The Effect of Turbulence on Two-Fluid Flow and Heat Transfer in Continuous Steel Casting Process

THEERADECH MOOKUM
Mae Fah Luang University
School of Science
333 Moo 1, Thasud, Muang, Chiang Rai 57100
THAILAND
t.mookum@sci.mfu.ac.th

BENCHAWAN WIWATANAPATAPHEE
Mahidol University
Department of Mathematics, Faculty of Science
272 Rama 6 Road, Rajthevee, Bangkok 10400
THAILAND
scbww@mahidol.ac.th

YONG HONG WU
Curtin University of Technology
Department of Mathematics and Statistics
Perth, WA 6845
AUSTRALIA
yhwu@maths.curtin.edu.au

Abstract: In this paper, we develop a mathematical model to study the coupled turbulent two-fluid flow and heat transfer process in continuous steel casting. The complete set of field equations are established. The turbulence effect on a flow pattern of molten steel and lubricant oil, meniscus shape and temperature field as well as solidification are presented in the paper.

Key–Words: Continuous steel casting process, turbulent flow, heat transfer, two-fluid flow, level set method

1 Introduction

Continuous casting (CC) is the process whereby hot steel is solidified into a “semifinished” billet, bloom, or slab for subsequent rolling in the finishing mills. Hot steel is drained from the tundish through a submerged entry nozzle (SEN) into a water-cooled mould, where intense cooling causes a thin shell of steel next to the mould walls solidifies before the middle section, called as a strand. The strand is continuously extracted from the base of the mold at a constant speed into a spray-chamber. The strand is immediately supported by closely-spaced, water cooled rollers after leaving the mould. During the process, the mould itself oscillates vertically to facilitate the process and to prevent the steel sticking to the mould walls. A lubricant can also be added to the steel in the mould to prevent sticking, and to trap any slag particles, including oxide particles or scale. Finally, the strand is cut into predetermined lengths by mechanical shears. In industrial practice, many problems still frequently occur. These problems mainly include molten steel breakouts, formation of surface defects and segregation of solute elements. As industry development is moving toward casting thin steel plates, these problems are expected to become more and more critical to the success of the process. Thus, further study of the CC process, development of robust mathematical models for simulating the complex phenomena occurring in the process become more and more important for the design of new systems and optimization of the process. Over the last three decades, extensive studies have been carried out to model many aspects of the CC process [1, 4, 5, 6, 7, 8, 10]. Little work has been done to solve the coupled turbulent two-fluid flow and heat transfer with solidification [11, 12, 13]. These studies have resulted in a basic understanding of the physics of the CC process and provided some basic guidelines for the design of the process. However, many phenomena such as the heat transfer process, the formation of oscillation marks and the meniscus behavior, have not been fully understood nor well controlled.

In this study, we propose a mathematical model for the problem of turbulent two-fluid flow and heat transfer with solidification in the continuous steel casting process. The effect of turbulence on the velocity field, temperature distribution and meniscus surface is investigated. The rest of the paper is organized as follows. In section two, a complete set of field equations is given. Section three represents a numerical study to demonstrate the effect of turbulence on the flow pattern of two fluids, the heat transfer with solidification and the meniscus shape.

2 Mathematical Model

In the CC process, there are two fluids, including hot steel and liquid lubricant. Materials are assumed to be incompressible Newtonian fluids. Three different computation regions of hot steel are the solidified region, the mushy region and the molten region. The solidified region presents near the edge of the casting in which every point moves along the casting direction at the constant casting speed. The molten region is in the center, and the mushy region is in between. For velocity field in the other both regions, we assumed that the fluid flow in the mushy region obeys Darcy's law for porous media and the influence of turbulence on the transport momentum and energy is modeled by the addition of the turbulent viscosity to the laminar viscosity and turbulent conductivity to the molecular conductivity, yielding the effective viscosity μ_{eff} and the effective thermal conductivity k_{eff} given by

$$\mu_{eff} = \mu + \mu_t, \quad k_{eff} = k + \frac{c\mu_t}{\sigma_t}, \tag{1}$$

where μ, k and c denote respectively the laminar viscosity, thermal conductivity and heat capacity of two fluids; σ_t is the turbulence Prandtl number assume as 0.9 [1]. The turbulent viscosity is determined by

$$\mu_t = \rho C_\mu \frac{K^2}{\varepsilon}, \tag{2}$$

where ρ is the density of two fluids, the coefficient C_μ is suggested to be 0.09 [7], K is the turbulent kinetic energy and ε is the turbulent dissipation rate. Thus, the governing equations are the continuity equation (3) and the Navier-Stokes equations (4) and the energy equation (5), namely

$$\nabla \cdot \boldsymbol{u} = 0, \tag{3}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right) - \nabla\cdot\left(-p\mathbf{I} + \mu_{eff}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)\right) = \boldsymbol{F}(\boldsymbol{u},\boldsymbol{x},t) + \rho\boldsymbol{g} + \boldsymbol{f}_{st}, \tag{4}$$

$$\rho c\left(\frac{\partial T}{\partial t} + \boldsymbol{u}\cdot\nabla T\right) = \nabla\cdot(k_{eff}\nabla T) + Q_T, \tag{5}$$

where $\boldsymbol{u}$ is the velocity of the fluids, p is the fluid pressure, $\boldsymbol{g} = (0,0,g)$ with g representing the gravitational acceleration, $\boldsymbol{F}$ is the forcing function, $\boldsymbol{f}_{st}$ is the surface tension force, T is the temperature, and Q_T is the heat source.

The influence of turbulence on the transport momentum and energy is modeled by the addition of the turbulent viscosity to the laminar viscosity and turbulent conductivity to the molecular conductivity. Various models have been proposed for calculating these turbulent parameters, namely simple mixing-length type models, one-equation models, two-equation models. Based on a critical review, the mixing-length type models is recommended for most boundary-layer type flows in the absence of recirculation, the one-equation model is suitable for simple recirculation flows, while the two-equation model can be used to model more complex flows [Launder & Spalding (1972) [7] and Ferziger (1987) [4]]. In the CC mould, the flow field is complex with circulation. Thus, we use the two-equation $(K-\varepsilon)$ model for calculating μ_t.

$$\rho\left(\frac{\partial K}{\partial t} + \boldsymbol{u}\cdot\nabla K\right) = \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_K}\right)\nabla K\right] - \frac{\mu_t}{\sigma_t}\beta\boldsymbol{g}\cdot\nabla T + \mu_t P(\boldsymbol{u}) - \rho\varepsilon \tag{6}$$

$$\rho\left(\frac{\partial \varepsilon}{\partial t} + \boldsymbol{u}\cdot\nabla \varepsilon\right) = \nabla\cdot\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + C_1(1-C_3)\frac{\varepsilon\mu_t}{K\sigma_t}\beta\boldsymbol{g}\cdot\nabla T + C_1\varepsilon\frac{\mu_t}{K}P(\boldsymbol{u}) - C_2\rho\frac{\varepsilon^2}{K} \tag{7}$$

where $P(\boldsymbol{u}) = \nabla\boldsymbol{u} : (\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)$, β is the thermal expansion of steel, the coefficients $C_1 = 1.44, C_2 = 1.92, \sigma_K = 1$ and $\sigma_\varepsilon = 1.3$ [7].

To determine the movement of the interface, the level set function is obtained by solving the following equation [9]:

$$\frac{\partial \phi}{\partial t} + \boldsymbol{u}\cdot\nabla\phi = \gamma\nabla\cdot\left(\epsilon\nabla\phi - \phi(1-\phi)\hat{\boldsymbol{n}}\right), \tag{8}$$

where ϕ is the level set function defined by:

$$\phi(\boldsymbol{x},t) = \begin{cases} 0 & \text{if } \boldsymbol{x}\in\Omega_s \\ 0.5 & \text{if } \boldsymbol{x}\in\Gamma_{int} \\ 1 & \text{if } \boldsymbol{x}\in\Omega_o. \end{cases} \tag{9}$$

The quantities γ and ϵ are reinitialization parameter and thickness of the interface, and $\hat{\boldsymbol{n}}$ is the unit normal vector at the interface. The reinitialization of equation (8) is given by

$$\frac{\partial \phi}{\partial t} = \gamma\nabla\cdot\left(\epsilon\nabla\phi - \phi(1-\phi)\hat{\boldsymbol{n}}\right). \tag{10}$$

The equation (10) is solved for obtaining the initial condition for the level set equation (8). The physical properties of fluids are represented in terms of the level set function as

$$\rho = \rho_s + (\rho_o - \rho_s)\phi, \tag{11}$$

$$\mu = \mu_s + (\mu_o - \mu_s)\phi, \tag{12}$$

$$k = k_s + (k_o - k_s)\phi, \tag{13}$$

$$c = c_s + (c_o - c_s)\phi, \tag{14}$$

where the subscripts s and o denote respectively the molten steel and lubricant oil. The heat source Q_T in equation (5) occurring only in the steel region and representing the rate of change of the volumetric latent heat is given by

$$Q_T = -\rho_s \left(\frac{\partial H_L}{\partial t} + \boldsymbol{u} \cdot \nabla H_L \right)(1 - \phi), \tag{15}$$

where $H_L = Lf(T)$ is the latent heat in which L representing the latent heat of liquid steel. The liquid fraction $f(T)$ is given by

$$f(T) = \begin{cases} 0 & \text{if } T \le T_S, \\ \dfrac{T - T_S}{T_L - T_S} & \text{if } T_S < T < T_L, \\ 1 & \text{if } T \ge T_L, \end{cases} \tag{16}$$

where T_S and T_L are the solidification temperature and melting temperature of the steel, respectively.

The forcing function $\boldsymbol{F}(\boldsymbol{u}, \boldsymbol{x}, t)$ in equation (4) is proportional to the velocity of the liquid relative to the porous media (mushy media) and is given by

$$\boldsymbol{F}(\boldsymbol{u}, \boldsymbol{x}, t) = C \frac{\mu_t (1 - f(T))^2}{f(T)^3} (\boldsymbol{u} - \boldsymbol{U}_{cast}), \tag{17}$$

where $\boldsymbol{U}_{cast} = (0, 0, U_{cast})$ with U_{cast} representing the constant downward casting speed and C is the morphology constant. The surface tension force in equation (4) acting only at the interface can be expressed as

$$\boldsymbol{f}_{st} = \sigma \kappa \delta \hat{\boldsymbol{n}}, \tag{18}$$

where σ is the surface tension coefficient, $\hat{\boldsymbol{n}} = \frac{\nabla \phi}{|\nabla \phi|}$ is the unit normal on the interface, $\kappa = -\nabla \cdot \hat{\boldsymbol{n}}$ is the interfacial curvature, δ is the delta function [3]. The smooth delta function used in the surface tension force is chosen to be [2]

$$\delta = 6 |\nabla \phi| |\phi (1 - \phi)|. \tag{19}$$

3 Numerical Results

To investigate the effect of turbulence on velocity field, temperature distribution and meniscus surface, we consider the case where the port angle is 12° downward, the inlet velocity of molten steel is 0.12 m/s, the molten steel has 5°C of super-heat, the delivery turbulent kinetic energy and its dissipation rate are respectively 0.0502 m^2/s^2 and 0.457 m^2/s^2. The values of other parameters are given in Table 1.

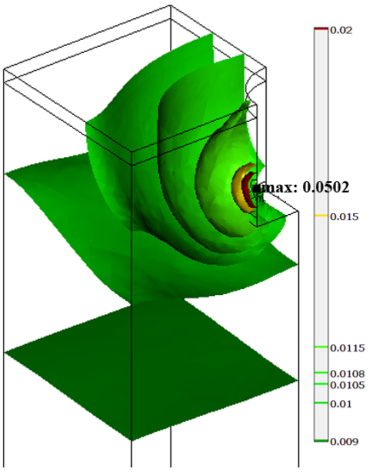


Figure 1: Isosurface plot of turbulent kinetic energy K.

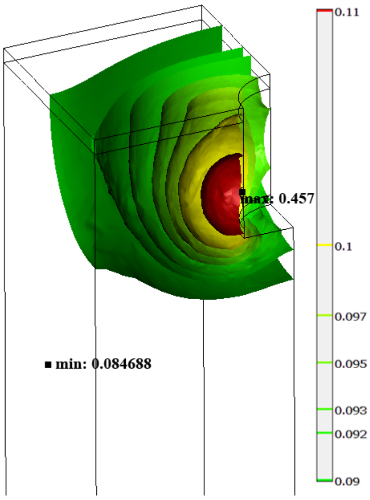


Figure 2: Isosurface plot of turbulent dissipation rate ε.

The models with turbulence effect and with no turbulence effect have been used in computation to investigate its impact on the two-fluid flow, heat transfer and meniscus shape in the casting region. Distribution of the turbulence quantities K and ε are shown in Figures 1 and 2. The quantities of turbulence variables K and ε are very high near the nozzle opening. Close to the solid boundary, the level of turbulence approaches zero. Values of turbulent kinetic energy and its dissipation rate rapidly decrease in the circulation region and then reach the smallest level in the solid-

Table 1: Parameters used in numerical simulation

Parameters	Value
U_{cast}	-0.000575 m/s
ρ_s	7800 kg/m^3
ρ_o	2728 kg/m^3
μ_s	0.001 $Pa \cdot s$
μ_o	0.0214 $Pa \cdot s$
σ	1.6 N/m
γ	0.01 m/s
ϵ	0.001 m
g	-9.8 m/s^2
β	3×10^{-5} °C^{-1}
T_L	1465 °C
T_S	1525 °C
c_s	465 J/kg°C
c_o	1000 J/kg°C
k_s	35 W/m°C
k_o	1 W/m°C
L	2.72×10^5 J/kg
C	1.8×10^6 m^{-2}

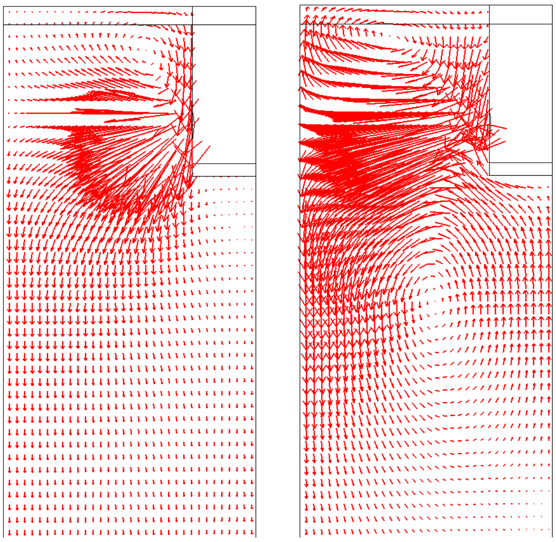

(a) (b)

Figure 3: Vector plot of velocity vectors in $xz-$plane near symmetry; (a) With turbulence effect; (b) With no turbulence effect.

ified steel shell. The results of the computed velocity field, turbulent kinetic energy, dissipation rate of turbulent kinetic energy, temperature distribution and meniscus shape are compared in Figures 3–7. The turbulence is found to have considerable effect on the flow pattern, heat transfer in the casting process and meniscus shape.

Figure 3 shows the velocity vectors in $xz-$plane near symmetry, Figure 4 shows the velocity vectors on the horizontal plane near the meniscus, and Figure 5 shows the streamline plot of the velocity fields. In the model with turbulence effect, the depth of the lower recirculation zone decreases, and the upper recirculation zone occurs near the nozzle. The velocity from the model with no turbulence effect is stronger than that with turbulence effect. Figure 6 shows comparison of the temperature profiles in the mould region. It indicates that the temperature field in both models with and with no turbulence effect drops very fast near the strand surface. The average temperature from the model with turbulence effect is lower than that with no turbulence effect in the region.

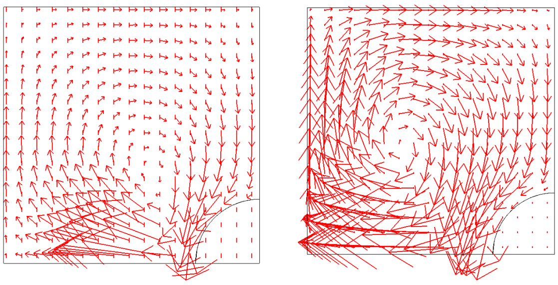

(a) (b)

Figure 4: Vector plot of velocity vectors on the horizontal plane near the meniscus; (a) With turbulence effect; (b) With no turbulence effect.

Figures 7(a) and 7(b) compare the meniscus shape obtained respectively by models with and with no turbulence effect. The results indicate that when turbulence is taken into account, the depth of the meniscus shape near the edge of casting is predicted to be deeper.

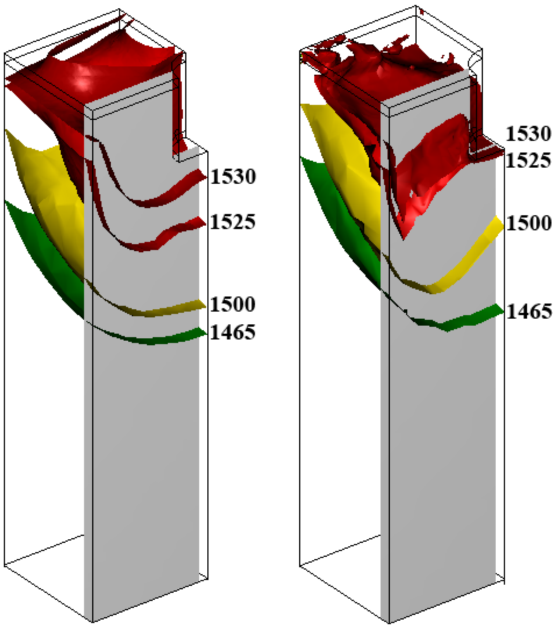
4 Concluding Remarks

A sophistication mathematical model for simulating the coupled turbulent two-fluid flow-heat transfer-solidification process in the continuous casting has been constructed utilizing a modified $K - \varepsilon$ turbulence model and level set equation. Based on the highly nonlinear model established, an efficient level set Bubnov-Galerkin finite element method has been developed and applied to study the turbulent two-fluid flow and temperature distribution in the casting region. The results clearly show that the effect of turbulence on solidification is big. Thus, in most case, we can use the model with turbulence effect taking into account the two-fluid flow to obtain a reasonable approximation.

Acknowledgements: The authors gratefully ac-

(a) (b)

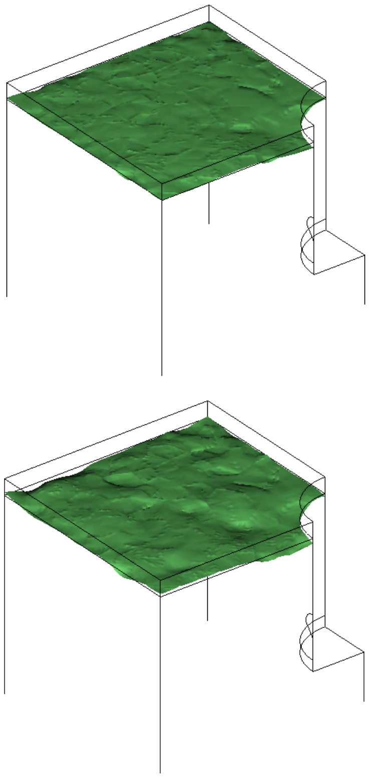
Figure 5: Streamline plot of velocity fields; (a) With turbulence effect; (b) With no turbulence effect.



(a) (b)

Figure 6: Temperature distribution at 1465, 1500, 1525, and 1530°C; (a) With turbulence effect; (b) With no turbulence effect.

knowledge the support of the Office of the Higher Education Commission and the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program (Grant No. PHD/0212/2549), and an Australia Research Council Discovery project grant.



(a)

(b)

Figure 7: Meniscus surface pattern; (a) With turbulence effect; (b) With no turbulence effect.

References:

[1] M.R. Aboutalebi, M. Hasan and R.I.I. Guthrie, Coupled turbulent flow, heat and solute transport in continuous casting processes, *Metall. Mater. Trans.* 26B, 1995, pp. 731–744.

[2] J.P.A. Bastos and N. Sadowski, *Comsol multiphysics modeling guide version 3.4,* COMSOLAB 2007.

[3] J.U. Brackbill, D. Kothe and C. Zemach, A Continuum method for modeling surface tension, *J. Comput. Phys.* 100, 1992, pp. 335–353.

[4] J.H. Ferziger, Simulation of incompressible turbulecnt flow, *Comput. Phys.* 69, 1987, pp. 1-48.

[5] K.G. Kang, H.S. Ryou and N.K. Hur, Coupled turbulent flow, heat, and solute transport in continuous casting process with an electromagnetic brake, *Numer. Heat Trans. A.* 48, 2005, pp. 461–481.

[6] D.S. Kim, W.S. Kim and K.H. Cho, Numerical simulation of the coupled turbulent flow and macroscopic solidification in continuous casting with electromagnetic brake, *ISIJ. Inter.* 40, 2000, pp. 670–676.

[7] B.E. Launder and D.B. Spalding, The numerical computation of turbulent flows, *Comput. Methods Appl. Mech.* 3, 1974, pp. 269–289.

[8] P.R. Lopez, R.D. Morales, R.S. Perez and L.G. Demedices, Structure of turbulent flow in slab mold, *Metall. Meter. Trans. B.* 36B, 2005, pp. 787–800.

[9] E. Olssen, G. Kreiss and S. Zahedi, A conservative level set method for two phase flow II, *J. Comput. Phys.* 225, 2007, pp. 785-807.

[10] R. Sánchez-Perez, R.D. Morales, M. Díaz-Cruz, O. Olivares-Xometl and J. Palafox-Ramos, A physical model for the two-phase flow in a nontinuous casting mold, *ISIJ. Inter.* 32, 1992, pp. 521-528.

[11] Y.H. Wu and B. Wiwatanapataphee, Modelling of turbulent flow and multi-phase heat transfer under electromagnetic force, *Disc. Cont. Dyn. Sys. B* 8, 2007, pp. 695–706.

[12] Y.H. Wu and B. Wiwatanapataphee, An entralpy control volume method for transient mass and heat transport with solidification, *Int. J. Comput. Flu. Dyn* 18, 2004, pp. 577–584.

[13] B. Wiwatanapataphee, Y.H. Wu, J. Archapitak, P.F. Siew and B. Unyong, A numerical study of the turbulent flow of molten steel in a domain with a phase-change boundary, *J. Comp. App. Math.* 166, 2004, pp. 307–319.