Metallurgical Application of Advanced Fluid Dynamics

Li Baokuan

Metallurgical Industry Press

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Li Baokuan

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Metallurgical Industry Press

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PREFACE

In 1989, I entered the fascinating world of metallurgical application of advanced fluid dynamics for my doctorial program; the title of dissertation is the "Mathematical Modeling of Transport Phenomena in Gas Stirred Ladle". Later, my research work was expanded to the field of continuous casting of steel considering the effect of magnetic field application.

Supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, I studied in the University of Tokyo from October, 1998 to September, 2000. I greatly enjoyed the experience with which I developed insights to science and got to know many successful scholars in Japan. I spent the first one and a half years with Professor T. Umeda's laboratory of solidification till his retirement, and the latter half year with Professor F. Tsukihashi laboratory of chemistry of materials processing in the department of Advanced Materials Science of Graduate School of Frontier Sciences. I own a lot to Professor Tsukihashi for his guide and support, which covered not only my research but also my stay in Japan. It is my great honor to have his help and his highlighting me. I am greatly encouraged and inspired by him. The time with Professor Tsukihashi deserves most cherishment in my life.

I am also very grateful to Professor T. Umeda for his receiving me as postdoctoral student in his laboratory, and the later recommending me to Professor Tsukihashi upon his retirement from the University of Tokyo. My first paper submitted during my stay in Japan owned many to the discussion with professor Umeda, the revision by him as well as his encouragements.

Many other people has helped me in all kinds of ways to accomplish this work, technical assistant Dr. T. Okane, Dr. Guangqiang Li and Master students, Hiromi Yoshita and others. Here, I wish all of them healthy

and achieve more and more scientific success.

· Fluid flows are integral part of the steelmaking operations. The viability, effectiveness and efficiency of the refining and continuous casting of steel are significantly affected by the molten steel flow. A main part of advanced fluid dynamics is the computational fluid dynamics, which is undergoing significant expansion in terms of both the number of course offered at universities and the number of researchers active in the field. The codes of computational fluid dynamics are being accepted as design tools by industrial researchers. At present, researchers of advanced fluid dynamics need to be fairly knowledgeable and this requires education of both students and working engineers. The present book is an attempt to fill this need.

It is our belief that, to work in computational fluid dynamics, one needs a solid background in fluid mechanics and numerical analysis; people lacking knowledge in one or the other have made significant errors. We therefore encourage the reader to obtain a working knowledge of these subjects before entering into a study of the materials in this book. Because different people view numerical methods differently, and to make this work more self－contained, I have included one chapter on basic numerical methods in this book. This book is based on materials offered by the authors in published papers at The University of Tokyo and Northeastern University of China. It reflects the author's experience in both writing computer codes and using them to solve engineering problems. As part of a long-term effort to develop and apply comprehensive models of refining and continuous casting of steel, this book summarizes the many different findings obtained under National Natural Science Foundation, Grant No. 59604006 and 50274029.

Li Baokuan

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1 INTRODUCTION

1.1 Background

Fluid flow in refining and continuous casting of steel is of great interest because it influences many important phenomena, which have far-reaching consequences on product quality. Some operations such as the homogenization of steel and alloying addition of desired elements or removal of undesired elements, gas treatment, emulsification, deoxidation, inclusion removal, etc. consist of very complex multi-phase physicochemical reactions and transformation of phases[1]. Fluid flows affect the viability, effectiveness and efficiency of many reactors in physical and/or chemical nature. Figure 1.1 illustrates molten steel flow with the technological proceeding from steelmaking furnace, ladle, tundish to the molds of continuous casters.

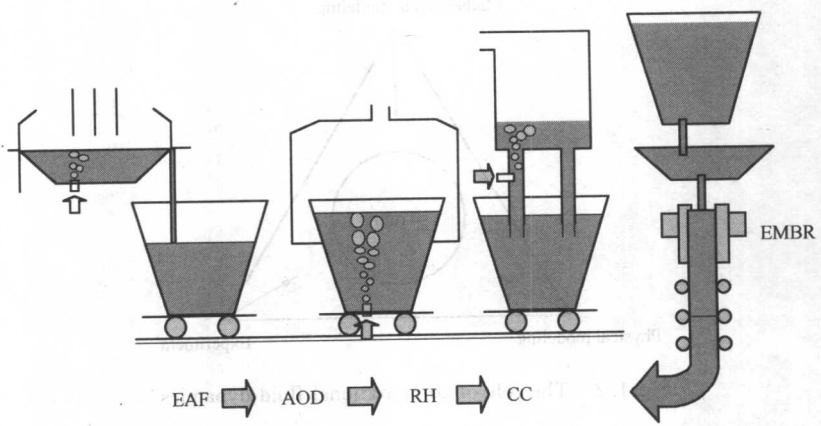


Fig. 1.1 Flow phenomena in refining and continuous casting processes.

The most reliable information about a physical process is often giv-

en by actual measurement. An experimental investigation involving full-scale equipment can be used to predict how identical copies of the equipment would perform under the same conditions. Such full-scale tests are, in most cases, prohibitively expensive and often impossible. The alternative then is to perform experiments on small-scale models, The resulting information, however, must be extrapolated to full scale, and general rules for doing this are often unavailable. Further, the small-scale models do not always simulate all the features of the full-scale equipment. Finally, it must be remembered that there are serious difficulties of measurement in many situations, and that the measuring instruments are not free from errors.

With the development of the numerical simulation technique and computer capacity, mathematical modeling is more and more developed and employed to explore the process phenomena and obtain the detailed and accuracy information. The computational fluid dynamics is the core of mathematical modeling in metallurgical processes. The roles of computational fluid dynamics (in Figure 1.2) are as follows:

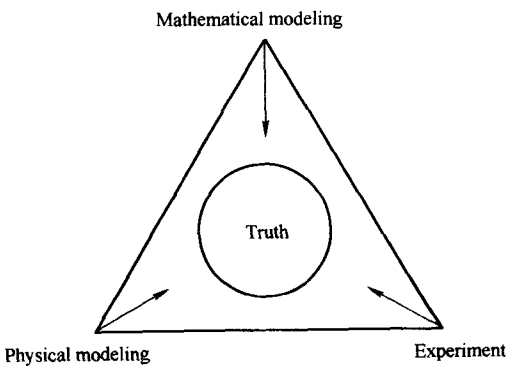


Fig. 1.2 The role of computational fluid dynamics.

1) Point the direction of physical experiment by predicting process;

2) Reduce the experimental losses and increase the design accuracy;

3) Understand profoundly physical and chemical processes;

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4) Provide the testing platform of the new ideas, which involve new technologies and operations.

There is no doubt that experiment is the only method for investigating a new basic phenomenon. In this sense, experiment leads and computation follows. It is in the synthesis of a number of interacting known phenomena that the computation performs more efficiently. Even then, sufficient validation of the computed results by comparison with experimental data is required. On the other hand, for the design of experimental apparatus, preliminary computations are often helpful, and the amount of experimentation can usually be significantly reduced if the investigation is supplemented by computation.

An optimal research effort should thus be a judicious combination of computation and experiment. The proportions of the two ingredients would depend on the nature of the problem, on the objectives of the prediction, and on the economic and other constraints of the situation. In some cases, the importance of combining modeling and experiments together cannot be overemphasized [2].

Mathematical modeling is indispensable technology for advances in iron and steel making industrials and has been coming to be used widely for the analysis/optimization of the established processes and the scaling up simulation of new processes. Numerical simulation has been growing in importance in research aiming at improving steelmaking processes. Especially during the last decade, the development of modeling software and the number of applications in materials science and metallurgy have been increasing rapidly. At present, a profusion of commercial software packages is available for fluid flow and heat transfer simulation. At the same time, there has been an exponential increase in the speed of computers. The increased speed and graphics sophistication of computers have also enabled more illustrative three-dimensional visualization of computed results.

Although the computer power and numerical simulation technology have been improved extremely, it is the fact that we encounter with the

difficulties when we want to analyze the iron and steel making processes. There is a little information about the mathematical modeling, method of analytical solution, setup of the boundary conditions, etc. Much information should be necessary to do a better analysis about the mathematical and physical modeling, details of the solution technique, properly boundary conditions, and so on.

1.2 Mathematical Description of Flow Phenomena[3]

Fluid flow problems in steelmaking processes can be categorized into the following groups of increasing complexity:

1) Forced convection (fluid flow and heat transfer in single-phase, confined, and unconfined, laminar and turbulent flows).

2) Natural convection.

3) Mixed, forced, and natural convection.

4) Flow and heat transfer with electric potential, current, and magnetic fields.

5) Flow and heat transfer with chemical reaction: reaction could be diffusion controlled or kinetically controlled.

6) Two-phase flow and heat transfer with chemical reaction and phase change.

7) Multiphase flow and heat transfer with simultaneous presence of solid, liquid, and gas phases.

In each of the above categories, many idealized problems have been solved by various analytical and/or experimental means. The results of these studies are available in textbooks, handbooks, and technical journals. This wealth of information has guided metallurgical engineers for decades and will continue to do so. However, the increasing competition in steel industry and the emerging new technology lead to ever-increasing additional demands for better understanding and for more accurate analyses of fluid flow phenomena. This calls for better analytical tools that allow a reduction in the number of assumptions and simplifications in problem formulations.

A general form of the fluid flow associated with heat and mass transfer equation is

$$\frac{\partial}{\partial t}(\rho\varphi)+\mathrm{Div}(\rho V\varphi)=\mathrm{Div}(\Gamma_\varphi \mathrm{Grad}\varphi)+S_\varphi \qquad (1\text{-}1)$$

Transience Convection Diffusion Source Terms

where φ is a general variable that can represent a velocity component (u, v, or w), enthalpy (h) or concentration of chemical species (c_1, c_2,...,c_n), etc. Γ_φ is the exchange coefficient, e. g. , molecular viscosity for momentum transfer in a laminar flow or thermal diffusivity for heat transfer. S_φ represents sources (and sinks) of φ, e. g. , pressure gradient, gravity force, or any other body force such as electromagnetic force etc. in a momentum conservation equation. Equation (1-1) can also be regarded as a general form of the heat conduction, radiation, and electric potential equations by recognizing that in these equations the convection terms are absent.

The inclusion of density (ρ) and the exchange coefficient (Γ_φ) inside the operand of divergence terms allows us to account for variable physical properties. Any spatial variation of a property (e. g. ρ) is easy to account for in a discretized method. In heat conduction problem, ρ could vary because of the complex metal composition, e. g. , laminated layers of different materials. On the other hand, in a flow problem, generally, ρ can be calculated from other fluid variables such as temperature, pressure, and concentration. Due to the nonlinearity and coupling of flow equations, the solution methods are of an iterative nature and hence are suitable (at least in principle) for nonlinear, multiple-variable dependences of ρ and Γ_φ. This capability has tremendous potential. Let us, therefore, look at the implications of variable ρ and Γ_φ separately.

(1) Variable ρ

Dependence of ρ on temperature allows simulations of natural convection and other buoyancy-influenced problems. Dependence of ρ on pressure permits simulation of compressible flows. Dependence of ρ on temperature and concentrations allows simulations of reactive flows.

(2) Variable Γ_φ

For a heat conduction or electric potential equation, Γ_φ, can vary with position due to the composition of materials and/or it could vary with temperature. For laminar flows also, fluid viscosity or thermal diffusivity can vary with temperature. All these variations are easily accommodated in a discretization method. The real use of the capability of accounting for variable Γ_φ has been made in the simulation of turbulent flows. By using the Boussinesq eddy-viscosity concept, the flow equation for a turbulent flow becomes identical to Eq. (1-1), with the exception that Γ_φ is replaced by $\Gamma_{\varphi,\text{eff}}$, given by

$$\Gamma_{\varphi,\text{eff}}=\frac{\mu}{Pr}+\frac{\mu_t}{Pr_t} \tag{1-2}$$

where μ is the molecular viscosity, Pr is the Prandtl number, and suffix t represents their counterparts under turbulent conditions. In the eddy-viscosity approach there are several turbulence models of different complexity, e. g. algebraic models such as the Prandtl mixing length model and two-equation models such as the k-ε model of turbulence. In case that the eddy-viscosity approach is not suitable, other models such as algebraic stress models (ASM) can be incorporated by replacing the diffusion terms of equation (1-1) with suitable expressions for the Reynolds stress.

(3) Variable source, S_φ

S_φ has different meanings and different forms for different variables. Often, there is more than one term in S_φ. The main point is that the source terms of all types (e. g. , fixed, linear, or nonlinear) can be handled in a discretization method.

(4) Two-phase flows

In two-phase flows there are two sets of equations (one for each phase), of the same kind as equation (1-1). Of course, equations of each phase contain additional source terms to account for the interphase exchanges of mass, momentum, and heat. All earlier remarks about variable ρ,Γ_φ, and S_φ apply for each phase.

1.3 Previous Works

1.3.1 *Electric arc furnace*

The electric arc furnace (EAF) process has gained increasing acceptance in the steel production and currently this process represents almost 40% of the total crude steel production in the world. Nevertheless, the levels of efficiency in the EAF are approaching an asymptotic behavior and it has become evident the need for more fundamental understanding to further impact the EAF efficiency.

Szekely et al.[4] developed a mathematical model to describe heat transfer and fluid flow in both the plasma region and the molten bath of a D. C. arc furnace. This work was one of the first attempts at modeling an EAF. It describes all major fluid dynamics phenomena that were present in the EAF steelmaking process. The model was an axisymmetric two-dimensional flow. More recent computational work treats heat transfer and fluid flow in the plasma region of the furnace. Qian et al.[5,8] developed a model similar to that of Szekely et al. with only the plasma region solved for. The aim of their work was to determine the relative importance of various modes of heat transfer from the electric arc. Using their model they determined the most efficient operating conditions for heat transfer to the metal bath. Zhang et al.[6] constructed a 1/4 scale isothermal water model to study gas stirring in an electric arc furnace. They looked at the effects of bottom bubbling gas flow rate and configuration on mixing time and two phases mass and heat transfer. They found mixing time was not a strong function of bubbler configuration. Figure 1.3 shows the experimental results of mixing time with the different gas flow rates. Tanski[7] developed a numerical model to predict the effects of gas stirring on bath homogeneity. The model assumed the axisymmetric geometry and a single point injection of gas. Recently, Liping Gu et al.[9-11] published physical and mathematical models of the fluid flow in the steel bath considering specific operations

in the EAF, such as gas bubbling injection, the use of oxy-fuel burners, and the effect of carbon boil on fluid flow. It is clear that only a few attempts to model the EAF operations have been reported in the past and that no radically new contributions have been made to this field of modeling.

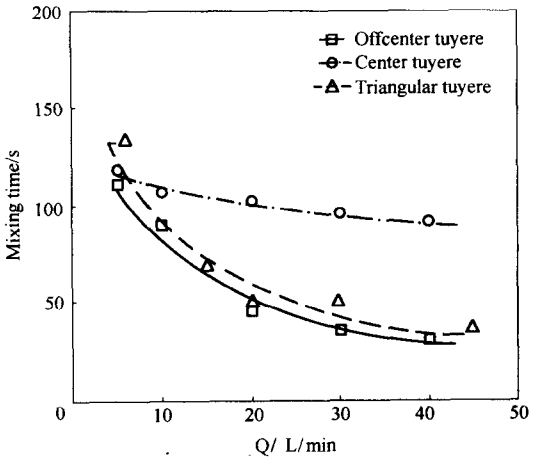


Fig. 1.3 The effect of gas flow rate on mixing time for 50% scrap case[6].

1.3.2 *RH degassing system*

The RH(Rheinstahl-Heraeus) vacuum system is widely used to produce ultra-low carbon steel. The refining process of the RH system is classified as degassing and decarburization of a steel melt which circulates between the ladle and vacuum vessel by blowing with Ar gas. Although the RH system can treat a larger volume of melt compared with other refining processes, the decarburization rate of molten steel with a low carbon content has a tendency to be low.

One of the dominant factors, which influence the decarburization rate in the RH process, is circulation flow rate. It is generally accepted that the decarburization rate increases as the circulation flow rate increases[12]. It was well known that the conventional RH vessel has two

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