International Journal of Air-Conditioning and Refrigeration Vol. 13, No. 2 (2005)/pp. 99-106

Experimental Study on the Hydrophilic Porous Film Coating for Evaporative Cooling Enhancement

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Key words: Evaporative cooling, Wettedness, Porous film coating, Surface characteristics

ABSTRACT: Falling film heat transfer has been widely used in many applications in which heat and mass transfer occur simultaneously, such as evaporative coolers, cooling towers, absorption chillers, etc. In such cases, it is desirable that the falling film spreads widely on the surface to form a thin liquid film to enlarge contact surface and to reduce the thermal resistance across the film and/or the flow resistance to the vapor stream over the film. In this respect, hydrophilic treatment of the surface has been tried to improve the surface wettability by decreasing the contact angle between the liquid and the surface. However, the hydrophilic treatment was found not very effective to increase the surface wettedness of inclined surfaces, since the liquid flow forms rivulet patterns instead of a thin film as it flows down the inclined surface and accelerates gradually by the gravity. In this work, a novel method is suggested to improve the surface wettedness enormously. In this work, the surface is treated to have a thin hydrophilic porous layer on the surface. With this treatment, the liquid can spread widely on the surface by the capillary force resulting from the porous structure. In addition to this, the liquid can be held within the porous structure to improve surface wettedness regardless of the surface inclination. The experiment on the evaporative cooling of inclined surfaces has been conducted to verify the effectiveness of the surface treatment. It is measured that the latent heat transfer increases almost by 80% at the hydrophilic porous layer coated surface as compared with the untreated surface.

Nomenclature

A : area [m^2]
c : mass fraction of the water vapor [kg/kg]
C_p : specific heat [J/kgK]
h : heat transfer coefficient [W/m^{2}K]
h_m : mass transfer coefficient [kg/m^{2}s]
i_{fg} : latent heat of water [J/kg]
$\dot{m}$: mass flow rate [kg/s]
q : heat flux [W/m^2]
Re : film Reynolds number, $4\Gamma/\mu_l$
T : temperature [℃]

Greek symbols

Γ : mass flow rate per unit length [kg/ms]
μ_l : viscosity of the water [kg/ms]
σ : wettedness

Subscripts

a : air

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h : hot side
i : inlet
o : outlet
s : dry surface
w : wet surface

1. Introduction

Falling film heat transfer has been widely used in many applications in which heat and mass transfer occur simultaneously, such as evaporative coolers, cooling towers, absorption chillers, etc. In such cases, it is desirable that the falling film spreads widely on the surface to form thin liquid film to enlarge contact surface and to reduce the thermal resistance across the film and/or the flow resistance to the vapor stream over the film. In this respect, a significant effort has been devoted to developing adequate surface treatment techniques to increase the surface wettability over many years.

Kim(1) reported the evaporation heat transfer increases almost by 100% on the low-fin tube as compared with that on plain tubes. Kim et al.(2) employed hydrophilic surface treatment and reported an increase in the evaporation heat transfer from the horizontal tube bundles simulating the evaporator of an absorption chiller.

In this work, a novel method is suggested to improve the surface wettedness enormously. In this work, the surface is treated to have thin hydrophilic porous layer on the surface as schematically shown in Fig. 1. With this treatment, the liquid can spread widely on the surface by the capillary force resulting from the porous structure. In addition to this, the liquid can be held within the porous structure to improve surface wettedness regardless of the surface inclination.

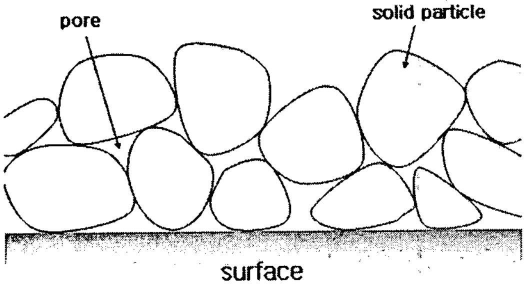


Fig. 1 Schematic of porous layer coating.

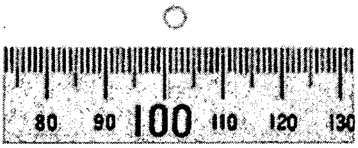
The experiment on the evaporative cooling of inclined surfaces has been conducted to verify the effectiveness of the surface treatment. Three aluminum plates with the untreated, the hydrophilic polymer coated, and the hydrophilic porous layer coated surfaces are tested and the evaporation heat transfer from each surface is compared. The experimental results are analyzed comprehensively to investigate the effect of the surface wettedness on the evaporative heat transfer from the surface.

2. Comparison of wettedness

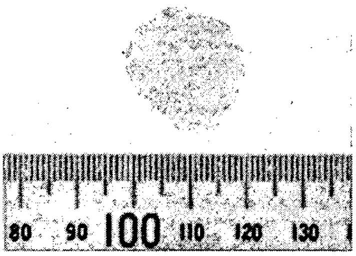
Figure 2 shows the comparison of the surface wettedness of three horizontal surfaces with different surface characteristics. The wetted area by water droplets of the same size is shown to increase enormously by the porous layer treatment as compared with the untreated or the hydrophilic polymer coated surface.

The porous layer treatment can be obtained by employing thermal spray process or coating solid particles on the surface using adequate reactive adhesives. In this work, the latter method was applied. The solid particle is 10~30 μm in diameter and the resulting coating thickness is about 50 μm.

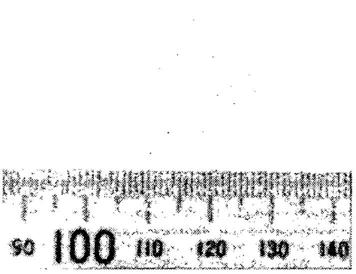
The water flow on inclined surfaces develops into various forms depending on the inclination angle, the water flow rate, the contact angle against the surface, etc.(3,4) Though increasing water flow rate may improve the surface wettedness, it also causes an increase in the film thickness resulting in an increase in the thermal resistance across the film, an increase in the circulation energy consumption and many other secondary losses due to the unnecessarily



(a) Bare surface, d=4 mm



(b) Hydrophilic polymer coated surface, d=15 mm



(c) Porous coated surface, d=30 mm

Fig. 2 Spreading of a droplet on the horizontal surfaces ($V_{droplet}$=0.013 cc).

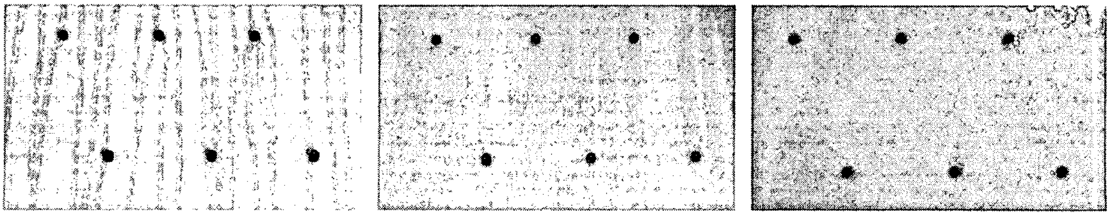
large circulation flow rate.(5)

The water flow patterns on the three inclined plates with different surface characteristics are displayed in Fig. 3. The plates are 300 mm wide and 200 mm high, and are inclined with an angle of 70° from the horizon. The water is supplied from 1 mm diameter holes arranged in the interval of 15 mm from the top edge of the plate. The water flow rate in Fig. 3 is 0.1 lpm.

The water flow spreads more widely on the hydrophilic polymer coated surface as compared with the untreated surface. Even on the hydrophilic polymer coated surface, however, the water flow forms a rivulet pattern and the rivulet becomes narrower as it flows down to accelerate due to the gravity. Consequently, the hydrophilic surface treatment is found not to be effective enough to make the inclined surface fully wet with a thin water film. Meanwhile, since the water on the hydrophilic porous layer coated surface spreads easily due to the capillary action, the water flow forms a thin film covering the surface completely even though the water is first supplied to the surface in the form of rivulets from the water distributor. This implies the surface can be made fully wet by the porous layer treatment even with a small water flow rate regardless of the specific feature of the water distributor.

Similar comparative images were obtained for water flow rates of 0.2 and 0.3 lpm. The surface wettednesses were evaluated by processing the images and are arranged in Table 1. The wettedness, σ, is defined as the ratio between the wetted area to the total surface area. The film Reynolds number is defined as

$$\mathrm{Re} = \frac{4\Gamma}{\mu_l} \tag{1}$$



(a) Bare surface (b) Hydrophilic polymer coated surface (c) Porous layer coated surface

Fig. 3 Flow patterns on inclined surfaces with different surface characteristics (inclination: 70°).

Table 1 Wettedness of various surfaces

	Film Re	σ (%)
Bare surface	31.8	29.5
	63.5	30.5
	95.3	31.0
Polymer coated surface	31.8	65.3
	63.5	73.6
	95.3	77.0
Porous layer coated surface	31.8	100
	63.5	
	95.3	

Table 1 shows the wettedness decreases as the water flow rate decreases in both cases of the untreated and polymer coated surfaces. This is because the uniform supply of the water from the distributor is more difficult for smaller water flow rates. On the contrary, the porous layer coated surface maintains fully wet condition regardless of the flow rate or the uniformity of the supply distribution.

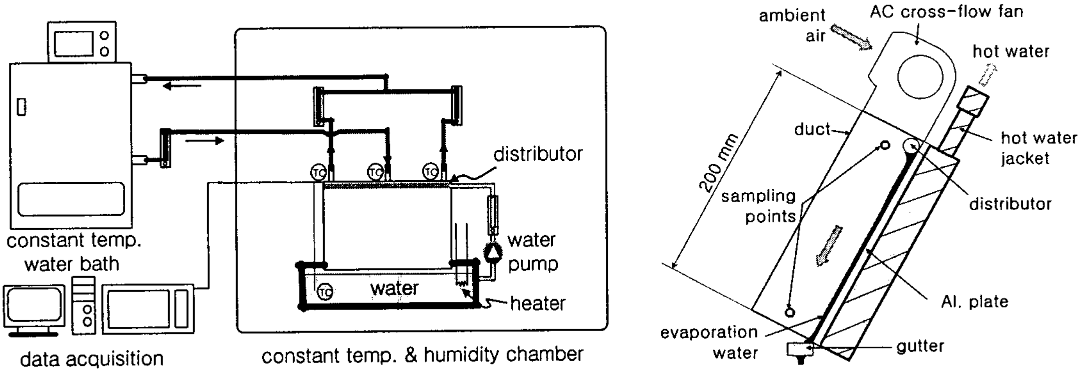
3. Experimental setup

The experiment was carried out on the evaporative cooling of the inclined plates having different surface conditions, i.e., the untreated aluminum surface, hydrophilic polymer coated surface, and the porous layer coated surface.

The schematic of the experimental setup is shown in Fig. 4. The test section is composed of the inclined plate of 300 mm wide and 200 mm high and the air duct placed on the plate. At the back of the plate, water jacket made of copper is attached securely to maintain the plate temperature uniform and constant. The evaporation water to cool evaporatively the inclined plate is supplied from a water distributor closely situated on the top edge of the plate. The water having flown down the plate gathers in a reservoir at the bottom of the test section and recirculates to the water distributor. The test section including the evaporation water circulation system was placed in a constant temperature and humidity chamber to control the ambient air condition surrounding the test section.

Five thermocouples were inserted to measure the temperature distribution of the plate between the aluminum plate and the water jacket; one at the center of the plate and four near each of the corners. The hot water, 40℃ in temperature is supplied from a constant temperature bath to the water jacket through an inlet at the top center of the water jacket. The water flows out of the two outlets each at the top corners, and returns to the water bath. The flow rate of the hot water was measured and adjusted by a rotameter.

An air duct with constant cross section of



(a) Schematic of experimental setup (b) Detail of the test-section

Fig. 4 Experimental setup.

Table 2 Experimental conditions

	Unit	Condition	Accuracy
Ambient condition	Temperature [℃]	24, 28, 32, 36	±0.1℃
	RH [%]	30, 50, 70	±0.5%
	Air velocity [m/s]	1.5	±3%
Hot water	Temperature [℃]	40	±0.1℃
	Flow rate [lpm]	1.0	±3%
Evaporation water	Flow rate [lpm]	0.1, 0.2, 0.3	±3%

320 mm by 80 mm is placed on top of the plate as shown in Fig. 4(b). At the upstream of the duct, a cross flow fan is situated to control the air flow rate. The air temperature was measured at four points, two at the upstream and the other two at the downstream. The average dew point temperature of the air was measured by sampling the equal amounts of air from the four points where the temperature sensors are located.

The water distributor supplying the evaporation water to the plate is made of a copper tube with multiple holes of 1 mm diameter arranged in the interval of 15 mm. The distributor is closely attached to the top edge of the inclined plate so that the evaporation water flows continuously out of the holes instead of dripping. The flow rate of the evaporation water was adjusted and measured by a rotameter.

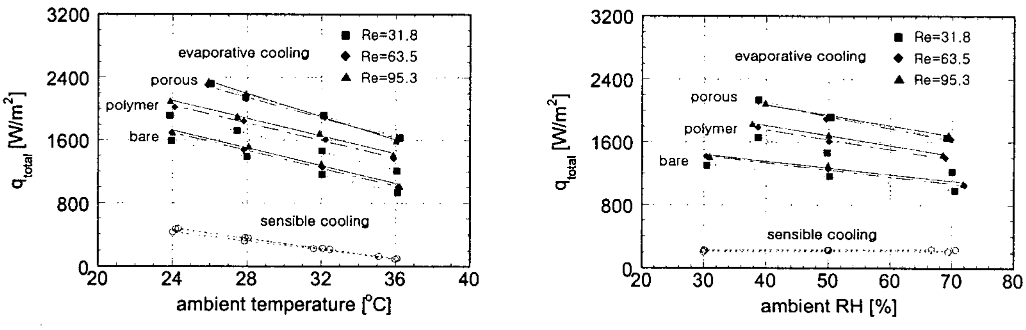
The supply temperature of the evaporation water was measured by two thermocouples inserted from each end of the water distributor. The water temperature after the water having flown down the inclined surface was also measured at the gutter placed at the bottom edge of the plate. To prevent sensible cooling by the evaporation water, the supply temperature of the water was controlled to have the same temperature as the return water after the evaporation process by an electric heater submerged in the water reservoir. The test section and the water reservoir were insulated with Styrofoam of 20 mm in thickness.

The experiment was performed in various ambient temperature and humidity conditions with three different flow rates of the evaporation water. The conditions are arranged in Table 2.

4. Discussion

4.1 Heat flux

The evaporative heat transfer from the in-



(a) Ambient RH: 50%

(b) Ambient temperature: 32℃

Fig. 5 Effects of ambient conditions on the total heat flux.

clined surface is evaluated from the hot water side as

$$q_{total} = \dot{m}_h C_{p,h}(T_{h,i} - T_{h,o})/A \qquad (2)$$

Figure 5 shows the total heat flux variations each at the untreated surface, the polymer coated surface, and the porous layer coated surface for various ambient air condition. For the sake of comparison, the heat flux when the plate is only sensibly cooled without the supply of evaporation water is also presented in the figure. The heat flux at the porous layer coated surface is found the largest and that at the untreated surface is the smallest. As compared with the heat flux at the untreated surface, the heat flux at the polymer coated surface increases by 30% and at the porous layer coated surface increases the heat flux by 60% in average within the tested range. The increase in the heat flux is attributed undoubtedly to the increase in the wettedness due to the surface treatment.

The heat flux when the plate is sensibly cooled is found almost unchanged regardless of the surface characteristics. This indicates the coating thickness is thin enough that the additional thermal resistance due to the coating is negligibly small.

4.2 Heat and mass transfer coefficients

The heat transfer from a surface containing wetted area comprises the sensible heat transfer from the dry and wet surfaces and the latent heat transfer from the wet surface. The heat flux is expressed as

$$\begin{aligned} q_{total} &= q_{sensible} + q_{latent} \\ &= h\sigma(T_w - T_a) + h(1-\sigma)(T_s - T_a) \qquad (3) \\ &\quad + h_m\sigma(c_w - c_a)i_{fg} \end{aligned}$$

The temperature of the dry surface, T_s, is evaluated as the average of the values measured by the five thermocouples placed underneath the plate between the plate and the hot water jacket. The temperature of the plate is found to have a symmetrical distribution with respect to the center, and the deviation from the average was measured less than ±0.7℃. Considering the thermal resistance across the aluminum plate, the difference between the actual surface temperature and the averaged value is estimated less than 0.1℃. The temperature of the wet surface, T_w, is evaluated as the average of the evaporation water temperatures measured at the water distributor and at the water gutter.

The heat transfer coefficient, h, and the mass transfer coefficient, h_m, at each of the surfaces are obtained using the least square error method by substituting into Eq. (3) the values of q_{total}, T_w, T_s, and σ from various experiment conditions. The resultant values are arranged in Table 3.

In case of the porous layer coated surface, the heat transfer coefficient is almost the same in either cases of the sensible heat transfer or the evaporation heat transfer. The relative rate of the mass transfer to the heat transfer, $h_m C_{p,a}/h$, is found 1.01.

In case of the untreated surface, the heat transfer coefficient is found about 20% larger and the mass transfer coefficient is almost

Table 3 Heat and mass transfer coefficients at various surfaces (Re=31.8~95.3)

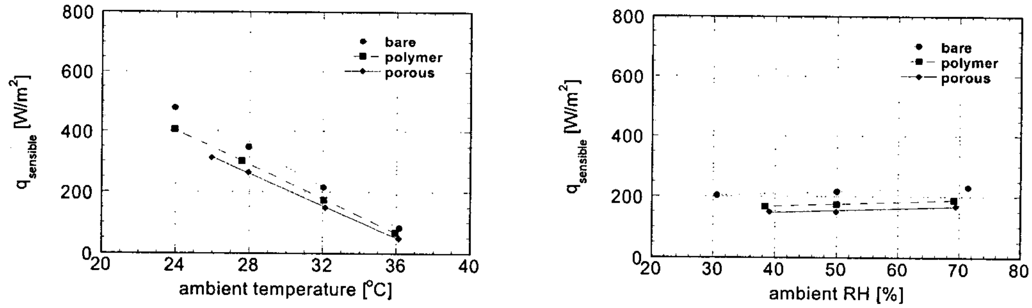
	Sensible heat transfer	Evaporation heat transfer		$\frac{h_m C_{p,a}}{h}$
	h	h	h_m	
Bare surface	30	36	0.053	1.49
Polymer coated surface	27	31	0.031	1.02
Porous layer coated surface	30	30	0.030	1.01

80% larger as compared with the case of the porous layer coated surface. Consequently, the ratio between the mass transfer and the heat transfer is found much larger than unity, 1.49.

One of the reasons why the heat and the mass transfer coefficients are larger at the untreated surface is that the evaporation water flow on the surface forms rivulets instead of a thin film to disturb the air flow over the surface. In addition to this, since the cross section of the rivulet is semi elliptical, the actual wetted surface contributing to the heat and mass transfer increases resulting in the apparent increase in the heat and mass transfer coefficients.(6) Moreover particularly for the mass transfer, the concentration boundary layer over the rivulet becomes thinner due to the water vapor diffusion from the rivulet surface to the adjacent space over the dry surface, which causes a large increase in the mass transfer coefficient at the untreated surface resulting in the ratio between the mass and the heat transfer much larger than unity.

In the meanwhile, the heat and the mass transfer coefficients at the polymer coated surface are similar to the values at the porous layer coated surface, since the rivulet over the polymer coated surface is much planer and wider than that over the untreated surface and the thinning of the concentration boundary layer is not very large due to the relatively small area of the dry surface compared with the wet surface.

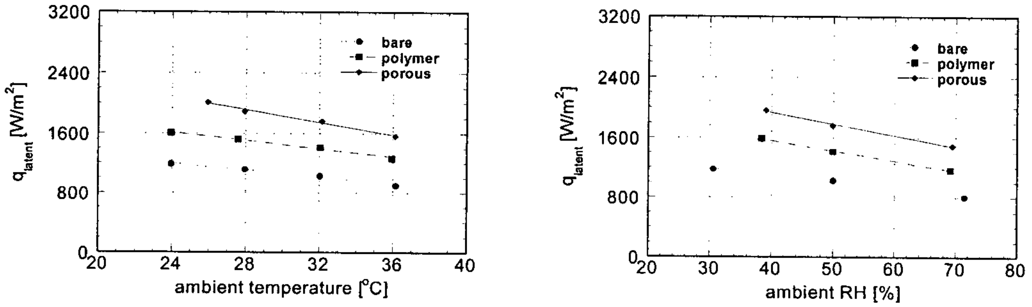
The portion of the sensible heat transfer among the total heat transfer is calculated using the heat transfer coefficient from Table 3 into Eq. (3) and is displayed in Fig. 6. The latent heat flux is obtained by subtracting the sensible heat flux in Fig. 6 from the total heat flux and is shown in Fig. 7. In Figs. 6 and 7,



(a) Ambient RH: 50%

(b) Ambient temperature: 32℃

Fig. 6 Variation of the sensible heat flux with respect to the ambient condition.



(a) Ambient RH: 50%

(b) Ambient temperature: 32℃

Fig. 7 Variation of the latent heat flux with respect to the ambient condition.

the influence of the evaporation water flow rate is not shown but only the average is presented.

Comparing Figs. 6 and 7, the latent heat flux is found about four times larger than the sensible heat flux. This implies the latent heat transfer is much more effective than the sensible heat transfer in cooling heat-dissipating objects. The sensible heat flux is shown to depend on the surface characteristics in Fig. 6. This is because the heat transfer coefficient differs depending on the surface.

The latent heat flux is found the largest for the porous layer coated surface. This is an obvious result since the latent heat transfer is related closely to the wettedness of the surface. However, the latent heat flux from the untreated surface is found not to decrease as much as the wettedness. This is because the mass transfer coefficient increases as the wettedness decreases. Consequently, the latent heat flux is about 40% larger for the polymer coated surface and 80% larger for the porous layer coated surface as compared with that for the untreated surface.

5. Conclusions

In this work, a novel method was presented to improve the surface wettedness enormously by coating the surface with a thin hydrophilic porous layer. With this coating, the liquid can spread widely on the surface by the capillary force resulting from the porous structure. In addition to this, the liquid can be held within the porous structure to improve surface wettedness regardless of the surface inclination.

It was shown that the inclined surface with the porous layer coating can be fully covered with thin water film even with a small evaporation water flow rate, while the untreated surface is wetted only by 30% with the same water flow rate. The conventional hydrophilic polymer coating was also tried but was found not very effective to increase the surface wettedness of inclined surfaces, since the liquid flow forms rivulets instead of a thin film as it flows down the inclined surface and accelerates gradually by the gravity. The experiment on the evaporative cooling of inclined surfaces was conducted to verify the effectiveness of the surface treatment. The latent heat transfer was observed to increase almost by 80% at the porous layer coated surface as compared with that at the untreated surface.

Since the thickness of the porous layer coating suggested in this study is only tens of micro meters, it is expected that this coating can be applied effectively to many complicated geometries common in air cooled heat exchangers.

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