Influence of Injection Distance on Water Droplet Behavior in High Pressure Descaling

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Hydraulic descaling is used in hot rolling mills in order to remove scale and prevent surface defects. Because the impact pressure of the descaling jet is one important factor from the viewpoint of mechanical breaking and applying thermal shock to scale layers, the water jet structure and the droplet velocity should have large effects on scale breaking properties. However, the influence of the injection distance on the jet structure and the droplet velocity has not been clearly understood. In this work, the behavior of changes in the descaling jet structure and attenuation of the water droplet velocity along the injection distance were investigated experimentally. High pressure descaling nozzles with pressures up to 25 MPa were used, and the injection distance was varied in the range from 30 to 400 mm. The jet structure was observed with a high speed camera, and the water droplet velocity and diameter were measured with a phase Doppler analyzer. The results confirmed that the jet structure changes continuously through a process of continuous flow, break-up, water lumps, and water droplets. It was found that a continuous flow can be maintained for a long distance by using a low injection pressure and large flow rate, and the water droplet diameter also becomes larger, which reduces velocity attenuation. These deformation properties of the jet structure are related to the Weber number expressed by the relative velocity between a water droplet and the surrounding air. A smaller Weber number is effective for reducing velocity attenuation over a long injection distance.

KEY WORDS: descaling; oxide scale; laser Doppler; hot rolling mill.

1. Introduction

In the hot rolling process, the primary scale generated in the heating furnace and the secondary scale generated during rolling are removed by hydraulic descaling in order to prevent surface defects. Recently, surface quality requirements for automotive steel sheets have become increasingly strict, and scale removal technology by hydraulic descaling is important.

Based on this background, various studies have examined the hydraulic descaling. Sheppard et al.1) reported that the impact pressure of the descaling jet is one important factor from the viewpoint of mechanical breaking and applying thermal shock to scale layers. In mechanical breaking of scale layers, the scale is removed more easily by hydraulic descaling as the injection pressure and flow rate increase and the injection distance decreases.2–4) Although the mechanism of the process by which a water jet removes scale has not been clearly understood,5) Wada et al.6) showed that the impact pressure of the descaling jet has a large effect on scale breaking properties, and the impact pressure decreases at longer injection distances due to the attenuation of the water droplet velocity.

In the field of water jet machining, impact pressure and erosion damage are evaluated by measuring the mass loss of metallic materials caused by water jet impact. Based on measurements with this method, Kobayashi et al.7) suggested that the impact pressure of a water jet decreases if the injection distance is too short. Generally, high speed water droplet impact generates water hammer pressure.8) However, immediately after injection, the water jet structure is a continuous flow, and the impact of the continuous flow generates dynamic water pressure, which is several times smaller than water hammer pressure.9) Therefore, in order to secure the required scale removal capacity by a high impact pressure, it is important to investigate the behavior of changes in the descaling jet structure and the attenuation of the water droplet velocity along the injection distance.

As pointed out in various studies on the atomization mechanism of the water jet injected from a nozzle, the continuous flow is broken up due to the fluctuation of the interface based on the relative velocity between the water flow and the surrounding air, and atomization occurs due to the breakup and aggregation of the water droplets. However, this atomization process is a complex, unsteady phenom-
enon, and its characteristics change depending on the type of nozzle, the injection condition, and the kind of liquid. Therefore, the influence of the injection distance on the water jet structure and the attenuation of the water droplet velocity along the injection distance has not been clarified yet. Although Yanaida et al. reported the attenuation characteristics of the impact pressure caused by a fan-shaped spreading water spray from a fine slit nozzle, the influence of the injection distance on the jet structure and the droplet velocity still has not been explained clearly.

In this work, the behavior of changes in the descaling jet structure and the attenuation of the water droplet velocity along the injection distance were investigated experimentally. High pressure descaling nozzles with pressures up to 25 MPa were used, and the injection distance was varied in the range from 30 to 400 mm. The jet structure was observed with a high speed camera, and the water droplet velocity and diameter were measured with a phase Doppler analyzer.

2. Experimental Procedure and Conditions

2.1. Observation with High Speed Camera

The behavior of changes in the descaling jet structure was observed with a high speed camera. Figure 1 shows the experimental set-up for high speed camera observation. The jet structure at the center in the spray width direction was observed with the high speed camera, which consisted of a Photron FASTCAM SA-X2 with a Nikon AF Micro-Nikkor micro lens (200 mm, f/4D; frame rate: 300 000 fps, exposure time: 0.29 μs). The image size of the photographs was 7 mm × 2.2 mm, resolution was 256 × 80 pixels, and the scale factor was 27.3 μm/pixel. Spray water from the descaling nozzle, which had a fan-shaped spreading angle of 40°, was pumped from the tank, in which the temperature of the water was maintained at 30°C. The water flow rate was changed in the range from 3.67 to 22.00 × 10⁻⁴ m³/s at the same injection pressure of 15 MPa, and the injection pressure was changed in the range from 10 to 25 MPa at the same water flow rate of 7.35 × 10⁻⁴ m³/s in order to investigate the influence of the water flow rate and the injection pressure. These conditions were adjusted by using descaling nozzles with different orifice diameters. The behavior of the water droplets was observed with the high speed camera at distances of 30 to 400 mm from the nozzle outlet.

2.2. Measurement with Phase Doppler Analyzer

The descaling water droplet velocity and diameter were measured with a phase Doppler analyzer. Figure 2 shows the experimental set-up for the measurements by the phase Doppler method. The experimental conditions were the same as those shown in Table 1. The experimental apparatus consisted of a TSI phase Doppler particle analyzer (PDPA) and Coherent INNOVA70C ion laser. The wavelength of the laser was 514.5 nm and the beam diameter was 1.77 mm. The laser was focused on the center of the spray width and thickness directions. The descaling nozzle position was adjusted in the spray injection and thickness directions individually by the displacement system in order to adjust the measurement position. The measurement was conducted until the number of data reached 10 000 points for each condition. The Sauter mean diameter was calculated by Eq. (1) and the arithmetic mean diameter was calculated by Eq. (2) from the measured water droplet diameter distribution. The descaling water droplet velocity was calculated by Eq. (3) as the average value of all measured water droplet velocities.

\[
D_{32} = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \quad \text{(1)}
\]

\[
D_{10} = \frac{\sum n_i d_i}{\sum n_i} \quad \text{(2)}
\]

\[
V_w = \frac{\sum n_i V_i}{\sum n_i} \quad \text{(3)}
\]

![Fig. 1. Experimental set-up for observation by high speed camera.](image)

![Fig. 2. Experimental set-up for measurement by phase Doppler method.](image)
3. Experimental Results

3.1. Water Droplet Behavior in High Pressure Descaling

Figure 3 shows the high speed camera images at the injection pressure of 15 MPa and the water flow rate of $7.35 \times 10^{-4}$ m$^3$/s. The black parts in the images indicate descaling water. The jet structure was a continuous flow at the injection distance of 30 mm, although water jet flow was turbulent. It can be seen that the breakup of the continuous flow occurred at the injection distance of 60 mm, and the breakup flow was sheared and divided into water lumps at 120 mm. Subsequently, as the descaling jet flow progressed downstream, the water lumps gradually changed to small water droplets through a process of repeated breakup and coalescence. Furthermore, water lumps and droplets of vari-
ous sizes existed at the same injection distance. Although the behavior of changes in the descaling jet structure in Fig. 3 was similar to the atomization process of the shear breakup model, the shape of the water lumps and droplets included a tail on the upstream side in the jet direction, which is similar to the phenomenon seen when there is a large difference in the relative velocities of a water jet and the surrounding air.

Figure 4 shows the effect of the injection pressure on the water droplet behavior. The injection pressure conditions were 10 MPa and 25 MPa at the same water flow rate of $7.35 \times 10^{-4}$ m$^3$/s. As shown in Fig. 4(a), when the injection pressure was 10 MPa, the continuous flow was maintained for a long distance and the water jet was not completely broken up even at the injection distance of 60 mm. At the injection distance of 400 mm, the water droplet size at the injection pressure 10 MPa was larger than that with the pressure of 25 MPa in Fig. 4(b).

Figure 5 shows the effect of the water flow rate on the water droplet behavior. Three water flow rate conditions were employed; namely, $3.67 \times 10^{-4}$, $13.82 \times 10^{-4}$, and $22.00 \times 10^{-4}$ m$^3$/s at the same injection pressure of 15 MPa. As the water flow rate increased, the continuous flow could be maintained for a longer distance and the water droplet diameter also became larger. In particular, at the water flow rate of $22.00 \times 10^{-4}$ m$^3$/s, large water lumps were observed even at the injection distance of 400 mm, as shown in Fig. 5(c).

As described above, the deformation properties of the descaling jet structure are related to the injection conditions, namely, the injection pressure and water flow rate. In the condition that the breakup of the continuous flow occurred at a relatively short distance, the void fraction was large. The void fraction was defined as the area ratio of air to descaling water. Consequently, the high speed camera images were binarized and the void fraction was evaluated in order to investigate the deformation properties of the descaling water jet. The evaluated void fraction is not the volume fraction including the spray thickness direction but the area fraction. An example of a binary image of the high speed camera images is shown in Fig. 6. The relationship between the injection distance and the void fraction is shown in Fig. 7. It can be seen that the void fraction is larger at higher injection pressures and smaller flow rates.

3.2. Results of Measurements of Water Droplet Diameter and Droplet Velocity

The water droplet diameter and velocity were measured with a phase Doppler analyzer to investigate the attenuation of the water droplet velocity along the injection distance. Figure 8 shows the influence of the injection distance on the Sauter mean diameter and mean velocity at the water flow rate of $7.35 \times 10^{-4}$ m$^3$/s and injection pressure of 15 MPa. As the descaling jet flow progressed downstream, the Sauter mean diameter became smaller, as shown in Fig. 8(a). It can be seen that the velocity attenuation in the region of continuous flow and breakup flow was smaller than that in the region of water lumps and droplets, as shown in Fig. 8(a).
At a distance 200 mm and over, the Sauter mean diameter was small and velocity attenuation was large.

Figure 9 shows the effect of the injection pressure on the Sauter mean diameter and mean velocity at the water flow rate of $7.35 \times 10^{-4} \text{ m}^3/\text{s}$. Here, the injection pressure was varied in the range from 10 MPa to 25 MPa. The Sauter mean diameter became smaller with increasing injection pressure and injection distance, as shown in Fig. 9(a). This result qualitatively agrees with the results of high speed camera observation in Fig. 4. Velocity attenuation increased with increasing injection pressure in Fig. 9(b).

Figure 10 shows the effect of the water flow rate on the Sauter mean diameter and mean velocity at the injection pressure of 15 MPa. The water flow rate was varied in the range from $3.67 \times 10^{-4} \text{ m}^3/\text{s}$ to $22.00 \times 10^{-4} \text{ m}^3/\text{s}$. The Sauter mean diameter became larger as the water flow rate increased in Fig. 10(a). This result qualitatively agrees with the results of high speed camera observation in Fig. 5. Further, velocity attenuation decreased as the water flow rate increased in Fig. 10(b).

4. Discussion

4.1. Influence of Injection Pressure and Water Flow Rate on Attenuation of Water Droplet Velocity

The following will discuss the mechanism of the attenuation of the descaling water droplet velocity. Assuming that a water droplet is spherical, gravity, buoyancy, and drag force act on a water droplet injected from a descaling nozzle. The equation of motion for a water droplet is expressed by Eq. (4). In the experimental conditions, the drag coefficient value $C_D$ was set to 0.4 because the Reynolds number of the droplet given by Eq. (9) was from 650 to 2500, which was in the Newtonian range.

$$m_w \frac{dV_w}{dt} = m_w g - D$$

$$m_w = \frac{1}{6} \rho_w \pi d^3$$

$$D = \frac{1}{2} \rho_a V_a^2 (1-a)^2 \frac{A}{C_D}$$

$$A = \frac{1}{4} \pi d^2$$

$$a = \frac{V_a}{V_w}$$

$$Re = \frac{V_w d}{\nu}$$

Where, $t$ (s) is time, $m_w$ (kg) is the mass of a water droplet, $g$ (9.8 m/s$^2$) is gravitational acceleration, $D$ (N) is drag force, $d$ (m) is the water droplet diameter, $\rho_w$ (kg/m$^3$) is the density of water, $\rho_a$ (kg/m$^3$) is the density of air, $C_D$ is the drag coefficient value, $V_a$ (m/s) is the water droplet velocity, $V_w$ (m/s) is the surrounding air flow velocity, $A$ (m$^2$) is the cross-section area of water droplet, $a$ is the slip ratio, and $\nu$ (m$^2$/s) is the kinematic viscosity of air.

When a water droplet moves in still gas, air entrainment
occurs and the drag force $D$, which is proportional to the square of the relative velocity between the water droplet and the surrounding air, acts on the water droplet. Therefore, the relative velocity is one important factor when considering the attenuation of the water droplet velocity. However, the surrounding air flow velocity $V_a$ was not measured in the experiment and is unknown. Therefore, in order to evaluate the ratio of the water droplet velocity to the surrounding air flow velocity, the water droplet velocity was calculated inversely by using the slip ratio as a fitting parameter and the experimental results of the water droplet diameter. The temporal change of the water droplet velocity can be derived from Eqs. (4)-(7) as Eq. (10).

$$\frac{dV}{dt} = g - \frac{3}{4d} C_D V_a^2 \left(1 - a^2 \right) \frac{D_w}{\rho_w} \quad \text{................. (10)}$$

It can be seen from Eq. (10) that velocity attenuation increases as the water droplet diameter becomes smaller. Although the water droplet diameter and the velocity of the surrounding air change successively and affect velocity attenuation, it is difficult to calculate the water droplet velocity from the elementary analysis considering these successive changes. Therefore, the water droplet velocity was calculated by finite difference calculation, using the slip ratio as a fitting parameter and the experimental results of the water droplet diameter. The water droplet velocity and the injection distance at a certain time are given by Eqs. (11) and (12), respectively.

$$V_{w,i+1} = V_{w,i} + \frac{dV_w}{dt} \Delta t \quad \text{.................. (11)}$$

$$x_{i+1} = x_i + V_{w,i} \Delta t + \frac{1}{2} \frac{dV_w}{dt} \Delta t^2 \quad \text{.................. (12)}$$

In Eqs. (11) and (12), the water droplet velocity was calculated with the time step $\Delta t$ set to 1 $\mu$s, using the experimental results of the arithmetic mean diameter $D_{10}$, which is an approximate value, as a function of the injection distance. Since the water droplet velocity was evaluated as the arithmetic mean diameter $D_{10}$ in the experiment, $D_{10}$ was also used in the calculation in order to secure the correspondence of the relationship between the water droplet velocity and the droplet diameter. The calculation was performed in the water lump and droplet region at the injection distance of 120 mm and over, as shown in Fig. 3. Further, the experimental result of the mean velocity at the injection distance of 120 mm was used as the initial value for the calculation.

The calculation was performed using a constant slip ratio over the full injection distance, and the calculation results were compared with the experimental results. Figure 11 shows the comparison of the calculated and experimental mean velocities. The calculated results show good agreement with the experimental results when the calculations are performed using different slip ratios depending on injection pressure and flow rate. Figure 12 shows the slip ratios that are fitted by the numerical approach as demonstrated in Fig. 11(a). It can be seen that the slip ratio decreased at higher injection pressures; that is, the relative velocity between the water droplet and the surrounding air increased at higher injection pressures. As shown in Fig. 9(b), the velocity attenuation was larger at higher injection pressures. This is because the injection velocity is larger at higher injection pressures, so the relative velocity and the drag force in Eq. (4) also become larger. Furthermore, since the shear force at the interface between the water flow and the surrounding air increases due to the larger relative velocity at the higher injection pressure, it is thought that the water droplet diameter decreases, as shown in Fig. 9(a), and this results in a further increase in velocity attenuation.

Figure 13 shows the slip ratios that are fitted by the numerical approach as demonstrated in Fig. 11(b). This figure shows that the slip ratio increased at larger flow rates; that is, the relative velocity between the water droplet and the surrounding air decreased at larger flow rates. Velocity attenuation was smaller at larger flow rates, as shown in Fig. 10(b). It is thought that the drag force becomes smaller at larger flow rates because air entrainment force becomes larger at larger flow rates, and the relative velocity decreases.
due to an increase in the surrounding air flow velocity. Furthermore, since the shear force at the interface between the water flow and the surrounding air decreases due to the smaller relative velocity at the larger flow rate, it is thought that the water droplet diameter was larger, as shown in Fig. 1(a), contributing to a further decrease in velocity attenuation.

Although the above-mentioned calculations were performed with a constant slip ratio, calculations were also performed with different slip ratios depending on the injection distance. **Figure 14** shows the effect of the injection distance on the slip ratio. The calculated results agree well with the experimental results when the calculations are performed with different slip ratios depending on the injection distance. This result suggests that the surrounding air flow velocity decreases as the air entrainment force becomes smaller with increasing injection distance. The reason for the decrease in the air entrainment force might be that the water flow density decreases with the injection distance due to the use of the fan-shaped spreading spray nozzle, and the droplet diameter becomes smaller with the injection distance, as shown in the high speed camera images and results of measurements of the Sauter mean diameter.

In summary, by comparing the results of the calculations and experiments, it was shown that the slip ratio increased with lower injection pressures and larger flow rates; that is, the velocity attenuation became smaller due to the decreasing relative velocity between the water droplet and the surrounding air.

### 4.2. Influence of Injection Pressure and Water Flow Rate on Water Droplet Diameter

As discussed in section 4.1, the change of the water droplet behavior along the injection distance is an important factor for the attenuation of water droplet velocity. Water droplet breakup can be evaluated by the droplet Weber number $We$ in Eq. (13). The condition of the critical Weber number for the occurrence of water droplet breakup is generally expressed by Eq. (14), although that condition depends on the water droplet diameter and the manner of contact between the water droplet and the surrounding air flow.²¹

\[
We = \frac{\rho_d d (V_w - V_j)}{\sigma} \geq 10 \quad \text{................. (13)}
\]

\[
\text{Where, } \sigma \text{ (N/m) is surface tension. The Weber numbers for all experimental conditions were calculated by using the slip ratio obtained in section 4.1 and the experimental results of the arithmetic mean diameter } D_{10}. \text{ **Figure 15** shows the relationship between the injection distance and the Weber number. As shown in Fig. 15(a), the Weber number is large at higher injection pressures. At the injection pressure of 25 MPa, the Weber number is over 10 at all injection distances, which means that water droplet breakup occurs easily under this condition. On the other hand, at the injection pressure of 10 MPa, the Weber number is 10 or smaller at injection distance. This result suggests that the surrounding air flow velocity decreases as the air entrainment force becomes smaller with increasing injection distance. The reason for the decrease in the air entrainment force might be that the water flow density decreases with the injection distance due to the use of the fan-shaped spreading spray nozzle, and the droplet diameter becomes smaller with the injection distance, as shown in the high speed camera images and results of measurements of the Sauter mean diameter.}

\[
V_a = aV_w \quad \text{................. (15)}
\]
As discussed above, the deformation properties of water droplets in high pressure descaling are related to the Weber number expressed by the relative velocity between a water droplet and the surrounding air. A smaller Weber number is effective for reducing the velocity attenuation of water droplets without an accompanying decrease in the water droplet diameter. Thus, it was suggested that a larger flow rate condition is effective for reducing velocity attenuation over a long injection distance.

5. Conclusions

Observation of water droplet behavior with a high speed camera and measurement of the water droplet velocity and diameter with a phase Doppler analyzer were conducted in order to investigate the influence of the water flow rate and injection pressure on the behavior of changes in the descaling jet structure and the attenuation of the water droplet velocity. The results obtained were as follows:

(1) It was confirmed that the jet structure changes continuously through a process of continuous flow, breakup, water lumps, and water droplets. It was found that a continuous flow can be maintained for a long distance by using a low injection pressure and large flow rate, and the water droplet diameter also becomes larger under these conditions, which reduces velocity attenuation.

(2) The attenuation of water droplet velocity was small at lower injection pressures and larger flow rates. As the reason for this, from the calculation results, it is thought that the drag force decreases due to the smaller relative velocity between the water droplets and the surrounding air.

(3) The deformation characteristics of water droplets in high pressure descaling are related to the Weber number expressed by the relative velocity between a water droplet and the surrounding air. A smaller Weber number is effective for reducing the velocity attenuation of water droplets without an accompanying decrease in the water droplet diameter. Thus, it was suggested that a larger flow rate condition is effective for reducing velocity attenuation over a long injection distance.

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