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## **An Experimental Study of the Air-side Particulate Fouling in Fin-and-Tube Heat Exchangers of Air Conditioners**

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### **ABSTRACT**

An experimental study is conducted to investigate the chronological performance variation such as pressure drop across a heat exchanger and cooling capacity due to the air-side particulate fouling of fin-and-tube heat exchangers for air conditioner evaporators used. 30 samples of air conditioners used in the field such as inns, restaurants, and offices are collected in chronological used order. This study is intended to provide factual long-term fouling data under actual operating conditions. It is found that the important parameters to influence the fouling of heat exchangers are the concentration and size of indoor pollutants, the filter efficiency, hydrophilicity of fin surfaces and fin spacing. The pressure drop of heat exchangers increases due to the deposition of indoor pollutants larger than 1  $\mu\text{m}$  in size and increases up to 44% in the samples used for 7 years. The air-side particulate fouling degrades the cooling capacity by 10-15% in the samples.

### **1. INTRODUCTION**

Fouling may be defined as the accumulation of unwanted deposits on the surfaces of heat exchangers. The presence of these deposits reduces the heat transfer, increases the pressure drop across a heat exchanger, and increases the maintenance cost of cleaning. The foulant may be crystalline, biological material, the products of chemical reactions including corrosion or particulate matter (Bott, 1995).

Fouling of heat exchangers used in heating, ventilating, and air conditioning (HVAC) system is important because of their widespread use in commercial, residential and industrial HVAC applications. Indoor and outdoor air contaminants foul these heat exchangers. The air-side fouling of air conditioners, the deposition of indoor dusts and other particulate matters on evaporator heat exchangers, increases system pressure drop, decreases system air flow and air conditioner performance. Moreover because the fouling materials act as bacteria cultivator, the fouling must be prevented and eliminated in the indoor heat exchangers in the HVAC applications (Ahn et al., 2002).

Air-side particulate fouling can be described as the accumulation of solid particles suspended in the air onto a heat transfer surface. In HVAC system, dust particles carried forward in the air are potential foulants for the heat exchangers. The theory associated with the transport of particles towards and onto surfaces is extensive and complex (Epstein, 1988). Transport of particles to the heat exchanger surfaces in the particulate fouling can occur by Brownian or laminar diffusion, turbulent diffusion, gravitational settling, inertial impaction, thermophoresis, or electrophoresis. In actual practice, two or more of these mechanisms will probably occur simultaneously. The sizes of particles have a large influence on the dominant mechanism. For instance, very small particles would be expected to be subject to Brownian diffusion and turbulent diffusion whereas the larger particles due to their mass would move under inertia impaction. Having arrived at the surface the particle must stick or adhere if it is to be regarded as part of the foulant layer residing on the surface.

The purpose of this study is to investigate the chronological performance variation such as pressure drop and cooling capacity due to the air-side particulate fouling of fin-and-tube heat exchangers for air conditioner evaporators used.

30 samples of air conditioners used in the field such as inns, restaurants, and offices are collected in chronological used order. The psychrometric calorimeter for measuring the cooling capacity and pressure drop of heat exchangers in the air conditioners is used in this study.

## 2. EXPERIMENTAL

Fig. 1 shows a schematic diagram of the psychrometric calorimeter (3S System, 7,000×8,200×3,000 mm<sup>3</sup>) for measuring the pressure drop and the cooling capacity of HVAC heat exchangers. It consists of a constant temperature and humidity chamber, a wind tunnel for measuring the performance of heat exchangers, an isothermal water bath and a control panel. The constant temperature and humidity chamber is composed of a chiller, a heater, a humidifier, and an air-handling unit. It keeps the temperature and the humidity inside the calorimeter constant. The dry and the wet bulb temperatures inside the calorimeter are set at 27 °C and 19.5 °C, respectively, based on the Korean Standard “Air Conditioners” (KS C 9306, 2002). The wind tunnel, (310×210 mm<sup>2</sup> for window-type and 750×210 mm<sup>2</sup> for wall-mounted type of air conditioners), is composed of the heat exchanger for testing, two couples of dry and wet bulb thermometer, an orifice and a suction fan. Two couples of dry and wet bulb thermometer measure the air temperature and humidity upstream and downstream of the test heat exchanger to obtain the air-side enthalpy variation. The air flow rate is monitored by the pressure drop of the orifice(65 ~ 150 mm in diameter) and can be controlled by adjusting the electric frequency of the suction fan motor.

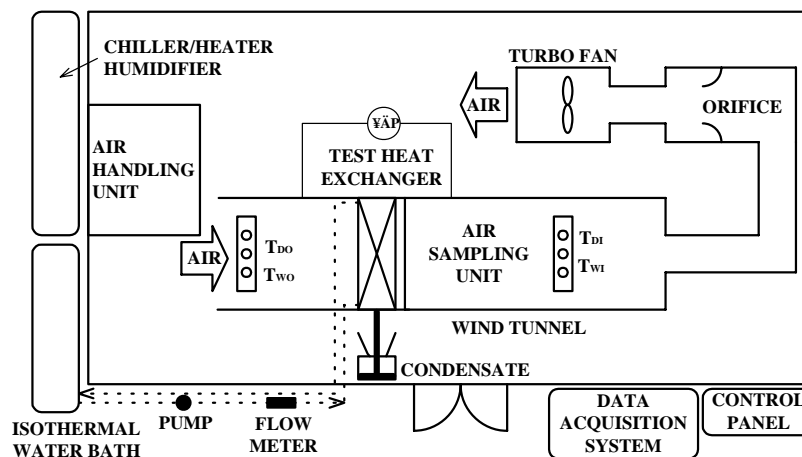


Figure 1: Schematic diagram of the psychrometric calorimeter for measuring the cooling capacity and the pressure drop of heat exchangers in the air-conditioner.

The isothermal water bath contains distilled water as a working fluid and the constant temperature (5 °C) water is supplied by pump to the heat exchanger at the flow rate of 430 kg/hr. The water-side enthalpy variation can be calculated because the temperature of the return water changes due to the heat exchange with the air stream. The deviation between the values of the air-side and the water-side enthalpy for measuring the cooling capacity of the heat exchanger maintains within  $\pm 3\%$  in order to stabilize the equipment and to give reliability.

The heat exchanger used in this study is the evaporator of the air conditioner which consists of a compressor, a condenser, an expansion device, and the evaporator. The evaporator heat exchangers used in this study is the fin-and-tube types with 15 ~ 18 fins per inch and the diameter of tubes is 7 ~ 9 mm. Table 1 shows specifications of the evaporators tested in this study.

The face velocity of the heat exchanger is set at 1 m/sec for measuring the pressure drop. On the other hand, the cooling capacity is measured at the initial pressure drop of the new heat exchanger. In that condition for measuring pressure drop across the heat exchanger, the face velocity is slightly slower than 1 m/sec. That is, the higher the

pressure drop, the slower the face velocity to have the same pressure drop as the initial value of the clean heat exchanger.

**Table 1: Specifications of the test heat exchangers**

Years used	Fin shape	Fins/Inch	Tube	
			Diameter	Arrangement
3	Slitted plate	18	7 mm	Staggered
4	Slitted plate	18	7 mm	Staggered
6	Slitted plate	18	7 mm	Staggered
7	Slitted plate	18	7 mm	Staggered
9	Slitted plate	18	7 mm	Staggered
13	Louvered plate	16	9 mm	Staggered
14	Louvered plate	16	9 mm	Staggered
15	Plane plate	15	9 mm	Staggered

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Analysis of fouling particles

Fig. 2 shows photographs of the fouled evaporator heat exchangers used in seaside inns for 6 and 14 years, respectively. The fouling materials consist of particulates and fibers. The particulates are mainly originated from indoor dusts and the fibers are separated from clothes, bedclothes, papers, and fur of pets. In general, the evaporator heat exchanger in the air conditioner repeats wet and dry cycles. The wet cycle ("ON" mode of air conditioners) means the operation that the evaporator has condensed water on the fin surfaces of the heat exchanger by the circulation of refrigerants, while the dry cycle (no refrigerant circulation and fan operation only) means the operation that the evaporator doesn't have condensed water on the heat exchanging surfaces. When the air conditioner repeats wet and dry cycles, the fouling particles agglomerate with adjacent particles and grow by condensation.

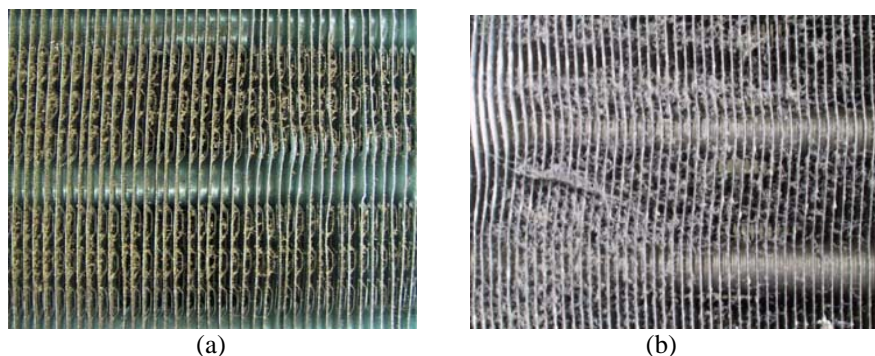


Figure 2: Photographs of fouled evaporator heat exchangers. (a) Used for 6 years, (b) Used for 14 years

The size of the fouling particles on the evaporator heat exchangers used in the office, the restaurant and the inn is analyzed using a particle analyzer (API, Aerosizer). The mean sizes of the fouling particles collected in the office, the restaurant, and the inn are 6.6, 9.8, and 20.9  $\mu\text{m}$ , respectively. The particle size of the inn sample is the largest one because the air conditioner installed in the inn has been exposed to somewhat high dust concentration and particle agglomeration due to long operation time. The air conditioners sampled from the inn are window-type, while those of the office and the restaurant are wall-mounted type. Actually the window-type air conditioner is installed 1.5 m above the floor and the wall-mounted air conditioner is installed 2 ~ 2.5 m above the floor. There exists a significant difference of the suspended dusts concentration due to the human activity. Thatcher and Layton (1995) investigated deposition and suspension of particles within a residence and showed that even light activity can have a significant impact on the concentration of airborne particles with diameters greater than 5  $\mu\text{m}$ . These particle sizes also contribute the majority in the size distribution of indoor air quality based on particle mass. Therefore the

window-type air conditioner is exposed to relatively high dust concentration and shows the largest size of fouling particles.

### 3.2 Chronological variations of pressure drop

Fig. 3 represents chronological variations for the pressure drop across the evaporator heat exchanger in air-conditioners used in the seaside inn. For the wet cycle (“ON” mode with refrigerant circulation), the pressure drop increases up to 145% compared with the initial pressure drop and shows the asymptotic increase. The pressure drops in the wet cycle are higher than those of dry cycle (no refrigerant circulation and fan operation only). It is believed that the water condensates formed on the fin and tube surfaces by condensing during the wet cycle result in flow resistances.

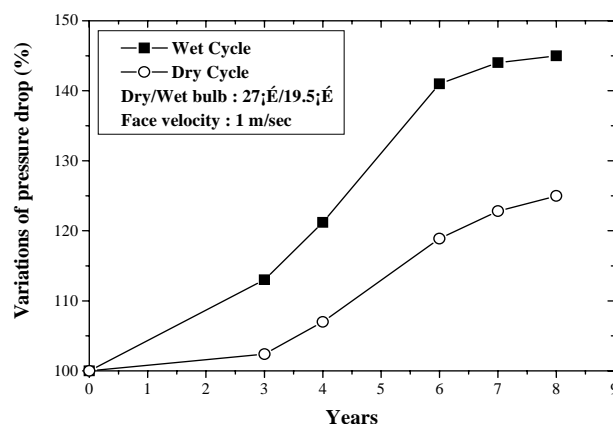


Figure 3: Chronological variations for the pressure drop of evaporator heat exchangers in air-conditioners used in the seaside inn (wet cycle: “ON” mode of air conditioners, dry cycle: no refrigerant circulation and fan operation only).

Table 2 shows variations of static contact angles in the fin surface of heat exchangers in the chronological order. Contact angle of fin surfaces influence the cooling capacity and pressure drop across the heat exchanger. Most heat exchangers of air conditioner evaporators have hydrophilic fin surfaces at the beginning due to hydrophilic coating. If the fin has hydrophilic surface, the condensed water flows down freely and the increase of the pressure drop across the heat exchanger can be minimized. However, the hydrophilic coating cannot sustain the hydrophilicity for long time due to fouling. The initial contact angle is  $20 \sim 30^\circ$  and shows good hydrophilicity, but the hydrophilicity becomes weak by the repetition of wet and dry cycle. Finally, the contact angle of fin surfaces increases up to  $80^\circ$ .

Table 2: Static contact angles of the fin surfaces in the evaporator heat exchanger

Years used	Type	Static contact angle( $^\circ$ )
Initial	-	20 ~ 30
3	Window	47 ~ 67
6	Window	81 ~ 88
6	Wall-mounted	61 ~ 64
7	Window	63 ~ 78
9	Wall-mounted	58 ~ 72
13	Wall-mounted	53 ~ 60
14	Window	45 ~ 65
15	Wall-mounted	45 ~ 81

\* Window-type collected from the seaside inn.

\* Wall-mounted type collected from the restaurant, office, and residence.

Fig. 4 shows the test summary of chronological variations for the pressure drop across the evaporator heat exchanger taking account into the decrease of hydrophilicity in the fin surface. The square symbols represent the pressure drop across the heat exchanger used for a few years divided by the pressure drop of the heat exchanger at the initial condition. The circle symbols represent the pressure drop across the used heat exchanger divided by the one across the heat exchanger cleaned from the used heat exchanger. Therefore, data of square symbols mean the effects of the particulate fouling and the decrease of hydrophilicity due to the repeated use in the field application, while data of circle symbols mean only the particulate fouling effects. The pressure drop due to the decrease of hydrophilicity in the fin surface contributes more than 10 ~ 30% of the total pressure drop. For preventing the deterioration of evaporator heat exchangers, the longer lasting hydrophilicity as well as the prevention of fouling is very important.

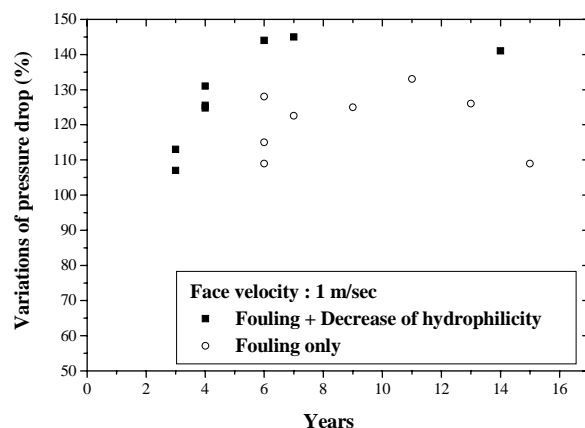


Figure 4: Test summary of chronological variations for the pressure drop of evaporator heat exchangers in air-conditioners with and without the decrease of hydrophilicity.

### 3.3 Chronological variations of cooling capacity

Fig. 5 shows the summary of chronological variations for the cooling capacity of evaporator heat exchangers in the air-conditioner at the face velocity of 1 m/sec being a representative velocity for the air conditioner initially. As explained in Fig. 4, data of the square symbols represent the cooling capacity due to the effect of particulate fouling in addition to that of hydrophilicity decrease. Data of the circle symbols represent the effect of particulate fouling only. The variations of the cooling capacity show no tendency even somewhat large deviations from 100%. It is believed that some amounts of particulate deposits on the surface of fins enhance the cooling capacity due to the increase of flow turbulence intensity. Even the dropwise condensations, formed by the decrease of hydrophilicity, have the larger heat transfer capacity than filmwise condensation when the pressure drop is neglected and the flow rate is constant [Incropera and DeWitt, 1996]. Therefore the decrease of the hydrophilicity in the fin surfaces doesn't affect directly to the decrease of cooling capacity unless the air flow rate reduces. However, in case the deposits become thick enough to change substantially the flow pattern across the fins, the particulate fouling degrades the cooling capacity due to increasing the heat resistance of heat transfer.

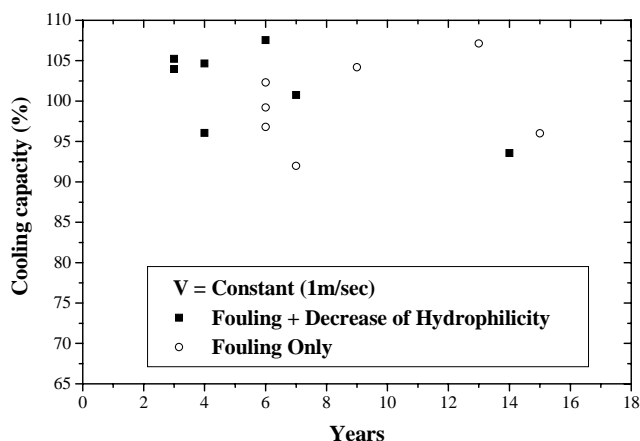


Figure 5: Test summary of chronological variations for the cooling capacity of evaporator heat exchangers at the face velocity of 1 m/sec.

Fig. 6 shows variations of cooling capacity for the evaporator heat exchangers used in the various application fields. The face velocity decreases with increasing operation time from year to year due to the air-side particulate deposition. This result is intended to provide the cooling capacity in the factual pressure drop data under actual operating conditions. In Fig. 6, the measurements of the cooling capacity are carried out at the same pressure drop across initially designed heat exchangers. All the samples are used for 6 years. The cooling capacities of the evaporator heat exchanger used in the seaside inn, the restaurant, the office and the residence are decreased by 14, 12, 7, and 4%, respectively. The evaporator heat exchanger used in the seaside inn shows maximum decrease of cooling capacity, because it has been exposed to somewhat high dust concentration and long operation time. The air conditioner used in the seaside inn is a window-type and the others are wall-mounted types. Generally, the window-type is installed 1.5 m above the floor and the wall-mounted type is installed 2 ~ 2.5 m above the floor. There exists a significant difference of the suspended dusts concentration due to the human activity. The window-type is more affected by the suspended particles due to the installation height.

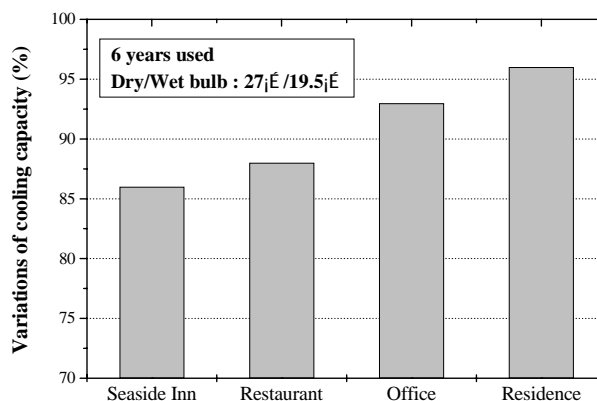


Figure 6: Variations of cooling capacity for the evaporator heat exchangers used in various places at the same pressure drop of initial heat exchangers.

Fig. 7 shows chronological variations for the cooling capacity of the evaporator heat exchangers in air-conditioners used in the seaside inn at the same pressure drop of the initial heat exchangers. In 7 years, the cooling capacity decrease down to 84% compared with the initial value. The cooling capacity decreases from year to year. It is believed that the deposition of indoor pollutants and the decrease of system flow rate due to increasing pressure drop degrade the cooling capacity of evaporator heat exchangers.

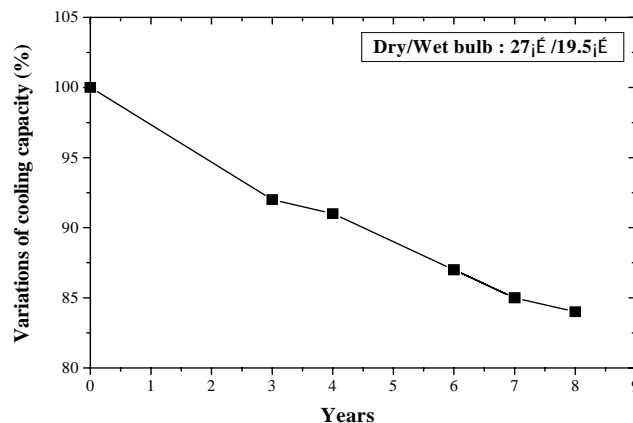


Figure 7: Chronological variations for cooling capacity of evaporator heat exchangers in air-conditioners used in the seaside inn at the same pressure drop of initial heat exchangers.

Fig. 8 shows chronological variations for the cooling capacity of the air conditioner sets including the evaporator, the compressor, the condenser, and the air handling unit at the same pressure drop of the initial heat exchangers. Data of the solid symbols represent the cooling capacity due to the effect of particulate fouling in addition to that of hydrophilicity decrease, while the open symbols represent the effect of particulate fouling only. The cooling capacities due to the effect of particulate fouling in addition to that of hydrophilicity decrease (solid symbols) show larger degradations compared with those of particulate fouling (open symbols). It is believed that the higher pressure drop due to the decrease of hydrophilicity in the fin surfaces causes the air flow rate to be reduced and the cooling capacity to be decreased. The square symbols represent the window-type, while the circle symbols represent the wall-mounted type. The window-type air conditioners show large degradations in cooling capacity compared with the wall-mounted types because the window-types are more affected by the suspended dusts as explained in Fig. 6. The cooling capacity of the air conditioner sets which can be shown from data of solid and square symbols, compared with the results of evaporator heat exchangers as shown in Fig. 7, shows somewhat larger degradations because the performance deteriorations of the fan, the compressor, and evaporators including the inside and outside tube fouling occur simultaneously.

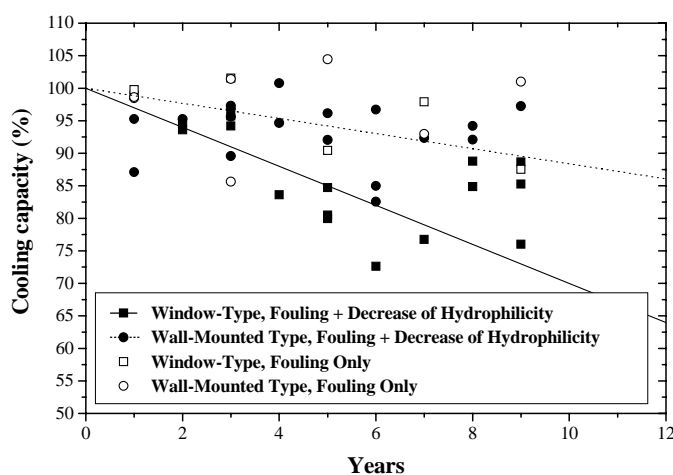


Figure 8: Test summary of chronological variations for the cooling capacity of air-conditioner sets.

#### 4. CONCLUSIONS

The chronological performance such as pressure drop and cooling capacity due to the air-side particulate fouling of fin-and-tube heat exchangers for the used air conditioner evaporators is investigated using the psychrometric



calorimeter. 30 samples of air conditioners used in the field such as inns, restaurants, and offices are collected in chronological used order. This study is intended to provide factual long-term fouling data under actual operating conditions.

Fouling of heat exchangers causes the decrease of cooling capacity and the increase of pressure drop as well as indoor air quality problems. The pressure drop of heat exchangers increases from year to year due to the deposition of indoor pollutants larger than 1  $\mu$ m in size and increase up to 44% in the samples used for 7 years. The pressure drop due to the decrease of hydrophilicity in the fin surface contributes more than 10 ~ 30% of the total pressure drop. Also the air-side particulate fouling degrades the cooling capacity by 10-15% in the samples used for 7 years. It is found that the important parameters to influence the fouling of heat exchangers are the concentration and size of indoor pollutants, the hydrophilicity of fin surfaces, and the structure of heat exchangers. For preventing the deterioration of evaporator heat exchangers, the longer lasting hydrophilicity as well as the prevention of fouling is very important.

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