

EFFECTS OF EVAPORATION WATER FLOW RATE ON THE COOLING PERFORMANCE OF AN INDIRECT EVAPORATIVE COOLER.

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ABSTRACT

In evaporative cooling applications, the evaporation water is supplied usually sufficiently larger than the amount evaporated to enlarge contact surface between the water and the air. Especially in indirect evaporative coolers, however, if the evaporation water flow rate is excessively large, the evaporative cooling effect is not used for heat absorption from the hot fluid but spent to the sensible cooling of the evaporation water itself. This would result in a decrease in the cooling performance of the indirect evaporative cooler. In this study, the effects of the evaporation water flow rate on the cooling performance are investigated theoretically. The cooling process in an indirect evaporative cooler is modeled into a set of linear differential equations and solved to obtain the exact solutions to the temperatures of the hot fluid, the moist air, and the evaporation water. Based on the exact solutions, it is analyzed how much the cooling performance is affected by the evaporation water flow rate. The results show that the decrease in the cooling effectiveness is substantial even for a small flow rate of the evaporation water and the relative decrease is more serious for a high performance evaporative cooler.

NOMENCLATURE

A	Heat transfer surface area [m^2]
C	Heat capacity ratio
c	Specific heat [kJ/kg K]
c_{wb}	Wet bulb specific heat [kJ/kg K]
h	Heat transfer coefficient [$\text{W/m}^2 \text{K}$]
i	Enthalpy [kJ/kg]
L	Length of the channel [m]
Le	Lewis number
$\dot{m}$	Mass flow rate [kg/s]
N	NTU
T	Dry bulb temperature [$^{\circ}\text{C}$]
t	Wet bulb temperature [$^{\circ}\text{C}$]
W	Width of channel [m]
x^*	Dimensionless length from the top end

Greek letters

ε	Effectiveness
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θ_w	Dimensionless temperature of evaporation water
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Subscripts

1	Top end of the channel
2	Bottom end of the channel
a	Air channel
h	Hot channel
w	Evaporation water

INTRODUCTION

Heat can be dissipated more effectively if the cooling effect brought by water evaporation is applied to a heat exchanger. Common examples of such application include cooling towers, evaporative condensers, evaporative coolers, evaporative air coolers, etc. In cooling towers, evaporative condensers and evaporative coolers, heat from the hot fluid is dissipated to the atmospheric air by direct or indirect contact through not only sensible heat exchange but also evaporative latent heat exchange. The cooling performance of such devices is known to be improved much by the effect of water evaporation. (1)~(4)

In the application of evaporative cooling, it is desirable that the evaporation water spreads widely to enlarge contact surface between the water and the air. In this respect, the evaporation water is supplied usually sufficiently larger than the amount evaporated. Though the large flow rate improves the surface wettedness undoubtedly, the water film tends to thicken to cause the increases in the thermal resistance across the film and the flow resistance to the air stream over the water film. Furthermore, especially in indirect evaporative coolers, if the evaporation water flow rate is excessively large, the evaporative cooling effect is not used for heat absorption from the hot fluid but spent to the sensible cooling of the evaporation water itself. This would result in a decrease in the cooling performance of the indirect evaporative cooler.

The effects of the evaporation water flow rate on the cooling performance are investigated theoretically in this study. The cooling process in an indirect evaporative cooler is modeled into a set of linear

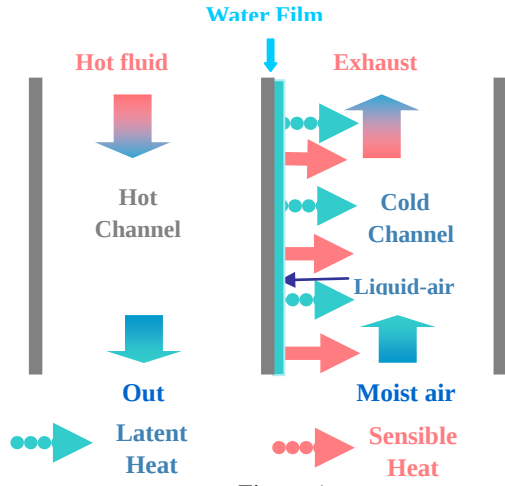


Figure 1

Heat transfer in an indirect evaporative cooler

differential equations and solved to obtain the exact solutions to the temperatures of the hot fluid, the moist air, and the evaporation water. Using the exact solutions, the changes in the temperature distributions with the increase in the evaporation water flow rate are investigated.

It is also analyzed how much the cooling performance is affected by the evaporation water flow rate. Finally, the exact solution is simplified to yield a simple correlation between the cooling performance and the evaporation water flow rate.

THEORETICAL ANALYSIS

The indirect evaporative cooler investigated in this study is shown schematically in Fig. 1. The cooler consists of two channels separated by a thermally conductive plate. The evaporation water flows downward along the separation plate in the cold channel and is cooled evaporatively by the airflow in direct contact with the water flow. Then the temperature difference between the hot fluid and the evaporation water causes heat transfer from the hot fluid to the evaporation water. The heat transferred to the evaporation water is finally dissipated to the air partly by the sensible heat transfer and partly by the latent heat transfer. To analyze the heat transfer process theoretically, following assumptions are applied. ^{(5)~(7)}

1. The heat transfer in each channel is fully developed.
2. Variation of thermophysical properties with temperature is negligible.
3. Lewis number for the air-moisture mixture is considered 1.0.
4. Conductive resistance through the separation plate and the water film is negligibly small compared with the convective resistance either in the hot fluid or the moist air.
5. Enthalpy of the moist air is a linear function of the wet bulb temperature ($\Delta i_a = c_{wb} \Delta t_a$).

With these assumptions, the heat transfer in the indirect evaporative cooler can be described as follows:

$$\frac{dt_a}{dx^*} = N_a (t_a - T_w) \quad (1)$$

$$\frac{dT_h}{dx^*} = N_h (T_w - T_h) \quad (2)$$

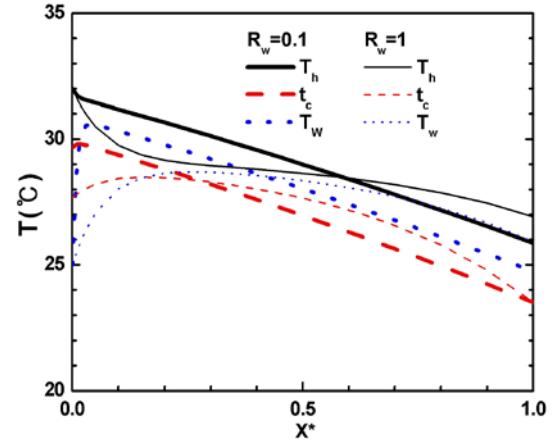


Figure 2

Temperature distributions in the evaporative

$$N_h (T_h - T_w) + C \cdot N_a (t_a - T_w) - R_w \frac{dT_w}{dx^*} = 0 \quad (3)$$

$$N_h = \frac{h_h A}{c_h \dot{m}_h}, \quad N_a = \frac{h_a A}{c_a \dot{m}_a}, \quad C = \frac{c_{wb} \dot{m}_a}{c_h \dot{m}_h}, \quad (4)$$

$$R_w = \frac{c_w \dot{m}_w}{c_h \dot{m}_h}, \quad x^* = x / L$$

In the above equations, T is the temperature, t the wet bulb temperature of the moist air, N the number of transfer unit (Ntu), C the ratio of the effective thermal capacity between the hot fluid and the moist air, and R_w is the ratio of the thermal capacity between the evaporation water and the hot fluid. The subscripts, h , w , and a imply the hot fluid, evaporation water, and the moist air, respectively. Since the equations (1)~(3) are the simultaneous linear differential equations, the solutions can be obtained in an analogous manner to solving the simultaneous algebraic equations. Through a lengthy manipulation, exact solutions to the temperatures of the hot fluid, the evaporation water, and the moist air were obtained but are not shown here for brevity.

RESULTS AND DISCUSSIONS

The temperature distributions in the indirect evaporative cooler evaluated from the exact solutions are depicted in Fig. 2 for two different evaporation water flow rates. In this figure, the inlet temperatures of the hot fluid and the water were given as 32 °C and 25 °C, respectively, and the inlet wet bulb temperature of the moist air was 23.5 °C. When the flow rate of the evaporation water is small, i.e., $R_w = 0.1$, the water temperature increases rapidly directly after the water is supplied to the channel and then decreases gradually due to the evaporative cooling effect as it flows down. In this case, the effect of the inlet temperature of the evaporation water is confined to a narrow region near the inlet of the water. Meanwhile, when the flow rate of the evaporation water is large, i.e., $R_w = 1.0$, the temperature distribution of the evaporation water is found more uniform along the flow direction. This is because the water temperature does not change instantly in this case due to the large thermal inertia from the large flow rate. As a result, the temperature of the hot fluid is higher at the outlet end for a larger flow rate of the evaporation water, which appears as a decrease in the cooling performance.

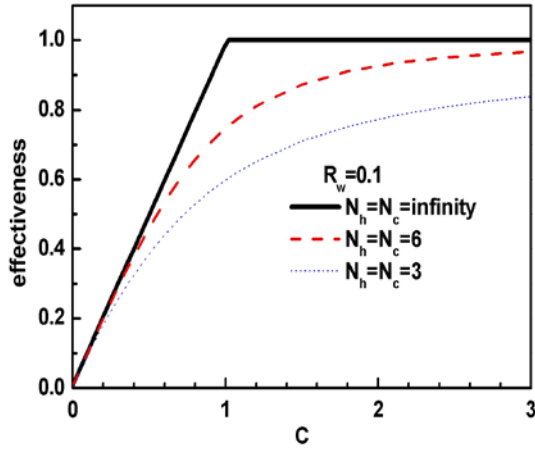


Figure 3

Effect of heat capacity ratio on the effectiveness.
($T_{h1} = 32^\circ\text{C}$, $t_{c2} = 23.5^\circ\text{C}$, $T_{w1} = 25^\circ\text{C}$)

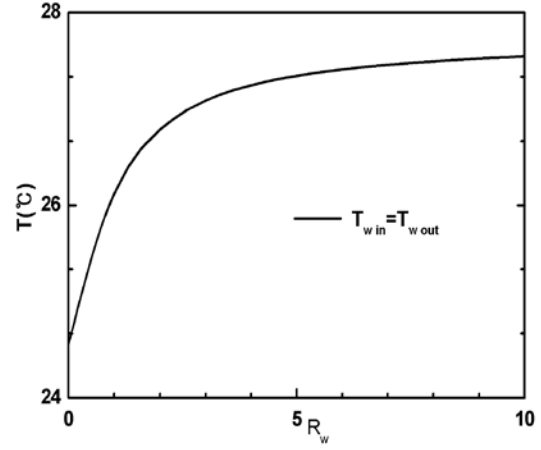


Figure 4

Circulation temperature of the evaporation water.
($N_h = N_c = 6$, $T_{h1} = 32^\circ\text{C}$, $t_{c2} = 23.5^\circ\text{C}$, $C = 1$)

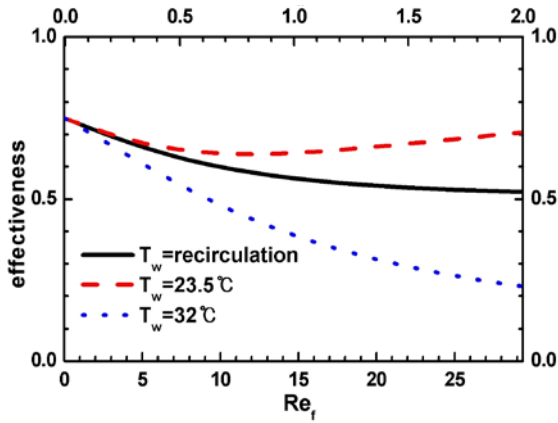


Figure 5

Effect of evaporation water flow rate on the effectiveness
($N_h = N_c = 6$, $T_{h1} = 32^\circ\text{C}$, $t_{c2} = 23.5^\circ\text{C}$, $C = 1$)

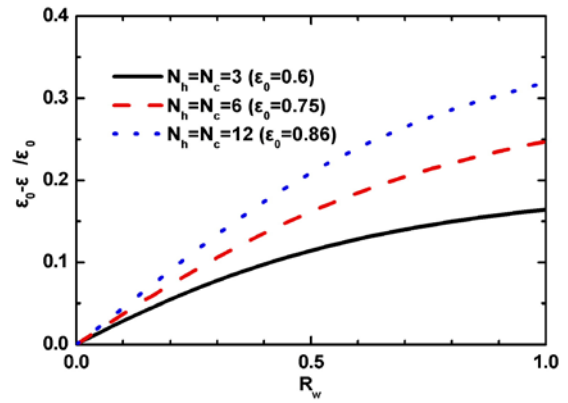


Figure 6

Relative decrease of effectiveness with the evaporation water flow rate.
($T_{h1} = 32^\circ\text{C}$, $t_{c2} = 23.5^\circ\text{C}$, $C = 1$)

The cooling performance of the indirect evaporative cooler can be evaluated by the effectiveness defined as

$$\varepsilon = \frac{T_{h1} - T_{h2}}{T_{h1} - t_{c2}} \quad (5)$$

where the subscripts, 1 and 2 imply the top end and the bottom end of the evaporative cooler shown in Fig. 1, respectively. Figure 3 shows the effect of the thermal capacity ratio of the moist air to the hot fluid on the cooling performance. As in common heat exchangers, the effectiveness increases as the thermal capacity ratio increases. However, since the increase of the thermal capacity ratio requires the excessively large flow rate of the air compared with that of the hot fluid, the balanced thermal capacity between the channels, i.e., the thermal capacity ratio of one is reasonable for practical applications in general.

In practical applications of the evaporative coolers, the evaporation water is usually circulated in the cooler with a small amount of compensation for the water evaporated. In such cases, the water temperature at the inlet of the cooler becomes the same as at the outlet and thus is determined during the process depending on the operation condition.

For a typical case of an indirect evaporative cooler, the circulation water temperature was evaluated as a function of the water flow rate and is shown in Fig. 4. It is found that the circulation water temperature increases as the water flow rate increases.

Figure 5 shows the effect of the evaporation water flow rate on the cooling effectiveness. Three cases of different evaporation water temperatures are depicted in this figure. As the evaporation water flow rate increases, the cooling effectiveness decreases and the degree of the decrease is larger for a higher inlet temperature of the evaporation water. In case of the water circulation, the decrease in the effectiveness is about 20% when $R_w = 1.0$. In this figure the evaporation water flow rate is also shown in terms of the film Reynolds number. The relation between the nondimensional water flow rate and the film Reynolds number can be written as

$$Re_f = 4R_w \frac{\dot{m}_h c_h / W}{\mu_w c_w} \quad (6)$$

The film Reynolds number in Fig. 5 is evaluated from equation (6) referring to the case of a typical indirect evaporative air cooler. It is noteworthy that the film Reynolds number should be controlled lower

than 10 to prevent a large decrease in the cooling performance due to the evaporation water.

Figure 6 shows the relative decrease in the effectiveness compared with the effectiveness in case of negligible effect of the evaporation water, ε_0 . When the evaporation water flow rate is small, the relative decrease is found linearly dependent on the evaporation water flow rate. The relative decrease ranges from 10 to 20% when $R_w = 0.5$. It is also found that the relative decrease is larger for a higher value of ε_0 , which implies the effect of the evaporation water flow rate is more serious for a high performance evaporative cooler.

The exact solution to the hot fluid temperature is simplified for extremely small water flow rates to yield the correlation between the relative decrease of the effectiveness and the water flow rate as follows:

$$\frac{\varepsilon_0 - \varepsilon}{\varepsilon_0} \approx R_w \left\{ \frac{1}{N_c} \cdot \theta_w + \varepsilon_0 \cdot \frac{N_c^2 - 2}{2 \cdot N_c^2} \right\}, \quad (7)$$

$$\left(\varepsilon_0 = \frac{N_h \cdot N_c}{N_h + N_c + N_h N_c}, \quad \theta_w = \frac{T_{w1} - t_{c2}}{T_{h1} - t_{c2}} \right)$$

The simple correlation was found to agree relatively well with the results in Fig. 6 for the water flow rate smaller than 0.5. As the equation shows explicitly, the relative decrease in the effectiveness depends on ε_0 as well as R_w .

CONCLUSION

In this study, the effects of the evaporation water flow rate on the cooling performance are investigated theoretically.

The cooling process in an indirect evaporative cooler is modeled into a set of linear differential equations and solved to obtain the exact solutions to the temperatures of the hot fluid, the moist air, and the evaporation water.

Based on the exact solutions, it is analyzed how much the cooling performance is affected by the evaporation water flow rate. The results show that the decrease in the cooling effectiveness is substantial even for a small flow rate of the evaporation water and the relative decrease is more serious for a high performance evaporative cooler.

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