Quantitative Evaluation of Stability of Water Flow Injected from Pipe Laminar Nozzle

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Cooling equipment of the pipe laminar type is utilized on run-out tables in hot strip mills. It is known that the stability of the water flow injected from the cooling equipment nozzles affects cooling performance. In this study, new criteria and an experimental method for quantifying water flow stability are proposed. The experimental apparatus consists of the water injection equipment, an electric circuit and a logger. The time variation of voltage represents the electric resistance of the injected water and is measured under various conditions of flow rate and nozzle diameter. A new laminar stability index, $R_{\sigma}/R_{\text{AVE}}$ was proposed, in which $R_{\sigma}$ and $R_{\text{AVE}}$ mean the standard deviation and the average value of electric resistance of water flow injected from the nozzle, respectively. The proposed index qualitatively shows good agreement with the appearance of the laminar flow in the experiment. Based on the experiment, an equation of continuous laminar length is suggested.

KEY WORDS: hot rolling; water cooling; run-out table; pipe laminar; electric resistance.

1. Introduction

In the hot rolling process in the production of steel, cooling is carried out on a run-out table. Especially when producing high tensile steel, non-uniform cooling has occurred in the strip longitudinal and width directions. A variety of research and development has been carried out with the aim of preventing this problem.1–4

One of the cooling devices used in run-out tables is cooling equipment of the pipe laminar type. It is known that the stability of the water flow (hereinafter, laminar stability) injected from the cooling equipment nozzles affects cooling performance.5,6 Therefore, in order to enhance the cooling uniformity of strips on the run-out table, it is important to improve laminar stability.

A water column injected from a pipe laminar nozzle is called liquid jet in gas flow. This phenomenon was studied experimentally by Chen et al.7 and theoretically by Weber et al.8 Chen measured the continuous length of water columns (hereinafter, continuous laminar length) in experiments and proposed an equation for their length. Weber obtained the continuous laminar length in the case of a uniform flow in the nozzle. From previous studies, liquid jet in gas flow is understood as follows.9 A momentum exchange between the liquid phase and the gas phase occurs on the gas-liquid interface. In the case of low Reynolds number liquid phases, the water flow is laminar and stable because the momentum exchange is small. As the Reynolds number increases, the water flow transitions from laminar to turbulent, and the momentum exchange becomes larger. Then, the flow becomes unstable as irregularities appear on the surface of the gas-liquid interface.

It is known that laminar stability is affected by the diameter and length of the pipe laminar nozzle, the flow rate and so on.5 When the flow rate is low, the water column breaks immediately after nozzle exit. The stable region expands as the flow rate increases, but when the flow rate is increased further, the shear force acting on the gas-liquid interface increases and the water column changes to liquid droplets.

If the water column breaks or changes to liquid droplets before reaching the strip, its ability to penetrate the water film on the strip will be reduced and, as a result, its cooling performance will decrease.10 The continuous laminar length was formulated in some studies, but the effect of gravity has not been considered thus far.7,8 In some cooling conditions similar to the pipe laminar nozzle, the flow rate and nozzle diameter affect the continuous laminar length, but this has not been quantified enough.10

As described above, in previous studies, the laminar stability of a pipe laminar nozzle has been evaluated and understood only qualitatively, and pipe laminar nozzles have been designed empirically. Therefore, an index of quantification has been required to establish the optimum nozzle design.

Kusui developed a quantitative evaluation method which did not depend on a visual method.9 However, it neither considered the effect of gravity as in Chen et al., nor satisfactorily quantified laminar stability.

Therefore, for optimization of the pipe laminar nozzle, a quantitative evaluation method for laminar stability was developed and the continuous laminar length was evaluated.

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2. Experimental Method

Figure 1 shows a schematic view of the experimental apparatus for quantitative evaluation of laminar stability. The experimental apparatus is composed of a header, a tube nozzle, a voltage logger and an electrical circuit. The electrical circuit is composed of a water column, a DC power supply and an electrical resistance. The value of the electric resistance is known, and time variation of the electrical resistance of the water column is evaluated by measuring the time variation of the potential difference between its ends by a voltage logger (Keyence Corp., GR-3000).

Because the electrical resistance of a water column varies depending on its shape, it is considered that the time variation of a water column shape can be evaluated by the time variation of electrical resistance. Photographs of water columns were taken for comparison with experimental data.

A water column was injected from a nozzle with a certain pressure raised by a pump. The temperature of the water was 303 K. After the flow achieved a steady state, the voltage of the electric circuit including the water column was measured for 5 seconds at intervals of 10 ms.

Table 1 shows the experimental conditions. The flow rate injected from the nozzle was changed from \(3.3 \times 10^{-4}\) to \(8.3 \times 10^{-4}\) m/s. The nozzle diameters used for the experiments were 16.1, 21.6 and 27.6 mm.

In addition, the experimental apparatus shown in Fig. 1 was also used to evaluate quantitatively the continuous laminar length. In this experiment, the distance between the nozzle exit and the SUS sheet, \(l_c\), was changed from 100 to 1600 mm at intervals of 100 mm. When the water column breaks, the electric circuit also breaks, and the measured voltage becomes zero. When the measured voltage was zero for more than half of the measurement time at a certain point, that point was defined as the breakpoint, and the length of the water column was defined as the continuous laminar length. When the measured voltage was zero for more than half of the measurement time, the breakpoint could be clearly seen in visual observation. Thus, this method of determining the breakpoint is considered to be reasonable.

Table 2 shows the experimental conditions. The flow rate injected from the nozzle was changed from \(8.3 \times 10^{-5}\) to \(8.3 \times 10^{-4}\) m/s, the nozzle diameter was changed from 16.1 to 27.6 mm, and the nozzle length was changed from 200 to 1000 mm.

3. Experimental Results and Discussions

3.1. Evaluation of Laminar Stability

Figure 2 shows the time variation of measured voltage and photographs of the water column in the case of the nozzle diameter of 16.1 mm. The average values, variation of voltage and appearance of the water columns changed with

<table>
<thead>
<tr>
<th>Flow rate (q) (\times 10^{-4}) m/s</th>
<th>Measured voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3 (\times 10^{-4})</td>
<td>20</td>
</tr>
<tr>
<td>5.0 (\times 10^{-4})</td>
<td>20</td>
</tr>
<tr>
<td>6.7 (\times 10^{-4})</td>
<td>20</td>
</tr>
<tr>
<td>8.3 (\times 10^{-4})</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1. Experimental condition.

<table>
<thead>
<tr>
<th>Flow rate (q) (\times 10^{-4}) m/s</th>
<th>3.3, 4.2, 5.0, 5.8, 6.7, 7.5, 8.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter, (d_n) mm</td>
<td>16.1, 21.6, 27.6</td>
</tr>
<tr>
<td>Nozzle length, (l_n) mm</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 2. Experimental condition.

<table>
<thead>
<tr>
<th>Flow rate (q) (\times 10^{-4}) m/s</th>
<th>0.8, 1.7, 2.5, 3.3, 4.2, 5.0, 5.8, 6.7, 7.5, 8.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter, (d_n) mm</td>
<td>12.7, 16.1, 21.6, 27.6</td>
</tr>
<tr>
<td>Nozzle length, (l_n) mm</td>
<td>200, 400, 600, 800, 1000</td>
</tr>
<tr>
<td>Nozzle standoff, (l_c) mm</td>
<td>100–1 600 (at 100 interval)</td>
</tr>
</tbody>
</table>

Fig. 2. Configuration of injected water and graph of measured voltage.
Changes in the flow rate. The reason why the voltage changed with the flow rate is that the cross-sectional area of the water column increased with the flow rate, and as a result, the electric resistance of the water column changed.

Electric resistance, $R$, can be calculated from Eqs. (1) and (2), which contain the measured voltage shown in Fig. 1.

\[
R = \frac{E_0 - R_0}{I} \quad \ldots \ldots (1)
\]

\[
I = \frac{E}{R_0} \quad \ldots \ldots (2)
\]

Here, $R_0$ is the electric resistance (750 Ω), $E_0$ is the power supply (11 V) and $E$ is the measured voltage. From Eqs. (1) and (2), the measured variation of voltage corresponds to the variation of the electric resistance of a water column.

In Fig. 2, in the case of a low flow rate, the degree of white turbidity on the surface of the water column is low, and the variation of electric resistance of the water column is small. The degree of white turbidity and variation of electric resistance both increase with the flow rate.

An increase of white turbidity indicates a decrease of laminar stability, and the variation of electric resistance correlates with laminar stability.

From the experimental results, it is considered that laminar stability can be quantified by quantifying the disturbance of a water column, in other words, its variation of electric resistance.

As described above, because laminar stability corresponds to the electric resistance of a water column, laminar stability displays a correlation with the standard deviation of electric resistance variation. Here, the average value of electric resistance changes with the nozzle diameter, flow rate, quality of the water and so on. It is considered that the average value of electric resistance should be taken into account in order to compare various conditions.

For the reason mentioned above, an index of laminar stability according to the form of Eq. (3), which considers average resistance, was suggested.

Laminar stability index, $LI = \frac{R_\sigma}{R_{AVE}} \times 100$ [%] .... (3)

Here, $R_\sigma$ is the standard deviation of electric resistance and $R_{AVE}$ is the average value of electric resistance. In the laminar stability index, a lower value indicates higher stability.

This index corresponds to a coefficient of variation in statistics, and it is generally significant when the average value is proportional to the standard deviation. In this study, the average value was not necessarily proportional to the standard deviation. However, the standard deviation changed with the nozzle diameter, flow rate, quality of the water and so on, and these changes were much larger than those seen in visual observation. Thus, the value of the standard deviation divided by the average value was used as the index of laminar stability in order to compare various conditions.

Figure 3 shows photographs of water columns and the laminar stability index. Disturbance of the water columns and the laminar stability index increase with decreasing nozzle diameter. Therefore, the laminar stability index can evaluate laminar stability.

Figure 4 shows the effects of flow rate and nozzle diameter on the laminar stability index. Laminar stability increases with decreases in the flow rate and increases in the nozzle diameter.

### 3.2 Factors Affecting Laminar Stability

The factors affecting laminar stability were investigated based on the experimental results. Figure 5 shows the relationship between laminar stability and average velocity at nozzle exit.\textsuperscript{12,13} Average velocity at nozzle exit is defined as the value of the flow rate divided by the cross-sectional area of the nozzle exit. The value of the laminar stability index increases, in other words, laminar stability decreases, as the average velocity at nozzle exit increases. As discussed above, this is because the momentum exchange on the gas-liquid interface becomes active and the disturbance of the interface increases as a result of increases in the average velocity.
velocity at nozzle exit.

On the other hand, a disturbance which occurs on the liquid-gas interface travels from the surface to the inside of a water column. When the disturbance reaches the inside, the disturbance of the water column will be amplified. Disturbances travel to the inside more easily in thinner water columns. Thus, it is considered that the aspect ratio of a water column, that is, the ratio of column length to column diameter, affects laminar stability. The diameter at the bottom end was used as a representative value of the column diameter.

A continuity equation and motion equation considering gravity are used to calculate the diameter at the bottom end. These are shown as Eqs. (4) and (5), respectively. The calculation result is shown as Eq. (6).

\[
\pi \left( \frac{d_i}{2} \right)^2 v_i = \pi \left( \frac{d_n}{2} \right)^2 v \hspace{1cm} (4)
\]

\[
v_i^2 - v^2 = 2gl_w \hspace{1cm} (5)
\]

\[
d_i = \sqrt{\frac{\pi v}{\sqrt{v^2 + 2gl_w}}} d_n \hspace{1cm} (6)
\]

Here, \(\pi\) is a circular constant, \(v_i\) is average velocity at the bottom end, \(v\) is average velocity at nozzle exit, \(d_i\) is the diameter at the bottom end, \(d_n\) is the nozzle diameter and \(l_w\) is the continuous laminar length. The continuous laminar length, \(l_w\) corresponds to the distance between the nozzle exit and the SUS sheet, \(l_c\) in the case that the water column does not break.

Figure 6 shows the relationship between the length and diameter of a water column as calculated by Eq. (6) when the flow rate is \(5.0 \times 10^{-4} \text{ m}^3/\text{s}\) and the nozzle diameter is 16.1 or 27.6 mm. The diameter of the water column changes greatly depending on the nozzle diameter.

As described above, average velocity at nozzle exit affects laminar stability. Moreover, changes in the velocity injected from the nozzle exit also affect laminar stability. It is considered that a suitable index for expressing these effects is the change of velocity from the nozzle exit to the bottom end. As shown in Eq. (7), which is calculated from the motion equation, the difference between the velocity at the bottom end and the velocity at the nozzle exit corresponds to the product of gravity acceleration and the time of the water flow from the nozzle exit to the bottom end.

\[
v_l - v = gt \hspace{1cm} (7)
\]

Here, \(v_l\) is average velocity at the bottom end, \(v\) is average velocity at the nozzle exit, \(g\) is standard gravitational acceleration of free fall and \(t\) is the time of the water flow from the nozzle exit to the bottom end. \(t\) is calculated by Eqs. (5) and (7).

For all of these reasons, it is considered that the product of the aspect ratio of a water column and the change of velocity from the nozzle exit to the bottom end, which is expressed as Eq. (8), relates to laminar stability.

\[
\frac{v_l - v}{gt} \frac{l_w}{d_i} \hspace{1cm} (8)
\]

Figure 7 shows the relationship between Eq. (8) and the laminar stability index. The data lie on the linear function which is expressed by Eq. (9).

\[
LI = 0.01 \frac{v_l}{gt} \frac{l_w}{d_i} + 0.37 \hspace{1cm} (9)
\]

From Figs. 4 to 6, the factors affecting laminar stability are the average velocity at the nozzle exit, gravity, the time of water flow from the nozzle exit to the bottom end, the length of the water column and the diameter at the bottom end of the water column.

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Fig. 5. Relationship between velocity at nozzle exit and laminar stability index.

Fig. 6. Relationship between length of injected water and diameter.

Fig. 7. Relationship between \(v_l/gt\cdot l_w/d_i\) and laminar stability index.
3.3. Continuous Laminar Length

Figure 8 shows the relationship between the flow rate and continuous laminar length for the nozzle diameter of 12.7 mm. The curve in Fig. 8 is drawn for plots when the nozzle length is 200 mm. Figure 9 shows the relationship between the flow rate and continuous laminar length for the length of the nozzle is 200 mm. As the flow rate increases, the continuous laminar length also tends to increase. However, when the nozzle length is 200 mm, the continuous laminar length displays wavelike changes several times as the flow rate increases.

3.4. Factors Affecting Continuous Laminar Length

Figure 10 shows the relationship between the Reynolds number at the nozzle exit and the continuous laminar length in the case of the nozzle length of 200 mm and the nozzle diameter of 12.7 mm. The Reynolds number at the nozzle exit means the product of the average velocity and diameter divided by the kinetic viscosity of the water at the nozzle exit. The result showed a tendency similar to that in Kusui’s experiments. The continuous laminar length increases in the laminar boundary layer (low Reynolds number), decreases in the transition region between the laminar boundary layer and turbulence boundary layer (high Reynolds number), then increases in the turbulence boundary layer and finally decreases. As shown in Fig. 8, the tendency of the continuous laminar length when the nozzle length is over 400 mm is different from that when the nozzle length is 200 mm.

That is, when the nozzle length is long, the flow in the nozzle develops and the boundary layer becomes turbulent. Thus, when the nozzle length is over 400 mm, the above-mentioned wavelike change in the continuous laminar length does not occur, and the continuous laminar length increases monotonically.

Kusui studied the continuous laminar length in the range of nozzle diameters from 1.5 to 3.4 mm. A tendency similar to that observed by Kusui was also obtained when the nozzle diameter was around 15 mm.

Figure 11 shows the relationship between the continuous laminar length and the Reynolds number at the nozzle exit when the nozzle length is 200 mm and the nozzle diameter is 21.6 mm. Compared with Kusui’s results and Fig. 10, increase and decrease of the continuous laminar length occur in the low Reynolds number region. It is considered that the reason why the tendency changed was that the diameter of the water column changes greatly from the nozzle exit to the bottom end when the nozzle diameter is large.

Figure 12 shows the relationship between the continuous laminar length and the Reynolds number at the breakpoint of the water column. Here, the Reynolds number at the breakpoint means the product of the average velocity and diameter of the water column divided by the kinetic viscosity of the water at the breakpoint and is calculated by Eqs. (4) and (5). Although the results changed with the nozzle
diameter, they displayed the same tendency. Thus, the continuous laminar length can be evaluated by the Reynolds number at the breakpoint of the water column in cases where the nozzle diameter is large and the diameter of the water column changes greatly due to the effect of gravity. This tendency is expected to be independent of the nozzle length, but results for nozzle lengths over 400 mm have not yet been obtained because the continuous laminar length necessary to obtain the breakpoints is so long (over 1600 mm). Experiments under such conditions will be carried out in the future by improving the experimental apparatus.

Next, the continuous laminar length was formulated for various nozzle lengths and nozzle diameters. Kusui estimated that the continuous laminar length divided by the nozzle diameter depends on the Reynolds number, pressure loss at the nozzle, surface tension and viscosity.\cite{15,16} In this study, the surface tension and viscosity were constant; therefore, the Reynolds number at the breakpoint, the nozzle length and the nozzle diameter were chosen as parameters for evaluation. Here, the nozzle length and the nozzle diameter are related to pressure loss. By using a least mean square approximation, Eq. (10) was obtained as an expression of continuous laminar length.

$$\frac{l_n}{d_n} = 21.9 \ln \left( \frac{Re_b}{d_n} \right) - 225 \quad \ldots (10)$$

Here, $Re_b$ is the Reynolds number at the breakpoint.

Figure 13 shows a comparison of the experimental results and the results calculated by Eq. (10). As the correlation coefficient is sufficiently large, at 0.71, Eq. (10) can be regarded as representing the experimental results.

4. Conclusion

In order to evaluate quantitatively the stability of water columns injected from nozzles of the pipe laminar type, experiments in the laboratory were carried out. The following results were obtained.

(1) A laminar stability index, which is expressed by the standard deviation of the electric resistance of a water column divided by the average value of electric resistance was proposed. This index could successfully evaluate laminar stability quantitatively.

(2) The main factors affecting laminar stability were the velocity at nozzle exit and the diameter of the water column.

(3) One of the main factors affecting the continuous laminar length was the Reynolds number at the breakpoint of the water column.

(4) An equation of continuous laminar length which satisfactorily represents the experimental results was obtained.

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