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Characteristic Analysis of Condensate Carry-Over According to the Surface Tensions in the Wet and the Dry Conditions on the Fin Surfaces of Heat Exchangers

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Typically, condensate forms as droplets on the fin surfaces and may bridge the space between the fin surfaces. This is due to the dry characteristics inherent to the fin surface. The droplets increase the air-side pressure drop. In the case of high air velocities, these droplets may be blown off the fins and entrained in the air stream. To minimize the formation of condensate droplet, the wet ability of the fins must be improved. The carry-over velocity is affected by fin surface characteristics. To avoid carry-over in the air conditioner having the highest air velocity of 1.5 m/sec, the dynamic contact angle (DCA) should be at least lowly under 60°.

Key Words : Carry-Over, Evaporator, Hydrophilicity, Condensation, Plate Fin-Tube Heat Exchanger

Nomenclature

DCA : Dynamic Contact Angle [°]
FPI : Number of Fins Per Inch
Gair : Mass flow rate of air [kg/hr]
$\dot{m}_{cal}$: Calculated condensation rate [kg/hr]
SCA : Static Contact Angle [°]
Wi : Absolute humidity of entering air [kg/kg]
Wo : Absolute humidity of exit air [kg/kg]
ΔPdry : Pressure drop of dry coil [mmAq]

1. Introduction

The dehumidification process of heat exchanger in air conditioning equipment typically uses aluminium fins. Because the surface temperature of the fins on the tube is below the dew point, moisture condenses on the fins, and the condensate typically has a high contact angle on the aluminium fins, the water adheres as droplets, resulting in an increase air pressure drop. Eventually, the droplets agglomerate and the liquid intermittently drains from the fins. These droplets may be blown off the fins and entrained in the air stream. Normally it is called carry-over phenomenon. In general, in order to restrain these undesirable phenomena and increase critical air velocity for carry-over, conventional air conditioning evaporators has been applied hydrophilic-coated aluminum fin.

Brown et al. (1994) presented an analytical model, written in general terms, which predicts the trajectory of a spherical particle/droplet placed in a

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uniform fluid stream. That model was compared to an experiment in which three-millimeter diameter polypropolyene spheres (specific gravity= 0.91) were dropped in a uniform air stream (velocity varies from 0.9 to 3.8 m/s). Ha et al. (1998) has shown that as wet-to-dry cycle increases, dynamic contact angle increases locally, resulting in the droplets agglomerating and the liquid intermittently draining from fin surfaces. As a result of experiment, (1) Air side wet-to-dry pressure drop ratio can be correlated with static water holding capacity in heat exchanger (2) Good wettability surface need less time to reach fully wetted saturation than poor wettability surface do (3) A dry pressure drop model could predict slit fin pressure drop (4) Wet-to-dry pressure drop model for dropwise condensation was proposed. Ha et al. (1999) investigated condensation curve from partially to fully wet condition is proposed for air-side pressure drop, mass transfer rate, and air mass flux as wet exposed time increases. Five distinct regimes with respect to wet exposed time; no wet, partial dropwise, partial film with dropwise, filmwise developing, developed filmwise; show different slope in airside pressure drop and condensate drainage out of heat exchangers. Hong (1996) presented that three different fin geometries (wavy, lanced and louver) were tested and showed that the ratios of the wet-to-dry pressure drop of all heat exchangers were 1.2 at 2.5 m/s frontal air velocity. It was also found that the coatings have no influence on the heat transfer characteristics. A carry-over model for a coated heat exchanger was developed and the prediction from the model was compared with experiment. The model predicted the carry-over velocity within ±15%. The experiment showed that the water carry-over occurred when the free flow rate velocity was greater than 7.62±1 m/s. The objective of this experimental study is to investigate the carry-over phenomenon according to wetting performance out of surface characteristics. And this study includes the inclined and bended type evaporators applied in the air-conditioning system at the partially and fully wetted condition. The results from this study have been useful in form of air conditioning design tool.

2. Experiments

2.1 Experimental apparatus

Figure 1 shows a schematic diagram of experimental apparatus. The system consists of three independent parts; a water supply loop, a psychrometric chamber and a wind tunnel. The water supply loop consists of a constant water bath, a heater, a refrigerant supply system, a 2HP stainless steel pump and a mass flow meter. The psychrometric chamber includes an air handling unit and an air-sampling unit. The wind tunnel based on ASHRAE standard includes nozzles to measure airflow rate. Dry and wet bulb temperature at the entrance and the exit are measured by RTD (Pt 100Ω) sensors with accuracy of 0.05℃. The data are collected and sent to data acquisition system. Dynamic Contact Angle (DCA) can be applied to evaluate the wettabillity performance and amount of condensed water droplets remained on the surface of the evaporator. The surface tension can be calculated using DCA by means of measuring the surface tension when a test sample is receded and proceeded in the water, and conversing it into an angle form. The DCA measuring equipment (Sigma 70 manufactured by KSV) is used in this study. The transparent acrylic plate is installed at the position of 254 mm underside from the evaporator so that the carry-over phenomenon is observed and the air velocity is measured corresponding to the first and continuous drop of the condensated water. Laser Doppler Anemometer (LDA) system (DANTEC) is used

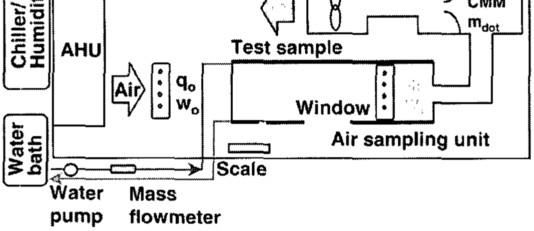


Fig. 1 Schematic diagram of the experimental apparatus for the test room control

to measure the exact air velocity in the front of evaporator. LDA system (DANTEC), which has a light source of Ar-ion laser, is an optical arrangement with all directional dispersion of 0.998 mm Gaussian beam diameter. Operational range of 3-dimensional probe traverse equipment is 540mm × 540mm × 540 mm with a minimum moving distance of 0.5 mm. A smoke generator (Model 2001) is used to generate paraffin oil particle for measurement of air velocity.

2.2 Test samples

Figure 2 shows the typical structure of plate fin-and-tube heat exchanger for air conditioning system. It consists of aluminum fin and Φ7 mm copper tube with staggered arrangement and Table 1 shows the detail specification of the evaporator. Fig. 3 shows a typical slit fin, which enhance convective heat transfer due to turbulence and mixing of boundary layer. In case of uncoated aluminum fins, dynamic contact angle is high. When it is applied to wet coil, condensate typically maintain a high dynamic contact angle on the aluminum fins, the water adheres as droplets, resulting in an increase of air side pressure drop. Figs. 3(a) and 3(c) are the hydrophilic surface. In practice, wettability can be defined by the degree of continuity and uniformity of condensate film at fully wetted condition. In order to investigate the effect of wettability on wet coil performance, the different surfaces ; uncoated and coated material are used classified by static and dynamic contact angle. Fig. 3 shows contact angle of samples. Prior to the experiment about carry-over phenomenon for the bending type evaporator, the experiment with straight type evaporator is conducted. Fig. 4 shows the installation of test samples. The straight type evaporator is installed with 45° inclined to test the bending type evaporator that is inclined 45° in the upper part. The straight type heat exchanger consists of 2 rows 9 columns of the tube and slit-shaped fins of 18 FPI (Fins Per Inch). Bending type evaporator used in this study, which consists of 2 rows, 10 columns of tube and fins of 18 FPI. In case of partially wet test, the cooled water for dehumidifying evaporator is applied to the upper part of evaporator but not applied to the lower part of evaporator. Typically horizontal travel distance of condensate water from evaporator is dependent on air stream velocity, gravity force and drag force. Therefore it is needed to test which is done with the upper part

Table 1 Specification of the evaporator

Type	Row ×Column	Size	Fin	
		W×D×H (mm)	Pattern	FPI
Straight	2×9	310×25.4×189	Slit	18
Bending	2×10	472×25.4×210	Slit	18

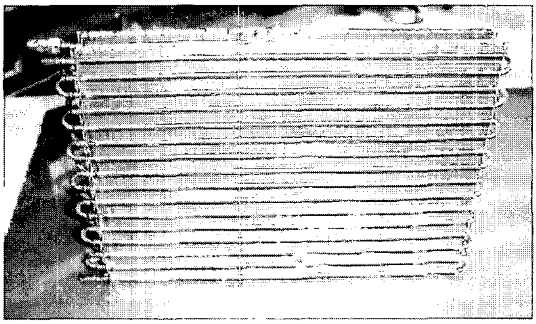


Fig. 2 Typical structure of the plate fin-and-tube heat exchanger for air conditioning system

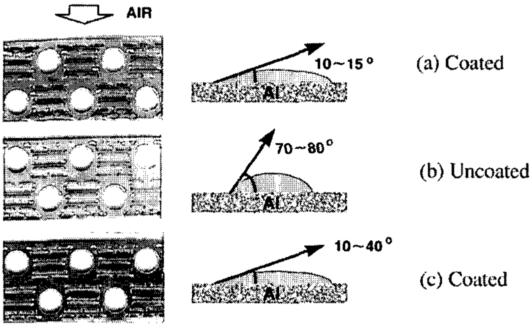


Fig. 3 Photographs of slit fin surface

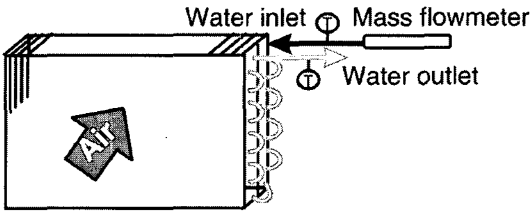


Fig. 4 Test circuit (Slit fins, 2R 9C 310 mmW, 7.0 mm, 18 FPI) for carry-over test

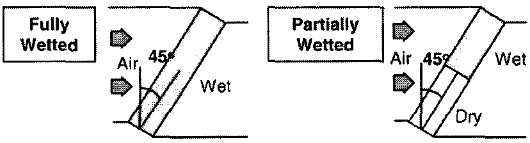
wet condition in evaporator and the lower part dry condition.

2.3 Test conditions

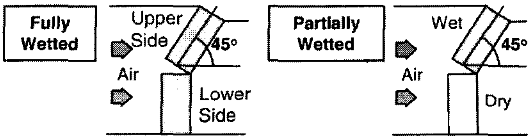
Table 2 lists the test conditions and Fig. 5 shows the test circuit. Tube side water flow rate is sustained more than 200 kg/h corresponding to Reynolds number, which is more than 10,000. To make the average water side temperature same as practical air conditioner, tube inlet and outlet temperature are set to 5℃ and 10℃, respectively so fin surfaces are maintained fully wetted. The amount of condensate drainage is measured by precise scale from which RS232C transfer data to data acquisition system. All data have energy balance within the accuracy of 3%. The test range of the frontal air velocity is from 0.5 to 5.0 m/sec and the frontal air velocity is increased by 0.5 m/sec for each step. Experiment for the fully and partially wetted evaporator is executed with the cold water circulating the whole path of the evaporator and only upper side of the evaporator, respectively.

Table 2 Test conditions for carry-over test

Parameters		Ranges
Air	Inlet dry bulb temp., ℃	27
	Inlet wet bulb temp., ℃	19.5
	Frontal air velocity, m/s	0.5~5.0
Water	Inlet temperature, ℃	5.0
	Flow rate, kg/h	200~550
	Reynolds number	>10,000



(a) Straight type evaporator



(b) Bending type evaporator

Fig. 5 Schematic diagram of installed samples

3. Result and Discussion

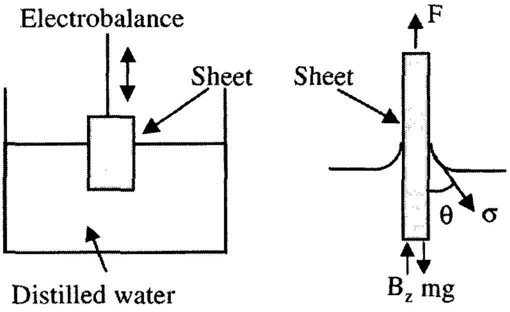
3.1 Evaluation of sheet wet ability

Various methods can impart hydrophilicity to the surface. In order to measure the dynamic contact angle of a surface, Wilhelmy plate method (Johnson and Dettre, 1969 ; Good, 1993) is used to measure electrobalance force that is related to the interfacial force between solid and liquid as a function of time in this study shown in Fig. 6.

The equilibrium of forces in Fig. 6(b) is

$$F = p\sigma\cos\theta - Bz + mg \tag{1}$$

F is electrobalance force, p is wetted perimeter of sheet, σ is surface tension of distilled water, Bz is the buoyancy, m is the weight of sheet and θ is the advancing and receding dynamic contact angle when sheet is lowered and raised. We can solve from the Eq. (1). The size of the sheet sample is 20 mm×30 mm. To compare with dynamic contact angle, the measurement method of water



(a) (b)

Fig. 6 Measurement method of Wilhelmy plates: (a) Schematic diagram and (b) Equilibrium of force

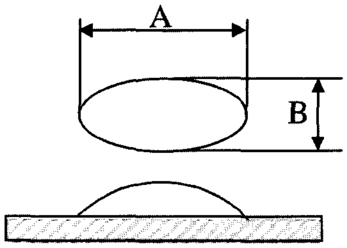


Fig. 7 Measurement of water droplet diameter

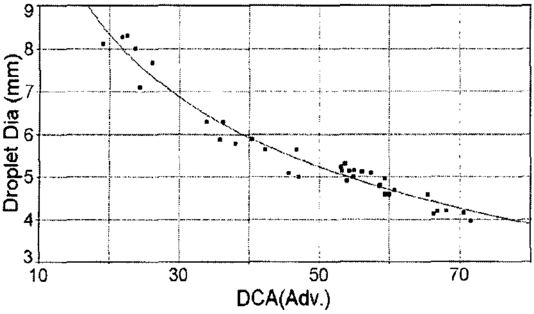


Fig. 8 Advancing DCA (Dynamic Contact Angle) according to the water droplet diameter

droplet diameter is used and shown in Fig. 7. This method is simple to evaluate wettability performance of the surface.

$$\text{Water droplet diameter} = (A+B)/2 \qquad (2)$$

The wet ability of surface can be evaluated by measuring the length of the water spread on the surface. In this study, a caliper is used to measure the water droplet diameter after dropping the distilled water 0.01 ml. The water droplet diameter is taken an arithmetic mean as is given in the Eq. (2). Fig. 8 represents DCA according to water droplet diameter. In reference to Fig. 8, DCA is highly related with water droplet diameter. According to these results, DCA is applied to sheet wettability performance index.

3.2 Carry-over velocity for straight type evaporator

Figure 9 represents carry-over velocity corresponding to DCA in the straight-type experiment for the fully and partially wetted evaporator. The outset of the carry-over as a first development of water droplet is defined as the diameter of more than 1mm on the transparent acrylic plate, and continuous carry-over as more than 5 times of water droplet development within 3 minutes. Carry-over velocity means the frontal air velocity on the point of occurrence of outset. The evaporator is dried before every experiment and the completion of dryness is confirmed by comparing the pressure drop with that of untested evaporator. The carry-over velocity with variation 10°~65° of DCA is constant in the case of fully wetted evaporator. However, it is decreased by 1.5 m/sec with increase of DCA from 85°. The carry-over velocity with increase of DCA from 85° is constant in the case of partially wetted evaporator. However, it is decreased by 1.0 m/sec with increase of DCA from 10°~65°. There is 1.5~2.5 m/sec difference between fully and partially carry-over velocity of variation 10°~65° of DCA. From increase of DCA from 85°, 1.0 m/s difference between fully and partially carry-over velocity. According to these results, the fully wetted evaporator is superior to partially wetted one in the carry-over phenomenon. In case of the partially wetted evaporator tends to be smaller than the average frontal velocity due to the increase in the flow resistance through the wetted part. But the outset of the carry-over in straight type evaporator is the boundary area between the wet and the dry area. Therefore the carry-over velocity of the fully wetted evaporator is higher than that of the partially wet evaporator.

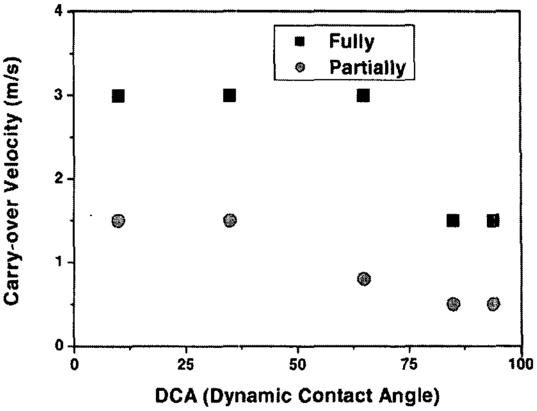


Fig. 9 Carry-over velocities corresponding to DCA in straight type evaporator

3.3 Drainage for straight type evaporator

Figure 10 shows the relationship of water drainage weight according to the frontal air velocity in the straight evaporator, which is installed with inclination in the condition of fully wet. Two types of evaporators, each surface characteristics angles are 35° and 85° are prepared and tested. Eq. (3) is applied to the amount of condensate calculated from the airside and the amount of really condensated water is collected from the evaporator and measured the weight with preci-

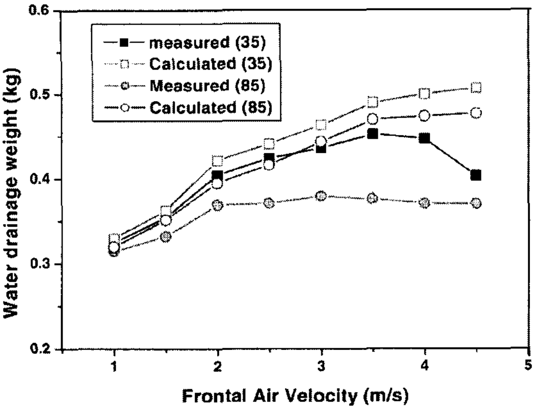


Fig. 10 Drain water according to frontal air velocity in the straight type evaporator

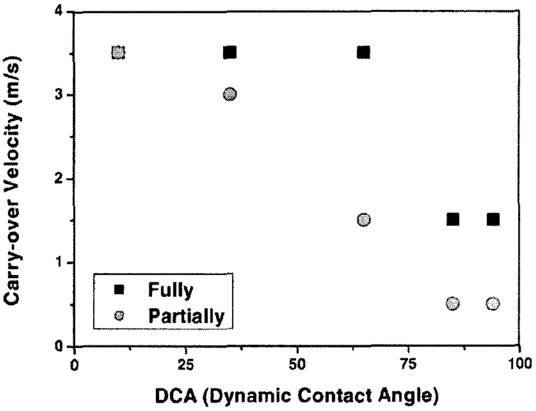


Fig. 11 Carry-over velocities corresponding to DCA in bending type evaporator

sion balance obtained.

$$\dot{m}_{cal} = G_{air} \times (W_i - W_o) \qquad (3)$$

$\dot{m}_{cal}$, G_{air}, W_i and W_o represent the calculated condensated water, air flow rate, absolute humidity of inlet air and absolute humidity of exit air, respectively. The measured values have a good agreement with the calculated value in the range of the low frontal air velocity. As the frontal air velocity increases, there is significant difference between calculated and measured value. This result implies that the condensated water is scattered by airflow from the evaporator. If the experimental time is increased, the humidity at the exit that is used in calculation process [Eq. (3)] is affected by scattering of the condensate water. However this test is almost finished within 20 minutes and there is a little difference in the humidity at the exit between the initial and the final stage.

3.4 Carry-over velocity for bending type evaporator

The carry-over velocity has to be considered as a very important factor according to the hydrophilic characteristics in product design and has to be checked at the partially wetted condition in case of bending type evaporator. The real operation conditions are possible to be different from the design condition. Consequently, the partially wetted phenomenon can be occurred from the change of the cycle characteristics, and the possibility of occurrence of carry-over phenomenon is very high if partially wetted condition is occurred in the early stage of operation. Although existing fins of Al PCM (Pre Coated Material) coated with surfactant is superior in the initial hydrophilic performance, it gets worse with operational time. Therefore, the possibility of occurrence of carry-over becomes high and it can be a cause of the customer dissatisfaction.

The heat exchangers which are tested in this experiment are 2 types; coated fins and without coating-treated. Fig. 11 shows the carry-over velocity according to DCA in the fully and partially wetted condition of bending type evaporator. The critical air velocity for carry-over is 3.5 m/sec at DCA 10°, and there is no decrease with increase of DCA up to 65°. Finally, it is 1.5 m/sec from 85° of DCA. In case of partially wet experiment, there is the highly decrease from 10° to 85°. There is no change in carry-over velocity in the region from 85° to 94°. Compared with Fig. 11 (straight type experiment result), some different parts are remained. Compared with straight type, bending type evaporator result has a steep decrease according to DCA. Consequently air-conditioning system with bending type evaporator is more dependent on the surface characteristics. The outset of the carry-over in bending type evaporator is similar with the straight type evaporator, the boundary area between the wet and the dry area. And the existence of the bended area is highly related with the dependence on the surface characteristics.

3.5 Drainage for bending type evaporator

Figure 12 shows the relationship of water drainage weight according to the frontal air velocity in the bending evaporator. Test conditions are fully wet and test evaporators are of two kinds being tested in surface characteristics 35° and 85°. Eq. (3) calculates the theoretical amount of the condensate water and the really condensated water is collected from the evaporator and measured with precision balance. The measured values match the calculated ones in the range of the low frontal air velocity. As the frontal air velocity is increased, there is significant difference between calculated and measured value. This result implies that the condensated water is scattered by airflow from the evaporator.

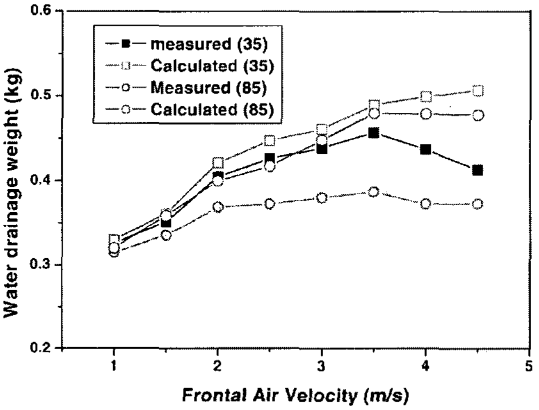


Fig. 12 Drain water according to frontal air velocity in the bending-type evaporator

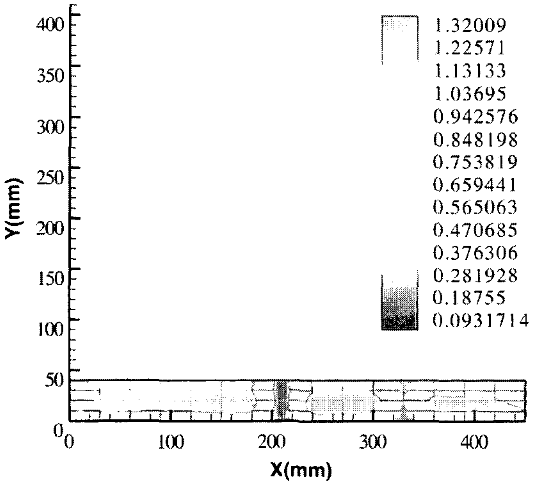


Fig. 13 Air velocity distributions in the upper side of indoor unit installed with bending type evaporator

3.6 Air velocity distribution of indoor unit in split type air-conditioner

Figure 13 represents the air velocity distribution that is measured by LDA in the upper side of indoor unit installed with bending type evaporator. As the result shows, air velocity peaks to 1.32 m/sec. According to Fig. 13, it is concluded that the carry-over phenomenon of the partially wetted bending type evaporator can be prevented when DCA is less than 60° with considering the safety factor of a bending type evaporator.

4. Conclusions

According to the experiment for the carry-over phenomenon of evaporator, these conclusions are obtained.

(1) The critical velocity for carry-over is affected by the hydrophilic characteristics of evaporator fin surface.

(2) For the straight-type evaporator, fully wetted evaporator has almost 2 times of carry-over velocity as compared to partially wetted one.

(3) For the bending type evaporator, carry-over velocity of partially wetted evaporator is highly dependent on the surface characteristics compared with straight type evaporator.

(4) The amount of measured condensate is less than that of the calculated one as the air flow velocity increase. According to the difference between the measured amount and the calculated one, it is analogized that the carry-over phenomenon is occurred.

(5) It can be concluded that the evaporator without carry over issues in the DCA area is less than 60° DCA of the fin surface. This test result can be applied to design of a product after comparing the frontal air velocity of real evaporator with carry-over velocity corresponding to the hydrophilic performance.

References

Brown, J. S., Terry, J. L. and Hutter, R. J., 1994, "An Analytical Prediction of Water Droplet Travel when Discharged from the Face of an Evaporator Core," 1994 SAE International Congress and Exposition, Detroit, Michigan, Paper 940501.

Good, R. J., 1993, "Contact Angle, Wettability and Adhesion : A Critical Review," in Contact Angle Wettability and Adhesion, Mittal, K.L. (ed.), VSP BV, The Netherlands, 3-36.

Ha, S. C., Kim, C. H., Ahn, S. P. and Dreitser, G. A., 1998, "Condensate Drainage Characteristics of Plate Fin-and-Tube Heat Exchanger," Proceedings of the International Conference on Heat Exchangers for Sustainable Development, pp. 423∼430, Lisbon, Portugal.

Ha, S. C., Kim, C. H., Ahn, S. P. and Dreitser, G. A., 1999, "Hydraulic Performance of Wet Fin-and-Tube Heat Exchanger for Various Wettability Surfaces," Proceedings of Compact Heat Exchangers and Enhancement of Technology for the Process Industries, pp. 463∼470, Banff, Canada.

Hong, K., 1996, "Fundamental Characteristics of Dehumidifying Heat Exchangers with and without Wetting Coating," Ph. D thesis, The Pennsylvania State University

Johnson, Jr., R. E. and Dettre, R., 1969, "Wettability and Contact Angles," in Surface and Colloid Science, Matijevic, E. (ed.), Vol. 2, Wiley.

Youn, D. H., Lee, S. W. and Moon, J. W., 2003, "The Experimental Study of Condensate Carry-Over in the finned Tube Evaporator," The 4th International Symposium on HVAC Beijing, China.