1. Introduction

In continuous hot-dip galvanizing process, a series of steel strip continuously passes through the molten zinc (Zn) pot of 460°C, and drosses are formed due to metallic compounds and chemical reaction. These drosses attach to the strip surface, degrading the quality of Zn-plated steel sheets.

In order to suppress the dross attachment on the steel strip, a snout device is commonly employed at the entrance region of moving strip into the Zn pot as shown in Fig. 1. However, evaporated Zn particles in the snout cause ash imperfection on the galvanized steel strip surface. In order to resolve this problem, the flow field inside the snout, both on the deoxidization gas flow above the free surface and the molten Zn flow in the Zn pot, has been investigated experientially. For a 1/10 scale water model, flow visualization and PIV (Particle Image Velocimetry) velocity field measurements were carried out at the strip speed \( V_S = 1.5 \, \text{m/s} \). Aluminum flakes (1 \( \mu \text{m} \)) and atomized olive oil (3 \( \mu \text{m} \)) were used as seeding particles to simulate the molten Zn flow and the deoxidization gas flow, respectively.

As a result, the liquid flow in the Zn pot is dominantly influenced by the up-rising flow in diagonal direction caused by the rotating sink roll. For gas flow in front of the strip inside the snout, the large-scale vortex formed by the downward moving strip is dominant. In the rear side of the strip, a counter-clockwise vortex is formed and some of the flow following by the moving strip impinges on the free surface of molten Zn. The liquid flow in front of the strip is governed by the up-rising flow entering the snout, caused by the rotating sink roll. The moving strip affects dominantly the liquid flow behind the strip inside the snout, and large amounts of liquid are entrained and followed the moving strip toward the sink roll. A thin boundary layer is formed on the front side due to the up-rising flow, however, a relatively thick boundary layer is formed in the rear side of the strip. Inside the snout, the deoxidization gas flow above the free surface is much faster than the liquid flow in the Zn pot. More ash imperfections are anticipated on the rear surface of the strip where larger influx flow moves toward the strip in the region near the free surface.

KEY WORDS: snout; single-frame PIV; continuous hot-dip galvanizing; velocity field; steel strip.
effect of a Z-shaped baffle located on the bottom surface on the suppression of dross formation in the Zn pot. Nakamura et al. analyzed the relationship between the quantity of drosses produced and the feeding speed of the steel strip. As far as we recognize, there was no published literature that studied the flow inside the snout.

The whole velocity field of flow inside the snout, is not easy to measure with the conventional point-wise velocity measurement techniques such as a LDV or a hot-wire anemometry. And flow visualization experiments can not give quantitative flow information, but also give qualitative results.

Due to rapid advance of computers, and digital image processing techniques, instantaneous velocity field can be extracted by specially implemented technique such as PIV (Particle Image Velocimetry) method. Recently the PIV system has been accepted in fluid mechanics field as a reliable velocity field measurement technique. In this study, a water model of the continuous hot-dip galvanizing process including the snout was made to investigate the flow inside the snout. The instantaneous velocity fields of flow inside the snout were measured using the double-exposed single-frame PIV system. In order to analyze the flow structure with high spatial resolution, a high-resolution CCD camera of 2K×2K pixels resolution was employed as a image recording device.

The main objective of this study is to understand the basic flow characteristics inside the snout of the continuous hot-dip galvanizing process. With a better understanding of the flow structure, the ash problem of continuous hot-dip galvanizing process may be resolved successfully.

2. Experimental Apparatus and Methods

2.1. Water Model

Figure 2 shows the schematic diagram of water model consisting of a rotating sink roll, an endless moving strip made of rubber band, DC motor, and a snout device. It is a 1/10 scale-down model of a continuous hot-dip galvanizing plant of POSCO KwangYang works. The snout was installed at the entrance region of the moving strip into the molten Zn pot. The inclination angle of the snout with the horizontal free surface was 56.4°. The snout was immersed 35.2 mm into the Zn surface and the bottom surface of Zn pot was curved with the radius of curvature of about 350 mm to maintain geometric similarity.

Flow visualization and velocity field measurement were carried out on the central plane, and working fluid for the molten Zn and the deoxidization gas were chosen as water, and smoke respectively.
2.2. Flow Visualization

Figure 4 shows the experimental set-up for flow visualization. White light from a 150 W halogen lamp provides the cold light sheet of approximately 5 mm thickness 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 strip with a single light source, two lighting systems of the same type were used simultaneously as shown in Fig. 4. To visualize the flow, neutral buoyant polyvinyl chloride particles were used as scattering particles. Visualization flow images were photographed with a Nikon F5 camera, at f = 4.0 and a shutter speed of 1/50 s. The strip speed \( V_s \) was fixed to be \( V_s = 1.5 \) m/s throughout the experiments.

2.3. Particle Image Velocimetry (PIV)

The PIV velocity field measurement system was used to analyze the flow inside the snout. The PIV system was 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. 5.

A high-resolution CCD camera (SMD 4M4) with a resolution of 2K×2K pixels was used to capture particle images. The air-cooled CCD camera having output signal of 12 bits at 100% fill factor can capture 4 images per second. The Nd:Yag laser has two heads specially developed for PIV measurement. The maximum energy is larger than 25 mJ per pulse. The CCD camera and the Nd:Yag laser were synchronized using a home-made control circuit. The signal diagram for synchronizing the Nd:Yag laser with the high-resolution CCD camera is shown in Fig. 6, where \( \Delta t \) is the time interval between two laser pulses.

For PIV velocity field measurement, two successive particle images can be recorded either on two individual frames or on a single frame. The single-frame recording method with double-exposure of laser pulses is superior for the experiment of high-speed flows because it works well even at small time interval \( \Delta t \). The single-frame PIV method encounters inherently the directional ambiguity in determining velocity vectors. The directional ambiguity has been solved by shifting the second image with a rotating mirror, which require elaborate efforts to adjust the mirror and time sequence. 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 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 translated a few lines forward or downward. Therefore, the second particle image is shifted a little distance corresponding the translated pixel lines. Depending on experimental conditions, the second image can be shifted in the range from 1 to 509 pixel lines in increments of 4 pixels.

2.4. Experimental Methods

The basic principle of PIV technique is to capture a double-exposed particle image using a CCD camera and determine the particle displacement vectors during the time interval \( \Delta t \) by calculating cross-correlation coefficients of the double-exposed flow image at each interrogation window. The displacement vectors are then divided by the time interval \( \Delta t \) to give an instantaneous velocity field.

To obtain well-contrasted particle images, aluminum flakes of about 1 \( \mu m \) in diameter and atomized olive oil particles of 1–3 \( \mu m \) in diameter were used as seeding particles for the liquid flow in the Zn pot and gas flow above the free
surface. The central plane of the flow inside the snout was illuminated with a pulsed laser light sheet. The thin laser light sheet was formed by passing the pulsed laser light emitted from the 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 image of the flow field.

As shown in Fig. 6, during the first exposure of the CCD camera, the particle image scattered by the first laser pulse is recorded on the CCD cell. The CCD sensor array then undergoes translation by prescribed pixel lines within the time interval $\Delta t$ and starts the second exposure to capture the second image. Therefore, the whole second image is shifted several pixel lines by translating CCD sensor array. In this experiment, the second image was shifted by 9 pixels, and the time interval between the two laser pulses was $\Delta t = 200 - 2000 \mu s$. The two images are superimposed on a single-frame of the CCD camera and this double-exposed single-frame image is then cross-correlated to extract instantaneous velocity field.

The single-frame cross-correlation PIV technique is schematically illustrated in Fig. 7. Two interrogation windows are selected such that the distance between two windows is equal to the shifted pixel distance of the second image. The particle images of the two selected interrogation windows are then cross-correlated, giving three correlation peaks. The smallest peak is discarded, and the displacement vector representing the interrogation window is determined from the other two peaks. In this study, the interrogation window size was 64×64 pixels and overlapped in 50%.

3. Results and Discussions

3.1. Flow Visualization

Flow visualization experiment was carried out to see the qualitative flow characteristics near the snout. The moving speed of the strip was fixed at $V_s = 1.5 \text{ m/s}$ and a typical visualization result and schematic with vector arrows of this flow are shown in Fig. 8.

In this figure, a high-speed up-rising flow is induced on the left side of the strip due to the rotating sink roll. Some of this up-rising flow penetrates into the snout, and the other fraction continues to rise vertically up to the free surface and divided into two streams having opposite flow directions (see region A). The flow stream moving to the right forms a clockwise vortex in front of the snout. In the front region of the strip, which moves down diagonally, the up-rising flow parallel to the strip was dominant. Only a thin viscous layer just near the strip surface moves downward following the moving strip.

In the rear side of the snout, the effect of the rotating sink roll is considerably weak, compared to that in front of the snout. At the bottom end of the snout (see region B), relatively large amounts of ambient fluid are entrained by the high-speed moving strip.

3.2. Velocity Field Measurements

For accurate PIV measurements, the test section was divided into 4 quadrants based on the moving strip and the free surface between the liquid and gas flow as shown in Fig. 3. Instantaneous velocity fields of flow in each quadrant were measured using the single-frame PIV technique.

3.2.1. Gas Flow inside the Snout

The instantaneous velocity field and vorticity distribution of the deoxidization gas flow in the 2nd quadrant are represented in Fig. 9. The instantaneous vorticity is resolved in sixteen gray levels between the maximum and minimum vorticity. The white region represents the counter-clockwise positive vorticity, and the dark region indicates the clockwise rotating negative vorticity. The gas flow moves downward along the strip and impinges upon the free surface of molten Zn. After that, the flow direction is turned toward region B of the snout wall. And a large clockwise rotating
vortex is formed in the region bounded with the free surface, the snout wall and the moving strip. As shown in Fig. 9, the large vortex hits and contacts the inner wall of the snout at region B. A secondary counter-clockwise vortex of smaller size is formed in the lower left corner between the large vortex and free surface. From this, we can conjecture that the Zn vapor evaporated from the molten Zn may be entrained into the large clockwise vortex and rise from region A to region B. Most of the Zn particles adhere onto the inner wall region B. And Zn particles of smaller size move upward to the middle part of the snout, some of them are entrained into the clockwise vortex and fall onto the moving strip in region C, and the others continue to rise and attach on the upper part of the snout wall.

The ash particles attached on the snout wall are accumulated with time and finally fall onto the free surface or onto the moving strip when they are grown sufficiently large. These Zn ash particles settled on the strip may cause defects on the galvanized steel sheet. The ash particles fell on the free surface are affected by the flow motion near the free surface. Most of them may be collected on the lower left corner where the flow velocity is comparatively lower than the other regions. The large clockwise vortex induced by the moving strip play a dominant role in the gas flow of the 2nd quadrant inside the snout.

**Figure 10** shows the velocity field of gas flow in the 1st quadrant located behind the strip moving at $V_s = 1.5$ m/s. The simulated deoxidization gas flow moves downward along the strip in the region near the strip. The gas flow following the moving strip is divided into two directions as it approaches to the free surface; one directly hits the free surface, and the other forms a counter-clockwise vortex in the region A and moves toward the rear wall of the snout. The shear layer thickness of flow following the moving strip is increased as the flow approaches to the free surface. The gas flow forms another large counter-clockwise vortex in the middle region C of 1st quadrant. These vortices formed at the regions A and C are positioned much closer to the rear snout wall, compared to the moving strip. These two vortices also deviate the smooth flow along the strip, causing a wavy flow structure in region E under the strip between region B and D.

From these results, it can be said that the Zn vapor evaporated from molten Zn moves with the gas flow and accumulates on the snout wall. When the attached ashes become larger than a critical mass, some of them may roll down along the snout wall and the other lighter particles are entrained into the vortex flow and fall on the free surface. Light Zn vapor particles rise up to the upper part of the snout, and some of them are entrained into the flow following the moving strip at region D. On the free surface, the Zn ashes move from right to left along the liquid surface toward the rear surface of the strip. Therefore, the ash particles floating on the molten Zn surface cause flaws on the galvanized steel sheet. This flow information, especially near the free surface may be useful for improving defects caused by Zn ashes in the continuous hot-dip galvanizing process.

### 3.2.2. Liquid Flow inside the Snout

The molten Zn flow fields under the free surface inside the snout are represented in **Figs. 11 and 12**. Figure 11
shows the velocity field in the central plane of the 3rd quadrant in front of the moving strip. The general flow pattern is quite different from that of the 2nd quadrant. This basically results from the difference of shear driving force acting on the flow. The strip movement works as a major source of momentum in the 2nd quadrant, but the rotating sink roll is more dominant on the flow field in the 3rd quadrant. The up-rising flow into the snout is mainly concentrated in the center region between the strip and the snout wall. This up-rising flow is divided into two streams at near the free surface, one moves to the snout wall and forms a small counter-clockwise vortex and the other moves toward the moving strip. Near the free surface, we can see downward flow motion in both corners near the strip, but the effect of influx caused by the rotating sink roll is still appeared at the center region.

Figure 12 shows the instantaneous velocity field in the central plane of the 4th quadrant. In the region, large amount of molten zinc is came out from the snout following the moving strip, causing the ambient fluid to penetrate into the snout in order to fill the empty space (to satisfy the continuity equation). At bottom end of the rear snout wall, the ambient fluid blocked by the rear snout is entrained at relatively high speed into the snout region. This entrained liquid turns around the bottom tip (region A) and rises into the snout. The flow then moves toward the moving strip until it is divided into two streams, one continues to go upward and the other moves downward along the strip in region B. The vertically rising flow contacts with the moving strip in region C, at which it changes suddenly the flow direction and moves downward along the strip. Only small fraction of the up-rising flow rises up to the free surface. With going downstream along the strip, the thickness of the flow following the strip is increased gradually. In the vicinity of the moving strip, the flow moves at high speed, compared to the remaining areas of the quadrant. Especially, near the rear snout wall, the flow is nearly tranquil. The flow on the free surface moves toward the strip, indicating that the Zn vapor particles would be gathered in the left corner bounded by the strip and the free surface. Such a flow motion would cause imperfections on rear surface of the strip. The downward flow along the strip and flow entrainment from the rear side of the snout are main flow phenomena for the 4th quadrant.

3.2.3. Velocity Field at Free Surface

The velocity information in the vicinity of the free surface inside the snout is very important for resolving the ash imperfection problem, because the vaporized Zn moves upward and Zn ashes fall on the free surface. The instantaneous velocity fields of the deoxidization gas flow and molten Zn flow are shown in Fig. 13. From this figure, it can be seen that the deoxidization gas flow is much faster than that of the molten Zn flow. In the gas flow region, the vortices formed in the front and rear side of the moving strip are clockwise and counter-clockwise, respectively. In
the liquid flow region, the vortices formed in front side of the strip is rotating counter-clockwise and the up-rising flow occupies the mid-section of the snout. The surface velocity of liquid flow was averaged to be less than 0.1 m/s, much smaller than the gas velocity above the free surface. The gas flow behind the strip moves downward along the strip and hits the free surface of the molten Zn. After impinging to the free surface of the molten Zn, the gas flow in the central plane diverges toward the side surfaces of the snout. For the liquid Zn flow behind the strip, the influx flow toward the strip is dominant near the free surface. However, the gas and liquid flows near the front surface of the moving strip move away from the strip as shown in Fig. 13. Therefore, if Zn ashes are distributed uniformly on the free surface inside the snout, more imperfection can be anticipated on the rear surface than the front surface of the strip.

4. Conclusions

For the continuous hot-dip galvanizing process of steel strips, the flow characteristics of the molten Zn and deoxidization gas flow inside the snout have been investigated experimentally. The instantaneous velocity fields of flow inside the snout were measured using the single-frame PIV technique at the strip speed of \( V_S = 1.5 \) m/s. The results are summarized as follows:

1) The flow inside the Zn pot is mainly induced by the rotating sink roll and the moving strip, the up-rising flow effect on the strip is decreased largely by installing a snout at the free surface. Inside the snout the speed of deoxidization gas flow above the free surface is much faster than that of the molten Zn flow.

2) Inside the snout, the deoxidization gas flow in front of the strip is governed by a large clockwise vortex formed by the moving strip. However, a counter-clockwise vortex is formed behind the strip and some of the influx flow following the moving strip hits the free surface of molten Zn at high speed.

3) The dominant flow behavior of molten Zn in front of the strip is the up-rising flow caused by the rotating sink roll. The influx flow following the downward moving strip is very thin thickness, and causes large velocity gradient by interacting with the up-rising flow.

4) The moving strip is the most dominant factor affecting the gas and liquid flows behind the strip in the snout, the flow near the strip moves downward along the strip. The thickness of the influx flow following the strip is much thicker than that in front of the strip and increases gradually as the flow goes downstream.

5) At the free surface, the efflux flow away from the strip is dominant for the gas and liquid flows in the front region of the strip. However, for the region behind the strip, the influx flow toward the strip is dominant near the free surface. Therefore, more imperfection can be anticipated on the rear side of the strip.

Acknowledgements

The authors wish to acknowledge the POSCO (Mr. H. Y. Kim and Mr. J. H. Chung) for the financial support on this work.

REFERENCES

1) J. Kurobe, N. Matsubara and G. Iguchi: CAMP-ISIJ, 9 (1996), 1080.
2) A. Yakawa, S. Yamanaka, K. Kurida, H. Kondo, I. Ishihara and K. Hashimoto: CAMP-ISIJ, 9 (1996), 1084.
3) T. Nakamura, T. Shibuya, K. Kokuji and M. Urai: CAMP-ISIJ, 9 (1996), 1076.
4) R. J. Adrian: Annual Review Fluid Mechanics, 23 (1991), 1202.
5) D. C. Bjorkquist and L. M. Fingerson: Progress in Visualization, 1 (1992), 313.
6) R. D. Keane and R. J. Adrian: Meas. Sci. Technol., 1 (1990), 1202.
7) Th. Dracos: 3D Velocity-Vorticity Measuring and Image Analysis Techniques, Kluwer Academic Publishers, Dordrecht, (1996).
8) L. M. Lourenco and A. Korthapalli: Experimental in Fluids, 18 (1995), 421.