Journal of University of Science and Technology Beijing
Volume 11, Number 3, June 2004, Page 207

Application of Computational Fluid Dynamics to analysis of metallurgical process for continuous casting tundishes

Shiheng Peng[1), *Xinfeng Li*[2), *Shengtao Qiu*[1), *Yong Gan*[1), *and Zeqiang Xiao*[3)

1) National Engineering & Research Center for Continuous Casting Technology, Central Iron and Steel Research Institute, Beijing 100081, China
2) National CIMS Engineering & Research Center, Tsinghua University, Beijing 100084, China
3) School of Materials and Metallurgy, Northeastern University, Shengyang 110006, China

(Received 2003-04-23)

Abstract: A series of simulations by mathematical and physical modeling on fluid flow, mass and heat transfer in continuous casting tundishes have been carried out. It was found by computational fluid dynamics (CFD) simulation that in most cases tundish flow must be treated as a non-isothermal reactor due to the existence of temperature difference between the transport ladle and the tundish. The critical conditions when the non-isothermal flow in the tundish can not be neglected have been found by CFD simulation and water modeling. A direct measurement in a 40 t tundish has confirmed the simulation results.

Key words: tundish; numerical simulation; application of CFD; mathematical modeling

1 Introduction

From early 1950's, continuous casting (CC) technology for treating liquid steel obtained by a series metallurgical processes to produce solid by-products has been used worldwide instead of using mould casting which has been used in industry for about a century. The tundish which locates between the transport ladle and the continuous casting machine acts as a reactor distributing liquid steel to one or more casting strands, to smooth the casting flow stream which significantly influences the product quality, and to control casting speed. The annual increase of the tundish production capacity in China during past 1-2 decades was more than 4 million ton of steel. Thousands of tundishes are operating in Chinese steel industry at present. So, the study of tundish processes attracts great attentions from many metallurgists including simulation engineers [1-5].

With an aim to improve the flow pattern of liquid steel in 40, 10 and 8 t tundishes, and sequentially to improve bath temperature homogenization, inclusion separation, *etc*., a series of Computational Fluid Dynamics (CFD) simulations including physical modeling and a direct measurement in industrial tundishes have been carried out in this paper. Basic results are presented with a discussion on the existence of non-isothermal flow and its influence on metallurgical results.

2 Mathematical model

2.1 Isothermal condition

The investigation of metallurgical processes in continuous casting tundishes is an important subject. A 3-D mathematical model was developed to simulate hydrodynamics and the associated heat and mass transfer phenomena in tundishes under the isothermal condition, using k-ε two equations model to describe turbulent flow. And the following governing transport equations need to be solved.

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_j)}{\partial x_j}=0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_j u_i)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

k-ε equation:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{\text{eff}}}{\sigma_k}\cdot\frac{\partial k}{\partial x_i}\right)+G-\rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho u_j \varepsilon)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\mu_{\text{eff}}}{\sigma_\varepsilon}\cdot\frac{\partial \varepsilon}{\partial x_i}\right)+(C_1 G\varepsilon-C_2\rho\varepsilon^2)/k \tag{4}$$

Corresponding author: Shiheng Peng, **E-mail:** shiheng_peng@126.com

where G is the generation term, given by

$$G=\mu_t \frac{\partial u_j}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

The effective viscosity μ_{eff} is the sum of laminar viscosity (μ_l) and turbulent viscosity (μ_t). And the turbulent viscosity is related to the turbulent energy and its dissipation rate by

$$\mu_t=C_D\rho k^2/\varepsilon \tag{6}$$

Constants adopted in the above model are the values recommended by Launder and Spalding [6].

Thermal energy conservation equation:

$$\frac{\partial\rho T}{\partial t}+\frac{\partial\rho u_j T}{\partial x_j}=\frac{\partial}{\partial x_j}\left(K_{\text{eff}}\frac{\partial T}{\partial x_j}\right) \tag{7}$$

Tracer diffusion equation:

$$\frac{\partial\rho C_i}{\partial t}+\frac{\partial\rho u_j C_i}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\Gamma_{\text{eff}}\frac{\partial C_i}{\partial x_j}\right) \tag{8}$$

2.2 Non-isothermal condition

Besides the above equations, several other considerations were made for non-isothermal fluid flow. In the non-isothermal system, the fluid flow and heat transfer are governed by both inertia force and thermal buoyancy force caused by density change. The control equation was simplified by Boussinessq approximation, *viz.*, the influence of buoyancy force was considered only in generation term. The momentum equation employing Boussinessq approximation may be written in the Cartesian tensor notation as follows [5,7-9]:

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{\text{eff}}\left(\frac{\partial u_i}{\partial u_j}+\frac{\partial u_j}{\partial u_i}\right)\right]+(\rho-\rho_0)g \tag{9}$$

In the above equation, ρ_0 is a reference density, and it is very important to choose it when calculating. The relation of molten steel density with temperature is given by [10]

$$\rho=8523-0.8358T,\ \text{kg/m}^3 \tag{10}$$

Other equations and their treatment are the same as those based on isothermal conditions.

3 Results and discussion

3.1 Process simulation in tundishes considered as isothermal reactors

(1) Investigation for an 8 t tundish in Guangzhou Steel Plant.

In Guangzhou Steel Plant there is a small caster working for producing billets, three strands parallelly working with a casting machine. Due to the layout limit in the plant, the tundish was designed with an eccentric location of the inlet flow to three outlet nozzles as shown in **figure 1**. The liquid steel poured into the tundish flows to each of the three nozzles with significant different time which leads to clogging problem at the far located nozzle and overheating problem at the nearest nozzle. This has been confirmed in **figure 2** by the residence time distribution curves of the three nozzles predicted by CFD simulation.

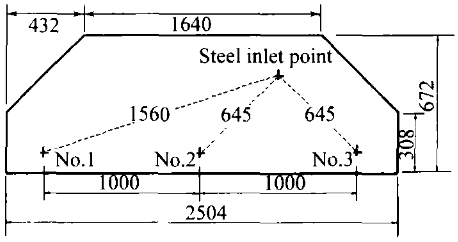

Figure 1 Location of steel inlet flow and three casting outlet nozzles in the 8 t tundish (unit: mm).

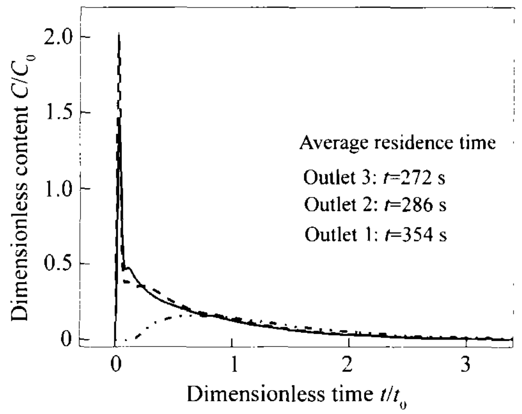

Figure 2 Predicted residence time distribution curves in the 8 t tundish before reconstruction.

The project was defined to find an optimum design to set up dams to control steel flow reaching each nozzle with almost equal time. V-type dam design has been proposed in this work after several choices of design have been evaluated by CFD simulation using homemade codes. **Figure 3** shows the comparison of flow pattern before and after the dam set-up. The average residence time of three strands in the new tundish were evaluated by physical modeling as 335, 398 and 370 s respectively, and evaluated by CFD calculation as 325, 383 and 338 s respectively. It was greatly improved by the dam set-up.

(2) Investigation for a 10 t tundish in Xinyu Iron & Steel Co.

One contract project offered by Xinyu Iron & Steel Co. was to find the proper design of a pair of dams for a 10 t slab casting tundish. Mathematical simulation confirmed by physical modeling proposed a design of the dam flow control system and illustrates the improvement in **figure 4** on the flow pattern and temperature distribution in the tundish.

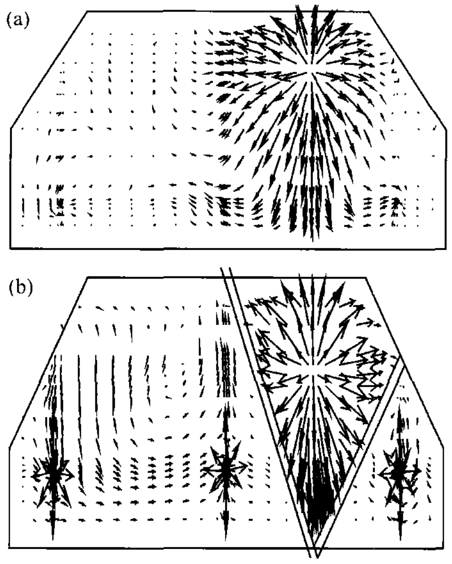

Figure 3 Comparison of flow pattern simulated by CFD before and after dam set-up: (a) before reconstruction; (b) after reconstruction (with a V-type dam with holes).

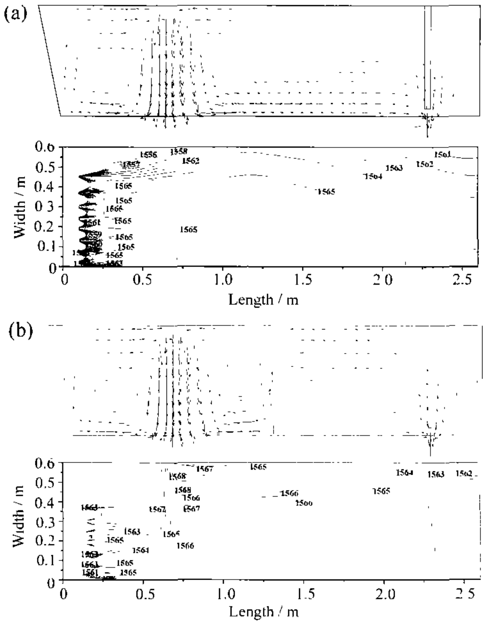

Figure 4 CFD simulation results on flow control for a 10 t slab casting tundish (flow pattern and temperature field): (a) without flow control; (b) with a pair of dams.

3.2 Process simulation in tundishes under non-isothermal conditions

It is known that during the steel casting process, steel temperature in the transport ladle and the tundish will not be equal. In most cases, steel temperature in the ladle is higher than that in the tundish (existing a positive temperature difference), but there could be a negative temperature difference when the last tons of steel pour from the ladle to the tundish. In past 40-50 years after continuous casting technology was used in steel industry the tundish was considered almost as an isothermal reactor as it was dealt with in the above sections for Guanggang and Xingang plants. It is interesting to investigate the non-isothermal phenomenon (also can be called as natural convection, thermal convection or thermal-driven buoyancy flow) in tundishes and its influence on metallurgical processes concerning productivity and product quality.

(1) Simulation of initial formation process of non-isothermal flow in tundishes.

In industrial practice the temperature difference of liquid steel between the ladle and the tundish could be vary from 100°C to 20°C. A CFD simulation describes the formation process of non-isothermal flow in the water tundish model when the temperature differences of 20°C (hotter water poured) and –20°C (colder water poured) were taken into consideration as the initial entry condition, respectively. In **figure 5** the simulation results show the complete different flow patterns for positive and negative temperature difference. When hotter water was poured into the tundish the entry water flow took an upper route closing to the tundish surface to reach the outlet nozzle and formed a dead zone above the central bottom of the tundish, but an opposite phenomenon could be seen when colder water flowed in. Obviously, the reaction condition of metallurgical processes to be finished in the tundish will significantly changed. The CFD simulation for non-isothermal flow in the water model tundish was fully confirmed by water model experiment (**figure 6**).

It must be noted that fluid flow in a reactor like the tundish is very sensitive to temperature difference. If the sensitivity of flow pattern to temperature change in the tundish is described by a number Zb (buoyancy force / inert force), it would be found experimentally that the value of Zb is related to temperature as

$$\mathrm{Zb} = \frac{Gr}{(Re)^2} = \frac{\dfrac{gl^3\beta|\Delta T|}{\nu^2}}{\left(\dfrac{ul}{\nu}\right)^2} = \frac{\beta gl}{u^2}|\Delta T| \qquad (11)$$

Putting water and steel concerned properties into equation (11) with consideration of tundish processing conditions, get $\mathrm{Zb} = 18.31\times|\Delta T|$. Through CFD simulation and physical modeling, it has been found that the critical condition when the non-isothermal flow in the tundish can't be neglected was ±2°C. Then, the critical value of Zb, under which non-isothermal fluid flow began to exist in the tundish was 36.62. It means that the tundish process in most cases must be considered as a non-isothermal flow system and the existing concepts for tundish design and process control in industry should be modified.

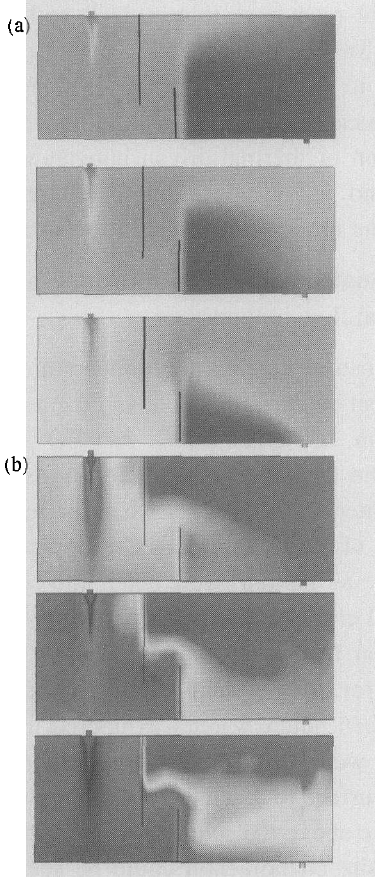

Figure 5 CFD illustration pictures of non-isothermal flow formation in the tundish when positive and negative temperature differences between the ladle and the tundish, (a) hotter water poured into the tundish bath; (b) colder water poured into the tundish bath.

(2) Simulation results in evaluation of a 40 t slab tundish process.

In 1999 a steel plant equipped with 2×150 t LD converters and a 40 t slab casting tundish has been put into operation in Meishan Iron & Steel (Group) Co. in China. A contract project was made to identify the basic property of the tundish process under production condition: the dominant flow in their tundish is isothermal or non-isothermal? For most production conditions in the plant the steel temperature in the ladle is about 40°C higher than that in the tundish. A CFD simulation done for this system was compared with data of temperature stratification and tracing material residence time obtained by directly measurement under production condition.

Flow Pattern:

The CFD prediction of flow pattern and temperature distribution in the 40 t slab tundish when steel temperature in the ladle is higher than that of in the tundish shows that molten steel flow in the tundish is a non-isothermal flow under production condition in Meishan Iron & Steel Co. (**figure 7**).

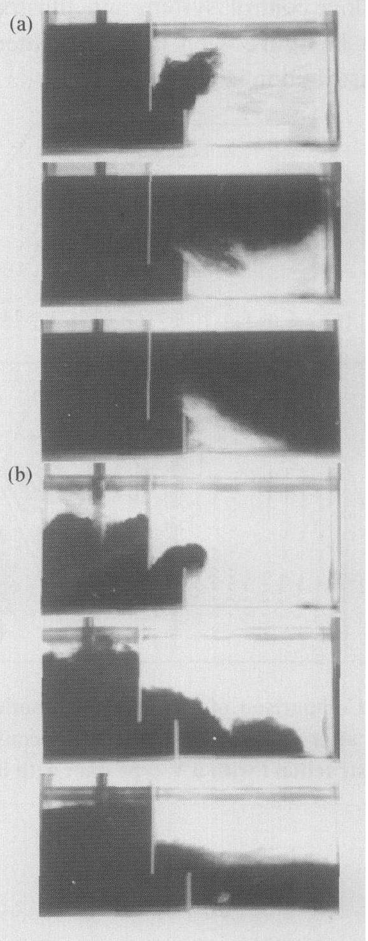

Figure 6 Photos of non-isothermal flow formation in the water model of the tundish: (a) hotter water poured into the tundish bath; (b) colder water poured into the tundish bath.

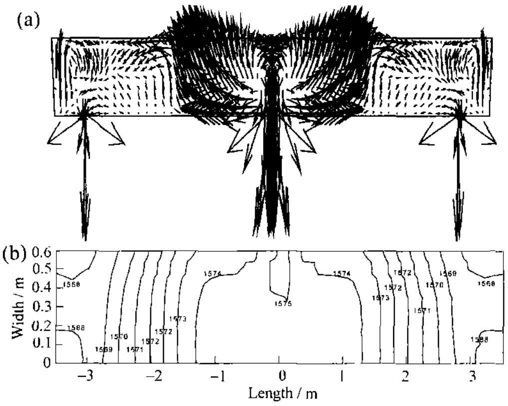

Figure 7 Predicted flow (a) and temperature field (b) by CFD simulation in the 40 t tundish under production condition.

Residence time:

One of the basic metallurgical properties of tundish reactors is the mass residence time which indicates the flowing route and pattern of liquid steel passing through the tundish, the mixing and homogenization condition, the location and dimensions of the dead zone, *etc.* A direct measurement of residence time that the predicted residence time obtained by CFD simulation based on non-isothermal flow is in good agreement with measured data. **Figure 8** shows the residence time of a tracer in the 40 t tundish obtained by direct measurement and CFD simulation based on isothermal and non-isothermal flow. The average residence time of molten steel flowing through the tundish were 670 s and 640 s, respectively, predicted by CFD simulation and direct measurement.

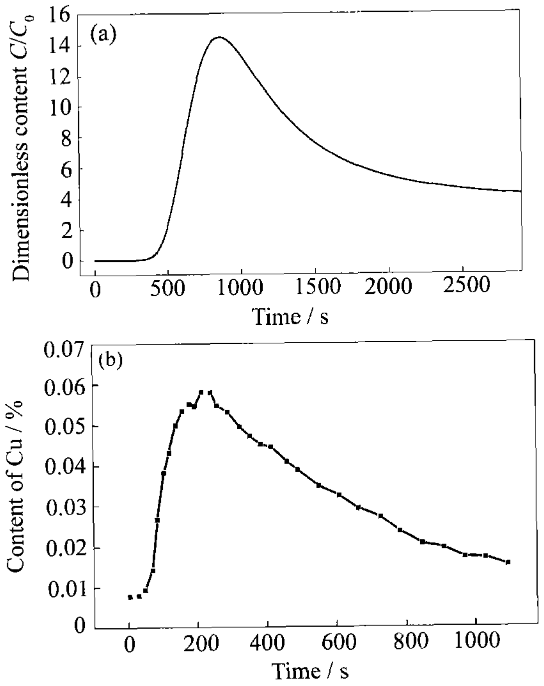

Figure 8 Comparison of residence time distribution (RTD) of a tracer obtained by CFD simulation and direct measurement in the 40 t slab casting tundish.

4 Conclusions

(1) CFD simulation and water model investigation combined with limited direct observation in prototype is an effective method to understand the transport and reaction phenomena in metallurgical reactors and to develop the proper control technology.

(2) The isothermal flow would not be the dominant flow in steel casting tundishes for most production conditions. The liquid steel flow in the tundish is very sensitive to the temperature difference between the transport ladle and the tundish even the difference is only several degrees.

(3) It has been found that in the 40 t tundish in Meishan Iron & Steel (Group) Co., the average residence time were 670 s predicted by CFD simulation and confirmed by direct measurement.

References

[1] D. Mazumdar and R.I.L. Guthrie, The physical and mathematical modelling of continuous casting tundish systems [J], *ISIJ Int.*, 39(1999), p.524.

[2] D.Y. Sheng, *Application of CFD in the Analysis of Fluid Flow, Combustion and Heat Transfer in Process Metallurgy* (in Chinese) [D], Northeastern University, Shenyang, 1997.

[3] D.Y. Sheng, C.S. Kim, and J.K. Yoon, *et al.*, Water model study on convection pattern of molten steel flow in continuous casting tundish Casting Tundish [J], *ISIJ Int.*, 38(1998), p.843.

[4] J.J. Wang, Y.P. Bao, and Ying Qu, *Tundish Metallurgy* (in Chinese) [M], Metallurgical Industry Press, Beijing, 2000.

[5] S.H. Peng, *Fundamental Study and Numerical Simulation on Isothermal and Non-Isothermal Process in Continuous Casting Tundishes* (in Chinese) [D], Central South University, Changsha, 2000.

[6] D.B. Spalding and B.E. Launder, *Numerical Prediction of Flow, Heat Transfer, Turbulence and Combustion* [M], Pergamon Press, New York, 1983.

[7] W.C. Fan and Y.P. Wan, *Model and Calculation of Fluid Flow and Combustion* (in Chinese) [M], Science and Technology University of China Press, Hefei, 1992.

[8] J.R. Cheng, *Turbulence Model and Finite Unit Analysis* (in Chinese) [M], Shanghai Jiaotao University Press, Shanghai, 1989.

[9] C. Damle and Y. Sahai, A criterion for water modeling of non-isothermal melt flows in continuous casting tundishes [J], *ISIJ Int.*, 36(1996), p.681.

[10] S. Joo, J.W. Han, and R.I.L. Guthrie, Inclusion behavior and heat-transfer phenomena in steelmaking tundish operations: Part II aqueous modeling [J], *Metall. Trans.*, 24B(1993), No.5, p.767.