially opened/closed, the steel mass flow rate is increased/decreased accordingly. At the SN gate and the SEN ports, the transitional time required to reach a steady flow is several seconds after the commencement of SN gate movement. At the meniscus, an even much longer time is required to reach a steady flow.

(cf. *ISIJ Int.*, **41** (2001), 1221)

Optimum magnetic flux density in quality control of casts with level DC magnetic field in continuous casting mold

H. YAMAMURA et al.

Application of level DC magnetic field (LMF) in continuous casting mold decreases the mixing length at the ladle change region in sequential casting of different steel grades and improves the inclusion quality of cast slabs. Until now control condition for the mixing of steel compositions which depends on the fluid flow of molten steel has only been clarified. However, control condition for the inclusion whose behavior is not always the same as the behavior of the molten steel flow has not been clarified yet. In this study, continuous casting experiment and numerical analysis were conducted to derive the control index for inclusion and to estimate the optimum condition for improvement of inclusion quality in cast slabs with LMF. The followings are results: Optimum magnetic flux density exists to control the inclusion quality in cast slabs with LMF. Inclusion behavior is explained by the balance between the penetration of inclusion controlled by magnetic field and the floatation of inclusion. This optimum magnetic flux density can be characterized by the interaction parameter, which is expressed by the ratio of inertial force caused by pouring flow to magnetic braking force (Lorentz's force) caused by magnetic field.

(cf. *ISIJ Int.*, **41** (2001), 1230)

Effect of magnetic field conditions on the electromagnetic braking efficiency

H. HARADA et al.

Effect of different types of in-mold electromagnetic brake (EMBr) technique, which forms a local magnetic field and a level magnetic field in the width direction of a mold, on the fluid flow phenomena in the strand pool was examined. A mercury model experiment revealed that the level magnetic field developed a plug-like flow in the strand pool, of which flow could not be obtained by the local magnetic field. Surface velocity near the meniscus could be stably controlled with the level magnetic field, while in the case of the local magnetic field, this surface velocity was greatly affected by the nozzle condition. Numerical analysis clarified the characteristics in the distribution of an induced electric current density and Lorentz force, and explained the flow behavior with the local and level magnetic fields, respectively.

(cf. *ISIJ Int.*, **41** (2001), 1237)

Evaluation of multiphase phenomena in mold pool under in-mold electromagnetic stirring in steel continuous casting

T. TOH et al.

Multiphase phenomena in the application of in-mold electromagnetic stirring in continuous casting were discussed through cold experiment using mercury and numerical simulation by using two fluid model. The result revealed the critical flow rate of argon injected in the submerged entry nozzle, which leads to the change in flow pattern in the bulk liquid metal inside the mold pool. This change does not have a large effect on the flow driven by in-mold electromagnetic stirring because the Lorentz force acts mainly in the vicinity of solidifying shell except for the case of large amount of the argon flow rate. The particle behavior under in-mold electromagnetic stirring in the vicinity of the solidifying shell was also discussed by solving near-wall fluid flow and employing the particle tracking method, which showed the important effect of lift force by the increase in velocity inclination near the solidifying shell by electromagnetic field.

(cf. *ISIJ Int.*, **41** (2001), 1246)

Mathematical model for transient fluid flow in a continuous casting mold

K. TAKATANI et al.

A mathematical model that can simulate the tran-

sient fluid flow phenomena in a continuous casting mold has been developed. In this mathematical model, multi-phase flow phenomena which consist of the Ar gas injected into the submerged entry nozzle, molten steel and solidified shell can be described. To verify the availability of the mathematical model, water cold model and fused metal hot model experiments were conducted and comparisons of the measured fluid flow phenomena were made with computational results. In the water cold model, the time fluctuation of the fluid flow just under the meniscus and the deformation of the meniscus shape were measured and in the fused metal hot model, effect of the Ar gas bubble on the fluid flow in the mold were investigated. Computational results gave good agreement with both experimental measured data. Real plant simulation were conducted to investigate the effect of Ar gas bubble on the fluid flow phenomena in the continuous casting mold by using this mathematical model.

(cf. *ISIJ Int.*, **41** (2001), 1253)

Comparison of four methods to evaluate fluid velocities in a continuous slab casting mold

B.G.Thomas et al.

Four different methods are compared for evaluating fluid flow velocities in the liquid pool in the mold region of a continuous caster of steel slabs. First, the instantaneous and time-averaged flow pattern in a 0.4-scale water model with single-phase flow is quantified using particle image velocimetry (PIV). Next, three-dimensional computations are performed to calculate the time-average flow pattern in the same system using a conventional finite-difference program, CFX, with the conventional K–ε model for handling turbulence. Transient computations are then performed using a 1.5-million node grid to resolve the turbulent eddies, both without a turbulence model (direct numerical simulation: DNS) and with a subgrid scale model (large eddy simulation: LES). Finally, measurements are obtained using electromagnetic sensors embedded in the mold walls of an operating steel slab casting machine. The comparisons reveal remarkable quantitative agreement between all four methods for the overall time-averaged flow pattern and surface velocities for these conditions. The time-averaged K–ε model is capable of accurate quantitative calculations of the steady flow field with the least effort, but has difficulty with transient behavior. The LES model predicts both steady and transient phenomena, but has severe computational cost. Water models with PIV are useful and practical tools, but are difficult to extend beyond the flow pattern to practical phenomena, such as heat transfer, solidification, surface slag entrainment, two-phase flow, and particle motion. The electromagnetic sensor has the advantage of measuring the real process, but is computed to be accurate only where the flow is roughly uniform and directly horizontally between the two probes, so is limited to measuring average speed at just a few points. Thus, each method has its own merits and disadvantages relative to the others, and can be a useful tool for investigating flow phenomena in processes with molten metal. Together, these methods reveal new insights into steady and transient flow in the continuous slab-casting mold, which are discussed in this work.

(cf. *ISIJ Int.*, **41** (2001), 1263)

Heating and Cooling

Numerical simulations of turbulent non-premixed combustion in a regenerative furnace

N.Stockwell et al.

The combustion process in an experimental regenerative, slab reheat furnace was simulated in order to validate several numerical models in the FLUENT, a computational fluid dynamics code. Total 13 cases employing different numerical models were simulated. The predicted results were compared against experimental measurements in terms of the energy output rate and the temperature distribution in the center of the slab.

(cf. *ISIJ Int.*, **41** (2001), 1273)

Mathematical simulation and controlled cooling in an EDC conveyor of a wire rod rolling mill

Á.Zufía et al.

The aim of this work was to build up a model, working on a PC, able to simulate the controlled cooling of wire rods in an EDC conveyor. The effect of the cooling pattern on the temperature profile and the austenite microstructural evolution during hot rolling have been studied.

This computing system will provide a high flexibility for simulating different operational conditions and for forecasting the thermal and microstructure evolution during the cooling after hot rolling, including the prediction of microstructural final properties, in the EDC conveyor of the SIDENOR wire rod rolling mill in Vitoria.

The use of this integrated model enables calculation of the temperature distribution through the section and along the width of the loop, and allows a systematic study of the parameters influencing the cooling behaviour. Besides, the effects of different parameters and their complex correlation can be studied.

(cf. *ISIJ Int.*, **41** (2001), 1283)