Numerical Simulation of Zinc Flow and Temperature Distribution in a Galvanizing Zinc Pot

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Zinc flows inside induction channel have been investigated as well as flows inside zinc bath. Lorentz force and heat have been obtained by detailed modeling of electro-hydrodynamics in the inductor channel. The Lorentz force gets added to momentum equations. Generated heat is utilized in energy equation. Flow vectors inside channel have great magnitudes of 540–200 cm/s range and directions from core to opposite. However molten zinc inlet has been clearly observed in the middle channel and outlets on two side channels. Two line speeds of 3.0 and 1.5 m/s have been adopted to see the effect of line speed. Flow pattern in the inside strip region was affected by line speed. The rest area of pot shows little difference. Temperature distribution was uniform over the entire bath within 1.3 degrees. The induction channel displayed an increase in temperature by approximately one degree Celsius compared to inside the zinc pot.

KEY WORDS: electro-hydrodynamics; inductor channel; zinc pot; flow vectors; temperature distribution.

1. Introduction

In continuous hot-dip galvanizing process, the understanding of molten zinc flow patterns and temperature fluctuations in the pot is of great importance in association of dross formation and strip surface quality. Several studies have been carried out to develop optimum flow control through experimental or numerical methods. Toussaint et al. determined the direction and intensity of movements by self-designed pot and using hot opaque liquid. The measurements resulted qualitative direction of flows and quantitative circulation speed. Lee et al. constructed a transparent water model to investigate the flow structure using PIV techniques. By varying the strip speed, the flow rate of induction heater, scraper and baffle arrangement instantaneous velocity fields were measured and analyzed. Ouellet et al. reported numerical simulation and experimental works to validate the numerical computation for isothermal and non-isothermal conditions. They concluded numerical simulations of the flow and heat transfer are in good agreement with the experimental data on a water model. Willis et al. also carried out numerical simulation for the fluid flow and temperature distribution for two pots: MCL4 and MCL1. They tried to support the hypotheses that the temperature distribution has to be uniform to inhibit dross formation and that flow conditions are related to intermetallic precipitation along with settling of the particles.

Heat source of galvanized zinc pot is supplied from channel inductors attached to it. Fluid flow momentum is driven by moving strip, sink roll and stabilizing rolls. To compute the fluid flow and temperature distribution of molten zinc, inductors have to be included in the calculation. However, previous studies did not include inductor channel in the calculation system. Instead, Willis and Ouellet imposed a mass flow rate to the inductor outlet and inlet. Lee selected the flow rate of heat of induction heater to the same as the real operation conditions. Inductors were modeled as recirculation device with an inlet and outlet. Buliggins investigated a flow inside industrial induction channel furnace without including pot. None of the above considered the zinc pot and inductor as one system to solve flow and energy equations. Although the inlet and outlet flows to and from throat channels are well observed in galvanized industry, it has been in question to understand exact flow pattern inside channel. In this study, we calculated the magnetic flux and generated heat of inductor that is operated through 60 Hz alternating current using OPERA-3D commercial software. The obtained Lorentz force and heat were added as source terms to Navier–Stokes and heat equations. Fluid vectors and temperature of molten zinc inside the Zn pot and inductor channel were solved by FLUENT software. The Zinc pot modeled in this paper is Gwang Yang 6 CGL line of POSCO strip mill. The pot size is 4 300 × 3 700 × 2 875 mm and strip is 1 253 mm in width and 0.96 mm in thickness. Two line speeds of 3 m/s and 1.5 m/s were used in the calculations. Ingot melting was not considered in this study.

2. Numerical Procedure

2.1. Inductor Modeling

Figure 1(a) shows a schematic diagram of half zinc pot with rotating sink roll, moving strip and two stabilizing rolls. The Zinc pot is surrounded by three layers of refractory, Sudeca-90SC, Fibertap-12D and Super-B. The most
The outer part is constructed by steel. The inductor is located off-center, close to strip entry side. It is located 1360 mm high from the pot bottom (z-direction) and 166 mm apart from side wall (x-direction) with an inclined angle of 60 degrees. The structure of Ajax channel inductor is separately shown in Fig. 1(b). Inductor is composed of iron core and two coils and insulated by Sudeca-90SC. By supplying electric current to the coil, magnetic flux ($B$) and the induced eddy current ($J$) were generated. The Lorentz force was obtained by using the relationship

$$F = B \times J$$

The alternating current is composed of real and imaginary parts for phase 0 and 90. The time-average Lorentz force was given by $F_{ave}=(F_0+F_{90})/2$. The average Lorentz force and the heat generated are shown in Fig. 2. The force and energy values in the picture have been obtained to suffice the pot temperature near 460°C by supplying 2000 amperes of current. Powerful Lorentz force vectors are directed from core to opposite direction. Heat is shown in the range of 165–1980 kW per unit volume. Thermo-physical properties of materials used to calculate the magnetic force are summarized in Table 1.

### 2.2. Fluid Flow Modeling

The flow was described by incompressible Navier–Stokes equations. It was assumed symmetrical with respect to the mid plane and one half of the pot was modeled. The moving wall boundary conditions were applied to the strip and rotating rolls. The $k$–$\varepsilon$ turbulence model was adopted for turbulent fluid motion. Solving energy equation, refractory and steel wall were included. The steady state equations for solving fluid and heat are summarized as follows.

$$\nabla \cdot \mathbf{u} = 0$$

(a) Lorentz force (N/m³), (b) generated heat (10⁵ W/m³) contours on cross-sectional plane of inductor and (c) diagram of cross-section of inductor.
\[
\rho u \cdot (\nabla u) = -\nabla p + \mu u + \mu_1 \nabla^2 u - \rho g \beta (T - T_{\text{ref}}) + F \cdots \cdots \cdots \text{(2)}
\]

where Boussinesq approximation term and magnetically driven Lorentz force of \( F \) are included.

\[
\rho u \cdot \nabla k = \nabla \left( \mu + \frac{\mu_1}{\sigma_k} \right) \nabla k + G_k - \rho \varepsilon + S_k \cdots \cdots \cdots \text{(3)}
\]

\[
\rho u \cdot \nabla \varepsilon = \nabla \left( \mu + \frac{\mu_1}{\sigma_\varepsilon} \right) \nabla \varepsilon + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho \varepsilon^2 \frac{\varepsilon}{k} + S_\varepsilon
\]

\[
(\mathbf{u} \cdot \nabla)(\rho C_p T) = \nabla \cdot (\lambda + \lambda_t \nabla T) + S_\theta \cdots \cdots \cdots \text{(5)}
\]

where \( G_k \) is the generation of turbulence kinetic energy due to the mean velocity gradients. \( S_k \), \( S_\varepsilon \) and \( S_\theta \) are added source terms of magnetically driven force or energy. Thermo-physical properties used to solve the above equations are summarized in Table 1.

### Table 1. Thermo-physical properties used in this calculation.5–8)

| Thermal conductivity (W/m·K) | Zinc | Copper | Steel | Sudeca-90SC | Fibertab-12D | Super-B |
|-------------------------------|------|--------|-------|-------------|-------------|--------|
|                               | 60   | 397    | 40    | 1.8356      | 0.1559      | 0.0711 |
| Resistivity (Ω·m)             | Zinc | Copper |       |             |             |        |
|                               | 5.45 \times 10^8 | 1.58 \times 10^8 |        |             |             |        |
| Heat capacity (J/kg·K)        | Zinc | Copper | Steel | Sudeca-90SC | Fibertab-12D | Super-B |
|                               | 512  | 386    | 750   | 1300        | 100         | 450    |
| Density (kg/m³)               | Zinc | Copper | Steel | Sudeca-90SC | Fibertab-12D | Super-B |
|                               | 6700 | 8960   | 750   | 2900        | 750         | 220    |

3. Results

Figure 3 shows the zinc flow vectors and temperature contours on the cross-section of channel when line speed is 3.0 m/s. The flow vectors show similar directions with electromagnetic force vectors seen in Fig. 2. It has been generally understood that zinc moves along lengthwise direction inside throat channels. Figure 3 shows inlet at middle channel, outlets at two side channels. Inside channel, vectors show directions pointing from core to opposite direction. Left half and right half vectors in the figure are not symmetrical, which may be explained by off-centeredness of inductor attachment to zinc pot wall. The largest vector magnitude is 540 cm/s and most vectors are greater than 200 cm/s. Temperature distribution is remarkably uniform in the range of 462.17–462.9°C, which is about one degree higher than the one inside the pot. Figure 4 shows fluid flow vectors on symmetry plane when line speed is 3 m/s and Fig. 5 shows fluid vectors when line speed is 1.5 m/s. The molten zinc is accelerated toward sink roll by the steel strip movement and it ascends passing the sink roll. The ascending flow turns the direction toward right side wall due to the blockage of the stabilizing roll. This flow impinges the wall, then separates into two flows of one upward and the other downward flow. Upward flow circulates counter clockwise and reaches the top surface where it encounters the reverse direction flow. It is in good agreement with Ouellet et al.’s results. Comparing Figs. 4 and 5, overall vector magnitudes are reduced by same rate as the line speed. The impingement angle shows a different direction. In Fig. 5 the impingement is more floated upward since the vectors are weak in case of line speed of 1.5 m/s. At top of the entry side strong flow goes downward until it reaches bottom and then makes ascending circulation in counterclockwise direction. But in Fig. 5, downward flow does not start at the top surface. Zinc flows from rear part of the pot (rear wall) toward the symmetry plane, hits center symmetry plane and diverted all directions. On top surfaces, exit

![Fig. 3. (a) Zinc flow vectors and (b) temperature contours on cross-sectional plane of inductor.](image-url)
side flows are much alike in both pictures but the entry side and inside strip region vectors show different streams. Inside the strip region, there is one circulation flow near entry strip and the flow along exit side is diverted toward left in the figure due to the blocking stabilizing roll. In Fig. 4, this vector moves to left till it joins the circulating flow near entry strip. In Fig. 5, there are two rotating flows in addition to a circulation flow near entry strip. Left diverted flow makes the counter-clockwise rotation and it meets in the middle with the clockwise rotational flow. This is a different result from Kim et al.’s,[9] who reported that the variation of strip speed did not produce discernible change in flow pattern. In the bottom section, there are no noticeable differences in both pictures. They show downward and circulating flows in each ends of symmetry plane and upward vectors in the rest of area. These upward flows move until they hit the stabilizing roll in the exit side and in entry side they encounter downward flows. Figures 6 and 7 show flow vectors on planes which include the outlet and inlet of inductor channels. In Figs. 6(a) and 7(a), outpoured zinc from induction channel makes big counterclockwise circulation ranging from top surface to bottom. In Figs. 6(b) and 7(b), counterclockwise rotating flows enter directly into induction channel of inlet.

In simulation, initial temperature of steel strip was given 460°C. Since the strip is very thin and thermal conductivity of steel is so high that it is assumed it reaches the same temperature with the surrounding molten zinc in a short time. Figure 8 shows temperature contours on symmetry, top and bottom planes in (a) and entry side wall, inductor attached rear wall and exit side wall planes in (b). The overall temperature distribution is quite uniform within 1.3 degrees. The highest temperature of 462.30°C is observed at the interface of inductor with pot at the rear wall and the lowest temperature of 461.0°C is observed at top corner of exit side wall. Since inductor is located off-centered toward left, left side of the pot (entry side) shows higher temperature than the right side (exit side) everywhere in the pot. Compared to line speed of 3 m/s, the temperature was lowered by 0.7 degrees in line speed of 1.5 m/s. Figure 9 confirms that temperatures on symmetry plane and inside induction have decreased. For refractory temperatures the most outer part of Sudeca-90SC, Supertab-12D and Super refractory are 410, 263 and 122°C and steel is 56°C. With same power of heat, decreasing the line speed lowers the zinc temperatures of inside of zinc pot, channel and inductor surface.

4. Conclusion

Numerical simulations were conducted to get magnetically driven Lorentz force and heat for channel inductor. Using these as source terms in momentum and heat equations, zinc fluid vectors and temperature distributions were obtained and the following statements have been reached.

(1) To get pot temperature around 460°C, 2000 amperes of current was applied and 165–1990 kW of heat density was obtained.

(2) Reducing the line speed resulted the same rate of zinc flow vectors to reduce. Line speed particularly affects the flow pattern inside the strip region.

(3) Temperature distribution was remarkably uniform over all area of zinc pot and reducing line speed from 3.0 m/s to 1.5 m/s resulted 0.7 degrees lower temperature.
With these results, we conclude that numerical simulation can be a good technique to determine circulation patterns of molten metal in zinc pot and can be further applied to hardware design of galvanizing line.

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Nomenclature

\[ \rho \] : Density of molten zinc

\[ p \] : Pressure

\[ g \] : Gravity

\[ \mu \] : Laminar viscosity

\[ \mu_t \] : Turbulent viscosity
\( \lambda \): Molecular thermal conductivity
\( \lambda_t \): Turbulent thermal conductivity
\( u \): Velocity
\( T_{\text{ref}} \): Melting temperature
\( C_p \): Specific heat
\( \beta \): Thermal expansion coefficient
\( \kappa \): Turbulent kinetic energy
\( \dot{\varepsilon} \): Rate of dissipation of turbulent energy
\( \sigma, \sigma_t \): Constants for \( k-\varepsilon \) turbulence model
\( C_1, C_2 \): Constants for \( k-\varepsilon \) turbulence model

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