Flow Field Analysis inside a Molten Zn Pot of the Continuous Hot-dip Galvanizing Process

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The flow field inside a molten zinc pot of the continuous hot-dip galvanizing process of steel strips was investigated experimentally. A 1/5-scale transparent water model with induction heaters, scrapers, and baffles was used in this study. Instantaneous velocity fields were measured using a single-frame PIV velocity field measurement technique with varying the strip velocity $V_S$, flow rate $Q$ of the induction heater, scraper location, and baffle type. The general flow pattern inside the strip region is hardly influenced by the strip speed $V_S$, flow rate $Q$, and the scraper location around the stabilizing roll. When the induction heater is not operated, a pair of vortices is formed in the inner part of the strip: a clockwise rotating flow at the entrance region and a counter-clockwise rotating flow at the exit region.

In the exit region outside of the strip, the flow detached from the stabilizing roll divides into two parts: a counter-clockwise rotating flow in the upper region and a clockwise rotating flow in the lower region. For the cases of no scraper and scrapper, detached from the stabilizing roll, the flow separates from the moving strip and ascends to the free surface. As the flow rate of the induction heater increases, the ascending flow is weakened and the counter-clockwise rotating flow in the upper area of the outside region becomes tranquil. This indicates that the flow in the upper area of the exit region is greatly influenced by the operation of the induction heater. When a scraper is attached onto the stabilizing roll, the separated flow from the strip is guided downward and the up-rising flow around the stabilizing roll becomes slow and tranquil. By attaching baffles near the moving strip in addition to the stabilizing rolls, the flow entrainment into the corner region between the strip and the stabilizing roll is greatly reduced. These flow control devices should be helpful in reducing top drosses in the zinc plating process.

KEY WORDS: Zn pot; dross; PIV; velocity field; flow control; galvanizing process.

1. Introduction

Many heavy industries such as the automobile and home appliance industries demand high quality zinc-plated steel strips with excellent corrosion resistance. In the continuous hot-dip galvanizing process a steel strip rotating around a sink roll embedded inside a molten Zn pot is galvanized with zinc. However, drosses form during this process due to metallic compounds and the chemical reactions that occur while the long steel strip passes continuously through the molten Zn pot. The suspending dross particles attach to the strip surface, degrading the quality of the zinc-plated steel plates. The metallic compound drosses suspended in the Zn pot are formed by chemical reactions between Fe erupted from the steel and Al or Zn components. These drosses are divided into a top dross of Fe–Al fractions and a bottom dross of Fe–Zn fractions. The densities of FeZn7, Fe2Al5 and molten Zn are about 7 300 kg/m3, 4 200 kg/m3 and 6 700 kg/m3, respectively. Therefore, the high density of FeZn7 causes it to be the main component of the bottom drosses of the molten Zn pot, whereas the low-density Fe2Al5 is suspended in the upper region of the molten Zn pot. The diameter of metallic compound dross ranges from several micrometers to several tens of micrometers. The drosses, especially the top drosses floating along the internal molten Zn flow, attach on the steel strip. The attachment of drosses causes coating defects on the strip surface and sometimes leaves scratches on the zinc-plated strip. To improve the quality of galvanized iron up to the level of cold rolling steel plate, the dross problems encountered in the current galvanizing process must be solved. Addressing the problem of dross in the galvanizing process requires detailed information on the flow structure inside the Zn pot and the development of effective flow control techniques.

Several studies on the flow inside the molten pot have been carried out to resolve this problem. However, most previous studies on the zinc-plating process have been qualitative analyses such as flow visualization of a simple water model. Some investigations have focused on flow around the sink roll.

Kurobe et al. visualized the dross movement and measured the flow characteristics inside a Zn pot model using a Laser Doppler Velocimetry (LDV) system. Yakawa et al. studied the effect on dross formation of a Z-shaped baffle located on the bottom of a zinc pot model. Nakamura et al. analyzed the relationship between dross production and
the speed of strip movement. Recently, Shin et al.\textsuperscript{4}) used the Particle Image Velocimetry (PIV) velocity field measurement technique in an experimental investigation of the flow fields inside a snout installed in the region where the steel strip enters the zinc pot. In recent times the PIV and Particle Tracking Velocimetry (PTV) techniques have been widely used as reliable velocity field measurement methods.\textsuperscript{5–7})

In the present study a transparent water model of the hot-dip galvanizing process was constructed to investigate the flow structure inside the Zn pot. The instantaneous velocity fields of the flow inside the model Zn pot were measured using the double-exposed single-frame PIV system. The effect on the flow of various parameters was considered, including the flow rate of the induction heaters, scraper location and baffle configuration. To analyze the flow structure with good spatial resolution, a high-resolution CCD camera (2 K×2 K pixels\textsuperscript{2}) was employed as an image-recording device.

The main objectives of this study were to understand the flow characteristics inside the Zn pot and to control the flow around the stabilizing roll effectively. A better understanding of the flow structure in this system should facilitate the control of the dross problem encountered in the zinc-plating process.

2. Experimental Apparatus and Methods

2.1. Water Model and Flow Visualization

Figure 1 shows a schematic diagram of the water model, which consists of a rotating sink roll, an endless moving strip made of rubber band, a pair of induction heaters, stabilizing rolls, a snout and scrapers. In this water simulation study, the geometric similarity and kinematic similarity were considered. The water model was made into 1/5-scale of the prototype hot-dip galvanizing plant and the bottom surface of the model Zn pot was curved to maintain geometric similarity. The experimental conditions such as the strip speed $V_s$ and the flow rate ($Q$) of induction heater were selected to the same as the real operation conditions. In order to make dynamic similarity, we tried to find a proper transparent liquid having the corresponding kinematic viscosity to match the Reynolds number, however, we could not find any good one. As the best alternative, we used tap water as working fluid to simulate the molten zinc as other researchers did.

The model Zn pot has dimensions 94 cm long×46 cm high×67 cm wide. The diameter of the rotating sink roll located at lower part of the Zn pot model is 16 cm. The endless rubber band passing the rotating sink roll passes between the stabilizing rolls. The strip was driven by a DC motor, and its moving speed was controlled by adjusting the voltage output of the DC power supply. Three strip speeds were tested in this study: $V_s=1.5$, 2.0 and 2.5 m/s. Two induction heaters were installed near the end of the snout, one on each side of the Zn pot. The induction heaters driven by outside pumps re-circulated some of the working fluid in the Zn pot. The flow rate of the induction heater ($Q$) was measured with a precision rotameter. Flow visualization experiments and PIV velocity field measurements were carried out in the central plane. Scrapers connected to a hinge could be attached, separated or removed from the stabilizing roll. The working fluid was distilled water.

White light from a 150 W halogen lamp provided a cold light sheet of thickness approximately 5 mm after passing through a fiber-optical cable, thermal adiabatic filter and a cylindrical lens. Because it was impossible to illuminate both sides of the opaque rubber strip with a single light source, three illuminators were installed that allowed simultaneous illumination of the strip from above and from each side of the Zn pot. To visualize the flow, neutral buoyant polyvinyl chloride particles of diameter 300 μm were seeded as scattering particles. Flow images were photographed with a film camera. The strip speed was fixed at $V_s=2.0$ m/s throughout the flow visualization experiments.

2.2. Particle Image Velocimetry (PIV)

The PIV velocity field measurement system was used to analyze the flow inside the Zn pot. The PIV system consisted of a high-resolution CCD camera, a 2-head Nd:YAG laser, an image grabber, a synchronizing device and a computer, as shown in Fig. 2. A high-resolution CCD camera (SMD 4M4) with a resolution of 2 K×2 K pixels\textsuperscript{2}) was used to capture particle images. The Nd:YAG laser has two heads and its maximum energy is larger than 25 mJ per pulse. The CCD camera and the Nd:YAG laser were syn-
chronized using a custom-built control circuit.

The CCD camera used in this study has a special built-in image-shifting feature that is ideal for resolving the directional ambiguity encountered in the conventional single-frame PIV technique. During the time interval $\Delta t$ between two laser pulses, the whole pixel lines of the CCD sensor array are moved a fixed number of lines before superimposing the second particle image on the first exposure of the CCD camera.

In the experiments reported here, the second image was shifted by 9 pixels and the time interval between the two laser pulses was set to $\Delta t=1$ ms. A pair of particle images is superimposed on a single-frame of the CCD camera and this double-exposed single-frame image is then cross-correlated to extract the instantaneous velocity vector field. In this study, the interrogation window size was $64 \times 64$ pixels and overlapped 50%. The second interrogation window was shifted 9 pixels when calculating the cross-correlation function for each interrogation window. The single-frame double-exposure PIV velocity field measurement technique used in this study is described in detail elsewhere.4) Vestosint 1111 particles of diameter $100 \mu m$ were seeded as tracer particles for visualizing the liquid flow in the Zn pot. The central plane of the flow inside the Zn pot was illuminated with a thin laser light sheet. The laser light sheet was formed by passing the pulsed laser light emitted from the 2-head Nd:YAG laser through mirrors, cylindrical and spherical lenses. The high-resolution CCD camera was installed perpendicular to the laser light sheet to capture the scattered particle images.

With varying the strip velocity $V_S$, the flow rate of induction heater $Q$, scraper location, and baffle type, the instantaneous velocity fields were measured at 14 sub-sections in the center plane of the scaled-down model of the molten Zn pot, as shown in Fig. 3. The field of view of each measurement section was $150 \times 150$ mm. Figure 4 shows a typical velocity field in 4 sub-sections at the exit region under the conditions $V_S=2.0$ m/s and $Q=6.67 \times 10^{-4}$ m$^3$/s.

Because the surface of the galvanized steel strips is mainly affected by top drosses, the detailed flow structure around the stabilizing roll located at the exit region is very important to the development of effective flow control techniques for reducing top drosses. One way to reduce the attachment of top dross onto the moving steel strips is to reduce the flow motion toward the strip and to decrease the flow speed around the stabilizing roll. We therefore focused on the flow around the stabilizing roll to resolve the top dross problem. PIV velocity field data for two sections (Section 1 and Section 12) that contain stabilizing rolls were mainly analyzed in this paper.

3. Results and Discussion

3.1. Flow Visualization

Flow visualization experiments were carried out to establish the qualitative flow structure in the entire Zn pot. The flow inside the Zn pot can be divided into two parts based on the moving strip: the outside region and the inside region (see Fig. 5). The moving speed of the strip was fixed at $V_S=2.0$ m/s and scrapers were attached onto the stabilizing rolls. A typical visualization result is shown in Fig. 6.

In the outside region the flow accelerates in the entrance region as the strip moves toward the sink roll. As the flow
passes the sink roll it ascends toward the exit region along the moving strip. The flow moving upward along the strip separates from the strip due to the blockage effect of the stabilizing roll. When the induction heater is not operated (Fig. 6(a)), the flow separated from the strip divides into two parts in the exit region, one part is a counter-clockwise rotating flow in the upper region and the other part is a clockwise-rotating flow in the lower region of the Zn pot. The counter-clockwise rotating flow in the exit region of the Zn pot may move with top drosses toward the moving strip. Therefore, this flow phenomena can increase the possibility of attachment of top drosses onto the strip surface.

When the induction heater is operated at a flow rate of $Q = 6.67 \times 10^{-4} \text{m}^3/\text{s}$ (Fig. 6(b)), the flow acceleration in the entrance region is enhanced and the clockwise rotating flow in the lower part of the exit region becomes strong. This enhancement seems to be due to the addition of momentum from the induction heater in the entrance region. The counter-clockwise rotating flow in the upper area of the exit region is weakened by the operation of the induction heater. This implies that the flow in the upper area of the exit region is influenced significantly by the flow rate of the induction heater.

In the inside region of the strip, the flow pattern consists of a clockwise rotating flow in the entrance region and a counter-clockwise rotating flow in the lower region near the sink roll. The general flow pattern in the inside region is almost unchanged by the operation of the induction heater.

3.2. Velocity Field Measurements

3.2.1. Effect of Strip Speed ($V_s$)

Instantaneous velocity fields were measured around the stabilizing roll at various values of the moving speed of the strip. The values of $V_s$ were selected to match up the real operation conditions at the hot-dip galvanizing plant of POSCO Kwang Yang works. The moving strip velocity $V_s = 2.0 \text{m/s}$ corresponds to the actual operating condition and the strip velocity $V_s = 2.5 \text{m/s}$ was selected to check the effect of increasing strip speed on the molten Zn flow. The total field of view of the two adjacent sections was $30 \times 15 \text{cm}^2$ and the flow rate of the induction heater was fixed at $Q = 6.67 \times 10^{-4} \text{m}^3/\text{s}$. The right side of Fig. 7 shows the instantaneous velocity fields in Sec. 1 around the stabilizing roll at strip speeds of 1.5, 2.0 and 2.5 m/s. When the strip speed is 1.5 m/s (Fig. 7(a)), the ascending flow following the moving strip is blocked by the stabilizing roll and separated from the strip. The separated flow is guided by the scraper attached to the stabilizing roll and moves diagonally downward to the lower region of the Zn pot. In the upper region around the stabilizing roll, the flow is nearly tranquil.

On increasing the strip speed (Figs. 7(b), 7(c)), the separation of the ascending flow from the strip occurs at a lower location in the upper region of the stabilizing roll. The speed of flow guided by the scraper is much faster than the strip speed $V_s$. The high-speed flow moving downward entrains the fluid of the upper region and the angle of downward flow becomes steep.
The left side of Fig. 7 shows the instantaneous velocity fields around the stabilizing roll in Section 12 at the three different strip speeds. At a strip speed of $V_S = 1.5 \text{ m/s}$ the ascending flow rises along the strip and separates from the strip before moving diagonally downward. Some of the separated flow rises to the entry region, but most of the flow forms a counter-clockwise rotating flow on the left side of the strip. The flow around the stabilizing roll is very slow and tranquil. Increasing the strip speed causes the speed of the ascending flow to increase and the counter-clockwise rotating flow formed below the stabilizing roll becomes strong. For the case of $V_S = 2.5 \text{ m/s}$, the speed of the flow rising to the entry region also increases and the flow around the stabilizing roll becomes active.

3.2.2. Effect of Induction Heater Flow Rate

Figure 8 shows the instantaneous velocity fields around the stabilizing roll for the three flow rates of the induction heater. The maximum flow rate of induction heater ($Q = 6.67 \times 10^{-4} \text{ m}^3/\text{s}$) tested in this experiment corresponds to the case of full operation (100%) at normal operation condition. The moving speed of the strip was fixed at $V_S = 2.0 \text{ m/s}$. When the induction heater is not operated (Fig. 8(a)), the ascending flow along the strip separates from the strip and descends quickly at a steep angle of decline. The flow speed in the upper part of the outside region is relatively high.

When the induction heater is operated (Figs. 8(b), 8(c)) the flow in the upper outside region becomes weak. This indicates that the operation of induction heater can reduce the top drosses around the stabilizing roll. However, the flow below the stabilizing roll in the inside region of the strip becomes strong due to the addition of momentum from the induction heater.

3.2.3. Effect of Scraper Location

Figure 9 shows the instantaneous velocity fields around the stabilizing roll for different arrangements of the scraper under the conditions $V_S = 2.0 \text{ m/s}$ and $Q = 6.67 \times 10^{-4} \text{ m}^3/\text{s}$.

By attaching scrapers to the stabilizing rolls (Fig. 9(a)), the flow separated from the strips is well guided by the scraper and moves diagonally downward at the speed of about 1.5 m/s. This enhances the flows below the stabilizing rolls in the inside and outside regions. However, the flow around the stabilizing rolls is slow and tranquil, except in the corner region between the strip and scraper.

When the scraper is removed from the stabilizing roll (Fig. 9(c)), the flow ascends toward the upper region of the
Zn pot along the stabilizing roll in the outside region. The flow around the stabilizing roll is therefore much faster than that in the system with the scraper attached to the stabilizing roll. In the inside region of the strip, the counter-clockwise vortical flow below the stabilizing roll becomes strong and the speed of the ascending flow along the left stabilizing roll is also greatly increased.

When the scraper is detached from the stabilizing roll to a distance of about the roll diameter, the general flow structure of the outside region is similar to that for the system with no scraper. One difference is the relatively high speed of the flow through the gap between the roll and scraper. In the inside strip region, the detached scraper causes rapid flow motion around the stabilizing roll, less effective than the attached scraper. To decrease the flow speed around the stabilizing roll, the scraper should be closely attached to the stabilizing roll.

### 3.2.4. Effect of Baffle Type

**Figure 10** shows the configuration of two baffle systems (A and B) for controlling the flow around the stabilizing roll. The A-type baffle consists of two baffles of the same shape located below the stabilizing rolls at an angle of 50°. The B-type baffle uses a left baffle about 3 times larger than that in the A-type, while the right baffle is the same as used in the A-type. The left baffle is installed at an angle of 70° to horizontal plane perpendicular to the strip and the height of the baffle tip is equal to the A-type case. **Figure 11** shows the effect of the A-type baffle on the flow field around the stabilizing roll under the conditions \( V_S = 2.0 \text{ m/s} \), \( Q = 6.67 \times 10^{-4} \text{ m}^3/\text{s} \). The flow structure in the outer region of the strip is very similar to that observed for the A-type baffle. In the inside region of the strip most of the ascending flow along the strip separates from the strip and rises diagonally. The flow rising diagonally along the baffle is blocked by the scraper attached to the stabilizing roll, and the flow thereafter descends along the scraper. This flow structure greatly decreases the flow around the stabilizing roll.

Comparing the flow fields for the two baffle types, the B-type baffle seems to give a better (more tranquil) flow around the stabilizing roll. However, in this case counterclockwise vortices form below the long baffle installed in the inside region of the strip.

From these results, we can conclude that the flow around the stabilizing roll becomes tranquil when the induction heater is operated and the scraper and baffle are attached to the stabilizing roll. Taking these findings into consideration in the implementation of the continuous hot-dip galvanizing process will help to reduce the top-dross attachment onto the steel strips in the Zn pot.

### 4. Conclusions

The continuous hot-dip galvanizing process of steel strips was modeled using a 1/5-scale model with water as the working fluid in place of the molten zinc. The flow fields inside the molten zinc pot model, especially around the stabilizing rolls, were investigated experimentally. The instantaneous velocity fields inside the molten zinc pot model were measured using the single-frame double-exposure PIV with varying the strip speed, the flow rate of induction heater, scraper and baffle arrangement. The results are summarized as follows:

1. As the moving speed of the strip increases, the counter rotating flow in the inside region of the strip becomes strong and the flow ascending along the strip is blocked by the scraper and separation from the strip occurs.
at a lower location.

(2) The upper outside area of the exit region is greatly influenced by the operation of the induction heater. When the induction heater is operated, the flow in the upper outside area becomes weak.

(3) When the scraper is removed from the stabilizing roll the ascending flow along the stabilizing roll in the outside region becomes strong. Attaching the scraper onto the roll causes the flow around the stabilizing roll to become slow and tranquil.

(4) Attaching baffles near the moving strip causes the flow in the corner region between the strip and the stabilizing roll to move smoothly outward, and the speed of the flow around the stabilizing rolls is greatly decreased.

(5) The flow around the stabilizing roll is made tranquil by attaching scrapers onto the roll, placing baffles near the strip and operating the induction heater. Knowledge of these factors will be helpful in reducing top dross attachment in the continuous hot-dip galvanizing process.

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