A Method for Controlling the Temperature Rise of Steel Panels during a Fire
Part 2 Behavior of the Water Film and Heat Transfer

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1. INTRODUCTION

The structural members of a building which are subjected to heating during a fire significantly lose structural stability. The rising temperature not only weakens the bearing force of the structural members but also assists in spreading the fire further by heating the surface of the compartmental members that are not exposed to the heat directly. The temperature of the structural members increases due to the heat transferred through the flame or the heated air. This experiment aimed at establishing a technique for controlling the temperature rise in the members by forming a water film, by using a sprinkler system that reduces the incoming heat transfer to the surface of the members subjected to heating. This report illustrates the experimental and analytical results with respect to the fundamental behavior of the water film that is formed on the surface of the member in particular the heat transfer properties of a steel plate subjected to heating.

2. PROPERTIES OF WATER FILM IN THE ABSENCE OF HEATING

In order to understand the fundamental properties of the water film with the equipment used in this experiment, the properties were assessed without using the radiant panel. In particular, this report describes the aspects regarding the thickness and the falling rate of the water film.

2.1 Basic equations governing the properties of the water film

By regarding the water film as a viscous fluid that would be formed by sprinkling water on the surface of the test object, and the flow of the water film as a Couette-Poiseuille flow, the thickness $\delta$ of the water film can be expressed through the following equation:
\[ \delta = \sqrt{\frac{3\mu Q}{\rho g}} \]  

(1)

The average falling rate of the water film, \( U_{\text{ave}} \), becomes
\[
U_{\text{ave}} = \frac{Q}{\delta} = \frac{2}{3} (U)_{y=\delta}
\]  

(2)

Here, the Reynolds number is
\[
R_e = \frac{U_{\text{ave}} h}{v} = \frac{Q}{\nu} = \frac{Q \rho}{\mu}
\]  

(3)

Therefore, the thickness of the water film \( \delta \) can be written as
\[
\delta = \sqrt{\frac{3\mu R_e}{\rho^2 g}} = \sqrt{\frac{3\nu^2 R_e}{g}}
\]  

(4)

Furthermore, by using the Reynolds number, the average falling rate of the water film can be expressed as follows:
\[
U_{\text{ave}} = \frac{1}{3} \sqrt{\frac{9g \mu R_e^2}{\rho}}
\]  

(5)

### 2.2 Thickness and falling rate of the water film

Figure 1 shows the relation between the maximum thickness, the time-averaged thickness of the water film as obtained from this experiment, and the Reynolds number on the other. Figure 2 shows the results based on the maximum thickness and the time-averaged thickness of the water film, as measured through the PIV system versus the Reynolds number. According to each result, the thickness and the falling rate of the water film increases approximately by a gradient of 1/3 and 2/3 as the Reynolds number increases as calculated from Equations 4 and 5.

![Figure 1 Relation between the thickness of the water film and the Reynolds number](image-url)
3. **HEAT TRANSFER PROPERTIES OF WATER FILM AND STEEL PLATE DURING HEATING**

3.1 **Temperature of the water film**

*Figure 3* illustrates the vertical temperature distribution of the water film. The result shown here corresponds to a distance $R$ between the radiant panel and the steel plate of 0.6 m and 1.5 m. As shown in *Figure 3*, in the vicinity where the supplied water flowed out from the slit of the watering tank (horizontal axis at 0 m is the position of the slit, and the length shown on the horizontal axis indicates the distance downward), the water temperature is approximately 16 to 17°C, which is almost the same temperature as when the water was put into the tank. However, the temperature of the water film increases as the water falls downward, and it reaches approximately 315K and 326K at 35L/min and 25L/min, respectively. The rate of the temperature rise tends to become greater when the water supply is lower, as well as when the distance $R$ between the radiant panel and the test object is shorter.

3.2 **Temperature of the steel plate**

*Figure 4* presents the result for the vertical temperature distribution of the steel plate. According to this result, when comparing the temperature of the steel plate under the same experimental conditions as the temperature of the water film, the temperature of the steel plate is slightly lower, and the inclination of the temperature rise also tends to be gradual.

3.3 **Heat transfer**

*Figure 5* shows the sorted results of plotting the thermal difference between the water film $T_w$ and the steel plate $T_s$ to the $x$-axis, and the heat transfer coefficient to the $y$-axis.
Here, the heat transfer coefficient on the $y$-axis is the result which was calculated from the temperatures of the water film and the steel plate as obtained from this experiment, using the analytical model for heat transfer described in Part 1 of this experiment. Based on this, it was found that the heat transfer coefficient is approximately 0.3 to 0.5 kW/m$^2$/K.

Figure 6 presents the calculated result with respect to the temperature of the water film ($x$-axis) and the net incoming heat flux to the steel plate ($y$-axis) by using the analytical model for heat transfer. According to this result, the incoming heat flux to the steel plate increases linearly as the temperature $T_w$ of the water film increases.

4. CONCLUSION

The experimental results regarding the behavior of the water film and the properties of the heat transfer to the steel plate were illustrated in this report. The analytical model for heat transfer was used to identify the properties of the heat transfer. As a result, the behavior of the water film formed on the surface of the steel plate in the absence of heating and the properties of the heat transfer with respect to the water film and the steel plate during heating were quantitatively investigated. Since it is difficult to identify the behavior of the water film when it is subjected to heating with this experimental equipment, the heat transfer between the water film and the steel plate was analyzed through the temperature distribution of the steel plate that undergoes the heat exposure. In future experiments, it will be necessary to collect more experimental and analytical quantitative data with respect to the properties of the heat transfer from the radiant panel to the specimen, in order to establish a temperature prediction tool for structural members that takes into account the heat reduction effect of the water film.

![Figure 3: Horizontal temperature distributions of the water film](image)

1) 35L/min 2) 25L/min

*Figure 3  Horizontal temperature distributions of the water film*
1) 35L/min  
2) 25L/min

Figure 4  Vertical temperature distributions of the surface of the non-heated specimen

Figure 5  Heat transfer rate

Figure 6  Temperature of the water film and net heat flux

REFERENCES


SYMBOLS

- $\rho$: density (kg/m$^3$)
- $\nu$: kinematic viscosity coefficient (m$^2$/s)
- $\mu$: viscosity coefficient (pa.s)
- $\delta$: Thickness (m)
- $g$: gravitational acceleration (m/s$^2$)
- $h$: heat transfer coefficient (kW/m$^2$/K)
- $U$: Rate (m/s)
- $Q$: water amount (m$^3$/m.s)
- $Re$: Reynolds number

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