1. Introduction

In a hot rolling process, cooling is carried out on a run-out table in order to control mechanical properties of steel. Especially when producing high tensile steel, non-uniform cooling has occurred in strip longitudinal and width directions. A variety of research and development has been conducted with the aim of preventing this problem.1–4) One of the cooling devices used in run-out tables is a pipe laminar type cooling equipment. The coiling temperature, which has a great influence on the performance of the steel strip, is controlled by using these cooling equipments. On the run-out table, the threading speed at the leading end is slow. The strip is then accelerated to reach the maximum speed, and is decelerated at the tail end. Because the target of the coiling temperature is constant, it is necessary to control injection area of cooling water from the cooling equipments according to the acceleration and deceleration of the strip. Therefore, it is desirable for a pipe laminar type cooling equipment to have a short response time in injection start and injection stop.5)

After the supply valve of cooling water is opened and cooling water fills the cooling equipment, injection starts. On the other hand, only after the valve is closed and the cooling water in the equipment is drained, injection stops. Thus, the response time of the stop is long compared to that of start. Therefore, it is important to shorten the response time of the stop of injection.

Asano et al., Shinohara et al. and Ichikawa et al. have studied drainage of pipes.6–8) In general pipe laminar type cooling equipments, water drainage continues until air enters headers because of the siphon effect. Thus, the water drainage time is long.9) Therefore, the behavior of water drainage of pipe laminar type cooling equipments is different from the previous researches. In this research, we studied a pipe laminar type cooling equipment equipped with an air inlet tube that prevents a negative gauge pressure in headers. There is little literature in this field.

Masking shields are effective for shortening the response time of a stop of injection. However, installation space is required, and costs are incurred in installation and maintenance. Therefore, in this research, we studied another way to shorten a response time of a stop of injection.

The evaluation and understanding of the drainage performance of pipe laminar type cooling equipments is insufficient. For this reason, pipe laminar type cooling equipments have been designed empirically, and the optimum conditions have not been established.

In order to propose the optimal pipe laminar type cooling equipment for water drainage performance, quantitative evaluations of drainage characteristics are conducted.

2. Experiment

2.1. Experimental Method

In this research, the experimental apparatus shown in Figs. 1 to 4 was used. Figure 1 shows an outline of the experimental apparatus. Figures 2 and 3 show cross sections A and B of Fig. 1, respectively, and Fig. 4 shows the outline of cross section A of Fig. 1. This apparatus consists of the air inlet tube, the roof part of the header, the bottom part of the header, the orifice, the nozzle and the water inlet. Here, an orifice has a circular hole in a cylinder, and
is installed to obtain a uniform water distribution in the width direction of a pipe laminar type cooling equipment. Although pipe laminar type cooling equipments installed in a mill has a large number of nozzles arranged in the width direction, a single nozzle was used in this research for simplification. Injection of cooling water starts after the water supply valve is opened and cooling water fills the roof part of the header, the orifice and the nozzle (region Y in Fig. 4). The bottom part of the header (region X in Fig. 4) is always filled with cooling water.

After the water supply valve is closed, injection stops by draining the cooling water in the air inlet tube (region Z in Fig. 4), the roof part of the header, the orifice and the nozzle. The air inlet tube is required to supply air to the header, whereas the pressure of the cooling header is operated with positive pressure. Thus, the air inlet tube is filled with water at the water level corresponding to the pressure of the header. If the air inlet tube is not drained and the water in the header is drained from the nozzle, the pressure of the header becomes negative and the drainage time becomes longer. Thus, early drain of the air inlet tube is necessary for shortening the water drainage time. Therefore, we investigated the pressure loss of the air inlet tube and the water level, which influences the drainage capacity. After air enters the header from the air inlet tube, drainage of the cooling equipment is completed by draining the water in the roof part of the header and the nozzle. Thus, it is also important to evaluate the drainage capacity of the nozzle. Therefore, we investigated the influence of the diameter of the orifice, which has an important relationship with the drainage capacity of the nozzle.
In order to observe the change of the water level inside the air inlet tube and to investigate the influence of the squeezing part and the orifice, laboratory experiments were conducted using the equipment shown in Fig. 5. Although only a part of the header is shown in Fig. 5, the header is the same as that shown in Fig. 1. The experimental conditions are shown in Table 1. The water level of the air inlet tube, the diameter of the squeezing part for controlling pressure loss, and the diameter of the orifice were used as parameters. Here, the water level of the air inlet tube means the distance from the boundary between the air inlet tube and the header to the water surface.

In the experiment, the pressure of the water was raised by using a pump. Water supply was started or stopped by opening or closing a valve. First, water was supplied to the header by opening the valve. Supply of the water was then stopped by closing the valve, and the water drainage from the nozzle was observed with a video camera. The frame rate of the video camera was 30 fps, and measurement error occurred at the start and finish of the water drainage. Therefore, the maximum measurement error was 1/15 s. In the experiment for investigating the influence of the water level on the water drainage time, the change of the water level in the air inlet tube was observed with a video camera. Here, the part of the air inlet tube with a water level of 300 mm or more was made of acrylic. Immediately after the supply of water was stopped, the flow of injected water from the nozzle is continuous. After several seconds, the flow of injected water becomes discontinuous. This time is defined as the completion time of water drainage. The water drainage time is defined as the interval of time between stopping the supply of water and the completion time.

2.2. Experimental Results

Figure 6 shows the influence of the water level and the diameter of the orifice on the water drainage time under the condition that the diameter of the squeezing part is 9.2 mm. As the water level decreased, the drainage time became shorter, and the water level and drainage time displayed a linear relationship. As the diameter of the orifice increased, the water drainage time became shorter.

Figure 7 shows the influence of the diameter of the squeezing part and the diameter of the orifice on the water drainage time under the condition that the water level is 600 mm. As the diameter of the squeezing part decreased, the water drainage time became shorter. As the diameter of the orifice increased, the water drainage time became shorter.

2.3. Discussion

Based on the experimental results, it is necessary to increase the drainage capacity of the air inlet tube and the nozzle in order to shorten the water drainage time. The influence of the air inlet tube and the nozzle on the drainage

![Fig. 5. Experimental apparatus.](image)

![Fig. 6. Relationship between height of water level and water drainage time.](image)

![Fig. 7. Relationship between diameter of squeezing part and water drainage time.](image)

| Height of water level | 300, 600, 900, 1200 |
|----------------------|---------------------|
| Diameter of squeezing part | 5.7, 9.2, 12.7 |
| Diameter of orifice | 6.0, 8.0, 10.0 |
capacity was examined. From the results of observing the water level, the water in the air inlet tube was drained first, and then the water in the roof part of the header and in the nozzle was drained. Therefore, the water drainage time is considered to be the sum of the drainage time of the air inlet tube, the roof part of the header and the nozzle.

Regarding the water drainage time of the air inlet tube, it is assumed that the drainage velocity from the initial water level to 300 mm was the same as that under 300 mm. The drainage velocity is obtained from the results of observation of the air inlet tube. The drainage time of the roof part of the header and the nozzle is obtained from the difference between the total drainage time and the drainage time of the air inlet tube.

Figure 8 shows the influence of the diameter of the squeezing part and the orifice on the water drainage time of the roof part of the header, the nozzle and the air inlet tube. The drainage time of the roof part of the header and the nozzle was less influenced by the diameter of the squeezing part and was more influenced by the diameter of the orifice. The influence of the diameter of the orifice on the drainage time of the air inlet tube was small, whereas the influence of the diameter of the squeezing part was large. Thus, it is possible to shorten the water drainage time by increasing the diameter of the orifice and the squeezing part for reducing pressure loss.

3. Calculation Model of Water Drainage Time

3.1. Calculation Model

Guidance for decreasing the water drainage time was obtained from the results in 2·3. In order to clarify the optimum conditions, we attempted to create a calculation model.

As described in 2·3, the total water drainage time is considered to be the sum of the air inlet tube, the roof part of the header and the nozzle. In order to shorten the total drainage time, each of these water drainage times was considered in the calculation model by calculating the pressure loss.

Figure 9 shows an overview of the calculation model. The energy equation for the air inlet tube is represented as formula (1)

\[
\rho v_A^2 \frac{d_1^2}{2} + \rho \left( \lambda_2 + \psi_{12} \right) \frac{v_A^2}{2} + \rho \left( \lambda_3 + \psi_{23} + \zeta_{34} \right) \frac{v_B^2}{2} = \rho g l
\]

(1)

Here, \( \rho \) is the density of water, \( v \) is the velocity in the tube, \( \lambda \) is the coefficient of pressure loss of friction in the tube, \( \psi \) is the coefficient of pressure loss in abrupt pipe expansion, \( \zeta \) is the coefficient of pressure loss in abrupt pipe reduction, \( d \) is the diameter of the tube, \( l \) is the length of the tube, \( A \) is the cross-sectional area of the tube, \( Re \) is the Reynolds number, and \( g \) is the acceleration of gravity. The suffixes \( i \) and \( j \) in formulas (2) to (4) correspond to 1 to 4 shown in Fig. 9. The suffix 5 means the roof part of the header and the suffix \( w \) means the water level of the air inlet tube. Formula (2) was written by Blasius’s equation, \( \lambda = 0.3164Re^{-1/2} \frac{l}{d} \) (2)

formula (3) was written by Borda-Carnot’s equation, \( \psi_{ij} = \left( 1 - \frac{A_i}{A_j} \right)^2 \) (3)

formula (4) was written by Merriman’s equation, \( \psi_{ij} = \left[ \left( 0.582 + \frac{0.0418}{1.1 - (d_i/d_j)} \right)^{-1} - 1 \right]^2 \) (4)

Here, \( v_i A_i = v_2 A_2 = v_3 A_3 = v_4 A_4 \) (5)

In the roof part of the header and the nozzle, it is assumed that the pressure of the header becomes atmospheric pressure after the water drainage of the air inlet tube is completed.

![Fig. 8. Relationship between diameter of squeezing part and water drainage time.](image-url)

![Fig. 9. Experimental apparatus.](image-url)
pleted. The energy equation is represented as formula (6) from the theorem of Bernoulli, and the continuous equation is represented as formula (7).

\[ \rho (\lambda_a + \xi + \eta) \frac{v_a^2}{2} + \rho \lambda_b \frac{v_b^2}{2} = \rho (l_a + b) g \]  
\[ v_a A_a = v_b A_b \]  

Here, \( \lambda_a \) is solved by formula (2), and \( \xi \) is solved by formula (3). \( \eta \) means the pressure loss from the header to the entrance of the nozzle. As the shape of this experimental equipment is a special one and its pressure loss has not been formulated, formulation was carried out by the method described in 3.2 below.

In order to obtain the water drainage time of the air inlet tube, the velocity in the tube was calculated from formulas (1) to (5). Because it is difficult to obtain an analytical solution, the calculation was performed according to the Newton method. Since the right side of formula (1) changes with the water level \( l_w \) and the velocity also changes, the calculation is performed multiple times in increments of 0.005 s until the water level becomes 0, and the water drainage time is obtained.

The velocity in the roof part of the header and the nozzle was calculated from formulas (2), (3), (6) and (7) according to the Newton method. The velocity was converted to the flow rate, and the water drainage time was obtained by dividing the sum of the volume of the roof part of the header and the nozzle by the flow rate. Unlike the air inlet tube, the roof part of the header and the nozzle are calculated only a single time because the pressure of the header is constant at atmospheric pressure and the value of the right side of formula (6) is constant.

### 3.2. Formulation of Pressure Loss

An experiment was conducted in order to obtain the coefficient of pressure loss from the header to the nozzle inlet. The experimental apparatus was almost the same as that in Fig. 1. The diameters of the nozzle used here were 16.1, 21.6 and 27.6 mm, and the diameters of the orifice were 12.7, 16.1 and 21.6 mm and no orifice. The flow rate, the diameter of the nozzle and the diameter of the orifice were changed, and the pressure of the header was measured with a pressure gauge. A Bourdon tube gauge was used as the pressure gauge, and was connected to the air inlet tube in Fig. 1. Since the pressure of the header corresponds to the right side of formula (6), the coefficient of the pressure loss \( \eta \) was obtained by using formula (6). The experimental conditions are shown in Table 2.

The Reynolds number and the diameter of the nozzle and the orifice were related to the pressure loss from the header to the nozzle. The pressure loss was strongly correlated with the Reynolds number of the orifice \( \alpha = \text{Re}_a \) and the diameter of the nozzle. Here, for generalization of the formula, the diameter of the orifice is divided by the nozzle diameter to obtain a non-dimensional expression. This expression \( = \frac{d_o}{d_b} \) is used as the parameter, and is written as formula (8).

\[ \eta = (\frac{d_o}{d_b})^{0.1} \text{Re}_a^{-1.2} \]  

Under the conditions of \( \alpha=0.1, \beta=-1.2, \) the correlation coefficient shows its highest value and \( R^2=0.75. \) As a result, formula (8) is written as formula (9).

\[ \eta = 25.8 \left( \frac{d_o}{d_b} \right)^{0.1} \text{Re}_a^{-1.2} \]  

### 3.3. Comparison of Experimental and Calculated Results

Figure 10 shows a comparison of the experimental results with the calculated results under the condition that the diameter of the squeezing part is 9.2 mm. Figure 11 shows a comparison of the experimental results with the calculated results under the condition that the water level is 600 mm. The plots show the experimental results, and the solid line shows the calculated results. The calculated results show rough qualitative and quantitative agreement with the experimental results. Figure 12 shows a comparison of the experimental results with the calculated results for all data. In this case as well, the calculated results show rough

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**Table 2.** Experimental condition.

| Flow rate  | ×10^{-4} m³/s | 2.3, 4.0, 5.7, 7.3, 9.0, 11, 12, 14 |
|------------|----------------|-----------------------------------|
| Diameter of nozzle | mm | 16.1, 21.6, 27.6 |
| Diameter of orifice | mm | 9.2, 12.7, 21.6, 27.6 |
qualitative and quantitative agreement with the experimental results. **Figure 13** shows a comparison of the experimental results with the calculated results for the time until the water level of the air inlet tube reaches 300 mm from the initial water level. In the experiments of investigating the influence of the water level and the squeezing part, the difference between the experimental results and the calculated results was large in the case that the orifice diameter is 6.0 mm.

### 3.4. Discussion

The reason for the large difference between the experimental results and the calculated results in Fig. 13 is investigated. The conditions that showed a large difference in the results were an orifice diameter of 6.0 mm and squeezing part diameters of 9.2 mm and 12.7 mm. Under these conditions, the calculated flow rate of the water drained from the air inlet tube exceeds that of the water drained from the nozzle. When the water is drained from the air inlet tube, it is drained through the nozzle. Since water drainage was limited by the nozzle under these conditions, the calculation model for these conditions was changed.

The flow rate of the air inlet tube is calculated by using formulas (1) to (5). However, for the conditions under which the flow rate of the air inlet tube is limited by that of the nozzle, the flow rate of the air inlet tube is calculated by using formulas (10), (6) and (7).

\[
\rho \left( \lambda_a + \xi + \eta \right) \frac{v_a^2}{2} + \rho \lambda_b \frac{v_b^2}{2} = \rho (l_a + l_b) g \quad \ldots \quad (10)
\]

This calculation method is almost the same as that of calculating the flow rate of water injected from the nozzle. Because the pressure of the header increases depending on the water level of the air inlet tube, \( \rho l_{w, g} \) is added to the right side of formula (6). Since the velocity changes with the water level, the calculation is performed multiple times in increments of 0.005 s until the water level becomes 0, and the water drainage time is obtained. However, when the water level becomes sufficiently low, the flow rate of the air inlet tube is not limited by that of the nozzle. Therefore, the water drainage time is calculated by using formula (1) to (5) below that water level.

**Figure 14** shows a comparison of the experimental results with the modified calculated results for the water drainage time. The water drainage time is where the water level of the air inlet tube changes from the initial level to 300 mm. The calculated results are substantially in agreement with the experimental results.

### 4. Study on Shortening Water Drainage Time

Optimization of the air inlet tube is conducted by using the modified calculation model. As described above, the pressure loss of the air inlet tube and the nozzle influences the water drainage time. On the other hand, the diameter of the orifice, which determines the pressure loss of the nozzle, also affects the flow distribution in the width direction of a pipe laminar type cooling equipment. Therefore, optimization was conducted only for the pressure loss of the air inlet tube.

In order to shorten the water drainage time, it is preferable that the pressure loss of the air inlet tube is small. Therefore, a squeezing part is not used, and the diameter of the air inlet tube is uniform. **Figure 15** shows the relationship between the diameter of the air inlet tube and the water drainage time under the conditions that the diameter of the orifice is 8.0 mm and the water level of the air inlet tube is 1 200 mm. The shortest water drainage time is obtained when the diameter of the air inlet tube is 12 mm. This is because the water drainage of the air inlet tube is limited by that of the
nozzle when the diameter of the air inlet tube is larger than 12 mm. As the diameter of the air inlet tube increases, the pressure loss of the air inlet tube decrease. On the other hand, as the water level increases, the amount of water also increases. Therefore, the water drainage time increases under the condition that the water drainage of the air inlet tube is limited by that of the nozzle.

5. Summary

Experiments in the laboratory and calculations were conducted with experimental equipment simulating the pipe laminar type cooling equipment of the run-out table in the hot rolling process. The following results were obtained:

1. The water drainage time is the sum of the water drainage time of the air inlet tube, the roof part of the header and the nozzle.
2. The water drainage time decreases if the pressure loss of the air inlet tube, the roof part of the header and the nozzle decreases.
3. The results of calculations using the model created in this research qualitatively agreed with the experimental results.
4. The calculated water drainage time shows its minimum value when the diameter of the water inlet tube is 12 mm under the conditions that the diameter of the orifice is 8.0 mm and the water level of the air inlet tube is 1 200 mm.

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