*Korean J. Chem. Eng.*, **20**(5), 873-877 (2003)

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

**Young-Chull Ahn, Jae-Min Cho, Hee-Soo Shin, Yu-Jin Hwang, Chang-Gun Lee, Jae-Keun Lee†, Hyun-Uk Lee* and Tae-Wook Kang****

School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-Dong, Kumjung-Ku, Busan 609-735, Korea
*Digital Appliance Company Research Lab., LG Electronics, 391-2, Gaeumjeong-dong, Changwon City 641-711, Korea
**Air Conditioner Division, LG Electronics, 76, Seongsan-dong, Changwon City 641-713, Korea
(*Received 17 February 2003 • accepted 14 April 2003*)

**Abstract**−An experimental study was 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. Thirty samples of air conditioners used in the field such as inns, restaurants, and offices are collected in chronological order of use. This study was intended to provide factual long-term fouling data under actual operating conditions. It was found that the important parameters to influence the fouling of heat exchangers are the concentration and size of indoor pollutants, the filter efficiency, the hydrophilicity of fin surfaces, fin spacing, and the structure of fins. The pressure drop of heat exchangers increases from year to year due to the deposition of indoor pollutants larger than 1 μm in size and increases up to 44% in the samples used for 7 years. Also, the air-side particulate fouling degrades the cooling capacity by 10-15% in the samples used for 7 years.

Key words: Heat Exchanger, Particulate Fouling, Pressure Drop, Cooling Capacity, Air Conditioner

## 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) systems 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., 2003; Lee et al., 1998, 2002].

Air-side particulate fouling can be described as the accumulation of solid particles suspended in the air onto a heat transfer surface. In an 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 inertial 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 was 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 the air conditioner evaporators used. Thirty samples of air conditioners used in the field such as inns, restaurants, and offices were collected in chronological order of use. The psychrometric calorimeter for measuring the cooling capacity and pressure drop of heat exchangers in the air conditioners is used in this study.

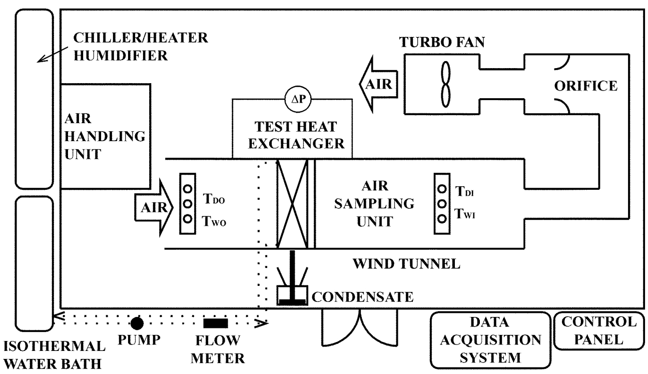



**Fig. 1. Schematic diagram of the psychrometric calorimeter for measuring the cooling capacity and the pressure drop of heat exchangers in the air-conditioner.**

†To whom correspondence should be addressed.
E-mail: jklee@pusan.ac.kr

## EXPERIMENTAL

Fig. 1 shows a schematic diagram of the psychrometric calorimeter (3S System, 7,000×8,200×3,000 mm$^3$) 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$^2$ for window-type and 750×210 mm$^2$ 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.

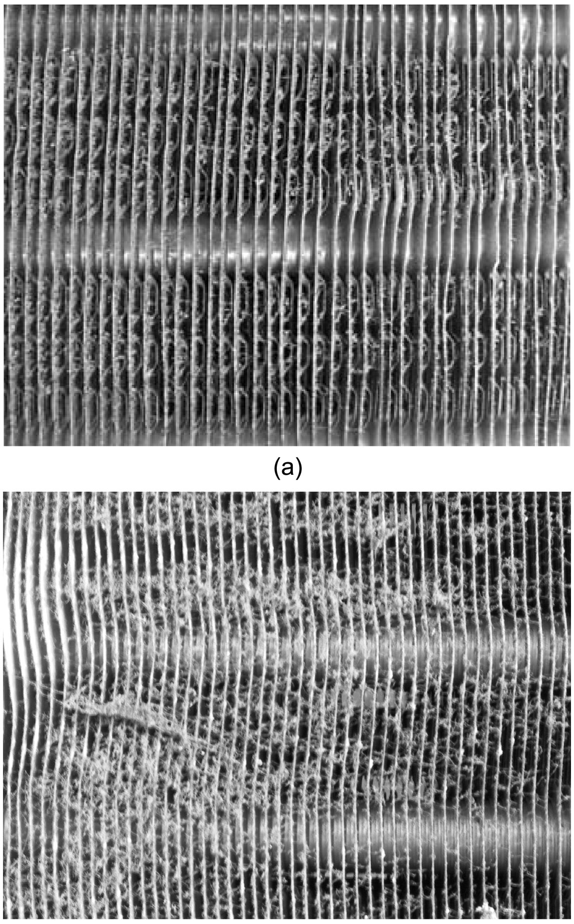
The isothermal water bath contains distilled water as a working fluid and the constant temperature (5 °C) water is supplied by pump to the heat exchanger at the flow rate of 430 kg/hr. The water-side enthalpy variation can be calculated because the temperature of the return water changes due to the heat 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 ±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 are 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 |



(a)

(b)

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

## RESULTS AND DISCUSSION

### 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 mainly originate 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 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 that the evaporator does not 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.

The size of the fouling particles on the evaporator heat exchangers used in the office, the restaurant and the inn is analyzed by 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 μm, respectively. The particle size of the inn sample is the largest one because the air conditioner installed in the inn had 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 dust 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 μm. 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 was exposed to relatively high dust concentration and shows the largest size of fouling particles.

**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 an asymptotic increase. The pressure drops in the wet cycle are higher than those of the 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.

Table 2 shows variations of static contact angles in the fin surface of heat exchangers in the chronological order. Contact angle of fin surfaces influences 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 a 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 20-30° 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°.

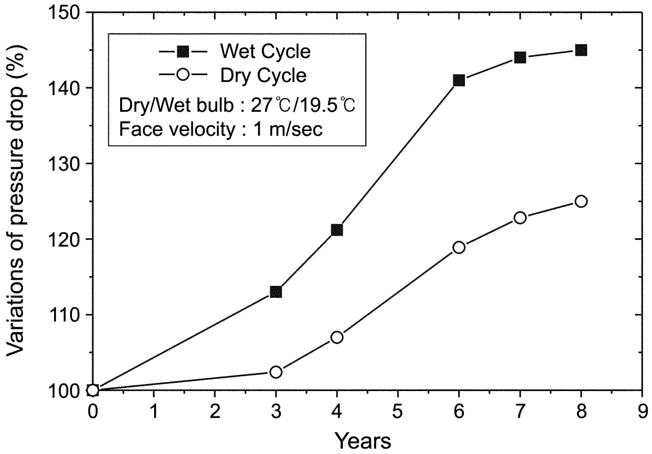



**Fig. 3. Chronological variations for the pressure drop of evaporator heat exchangers in air-conditioners used in the seaside inn (wet cycle: "ON" mode of air conditioners, dry cycle: no refrigerant circulation and fan operation only).**

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

| Years used | Type | Static contact angle (°) |
|---|---|---|
| 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.

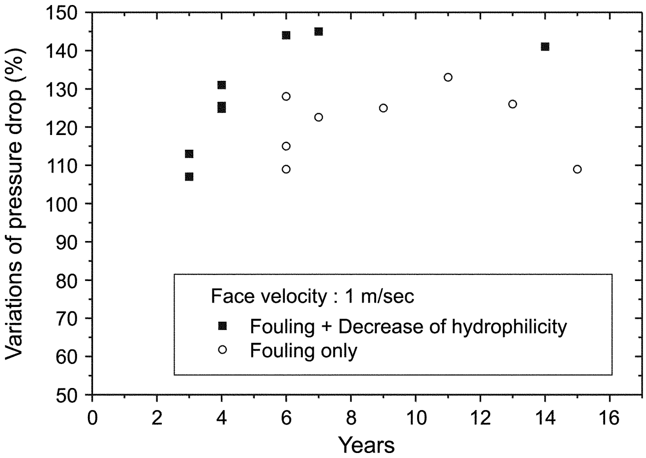



**Fig. 4. Test summary of chronological variations for the pressure drop of evaporator heat exchangers in air-conditioners with and without the decrease of hydrophilicity.**

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 heat exchanger used 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, longer lasting hydrophilicity as well as the prevention of fouling is very important.

**3. Chronological Variations of Cooling Capacity**

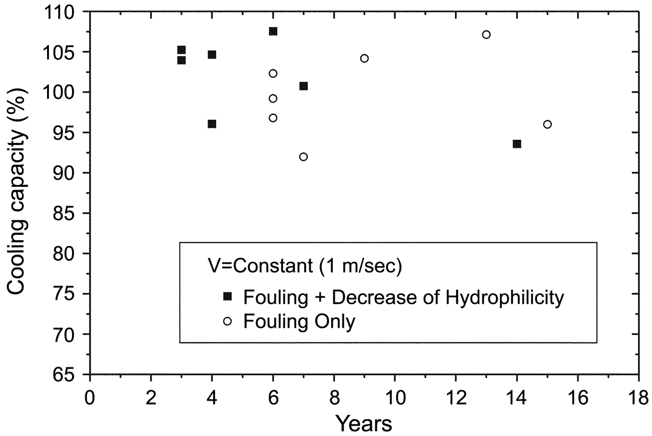



**Fig. 5. Test summary of chronological variations for the cooling capacity of evaporator heat exchangers at the face velocity of 1 m/sec.**

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 a 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 does not affect directly the decrease of cooling capacity unless the air flow rate reduces. However, if 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.

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.

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 decreases 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.

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 a higher pressure drop due to the decrease of hydrophilicity in the

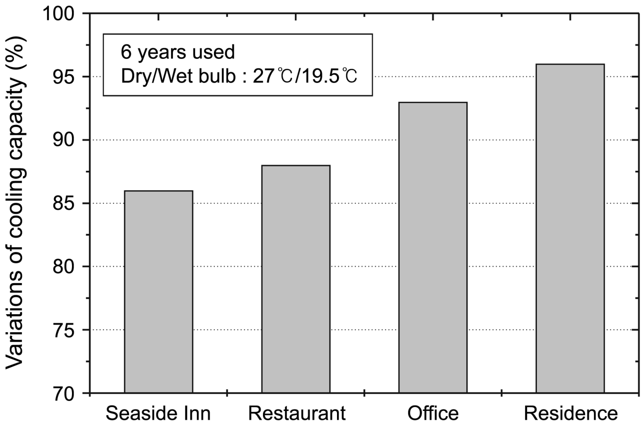



**Fig. 6. Variations of cooling capacity for the evaporator heat exchangers used in various places at the same pressure drop of initial heat exchangers.**

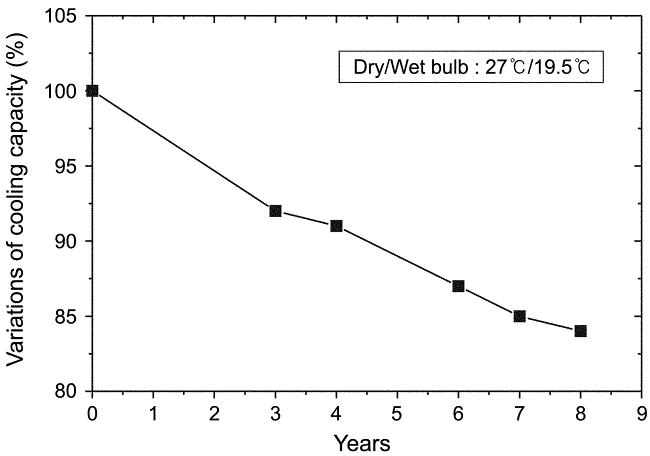



**Fig. 7. Chronological variations for cooling capacity of evaporator heat exchangers in air-conditioners used in the seaside inn at the same pressure drop of initial heat exchangers.**

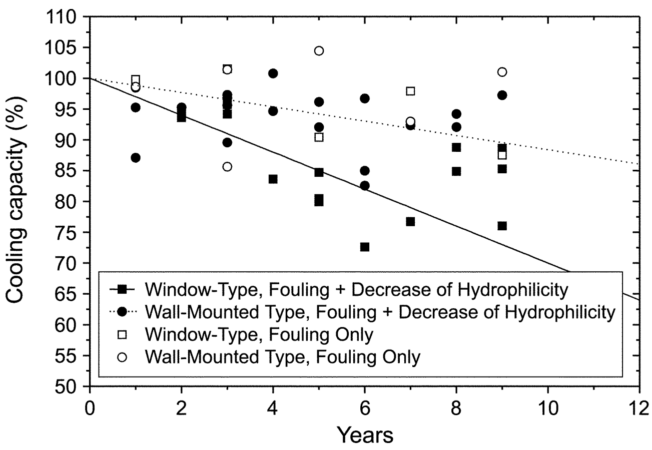



**Fig. 8. Test summary of chronological variations for the cooling capacity of air-conditioner sets.**

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.

## 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 was investigated with a psychrometric calorimeter. Thirty samples of air conditioners used in the field such as inns, restaurants, and offices were collected in chronological order. This study is intended to provide factual long-term fouling data under actual operating conditions.

Fouling of heat exchangers causes a decrease of cooling capacity and 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 μm 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.

## ACKNOWLEDGMENT

The authors wish to thank the LG Electronics Inc. for its financial support to this research.

## REFERENCES

Ahn, Y. C., Cho, J. M., Lee, J. K., Lee, H. U., Ahn, S. P., Youn, D. H., Ha, S. C. and Kang, T. W., "Performance Evaluation of the Heat Exchangers Due to Air-Side Particulate Fouling in the Air Conditioners," *Korean Journal of Air-Conditioning and Refrigeration Engineering*, **15**(5), 447 (2003).

Bott, T. R., "Fouling of Heat Exchangers," Elsevier, Amsterdam, Netherlands, 497 (1995).

Epstein, N., "Fouling Science and Technology - Particulate Fouling of Heat Transfer Surfaces: Mechanisms and Models," Kluwer Academic Publishers, Dordrecht, Netherlands, 143 (1988).

Incropera, F. P. and DeWitt, D. P., "Fundamentals of Heat and Mass Transfer 4th ed.," John Wiley & Sons, New York, U.S.A., 568 (1996).

Korean Standard, "Air Conditioners," KS C 9306 (2002).

Lee, H. J., Han, D. G., Lee, S. H., Yoo, J. W., Baek, S. H. and Lee, E. K., "On-Line Monitoring and Quantitative Analysis of Biofouling in Low-Velocity Cooling Water System," *Korean J. Chem. Eng.*, **15**(1), 71 (1998).

Lee, H. J., Park, J. S. and Moon, S. H., "A Study on Fouling Mitigation Using Pulsing Electric Fields in Electrodialysis of Lactate Containing BSA," *Korean J. Chem. Eng.*, **19**(5), 880 (2002).

Marner, W. J., MacDavid, K. S. and Muzio, L. J., "Development of a Gas Side Fouling Measuring Device," *National Heat Transfer Conference*, **108**, 305 (1989).

Siegel, J. A., "Particulate Fouling of HVAC Heat Exchangers," Ph. D. Thesis, University of California, Berkeley, U.S.A. (2002).

Thatcher, T. R. and Layton, D. W., "Deposition, Resuspension, and Penetration of Particles within a Residence," *Atmospheric Environment*, **29**(13), 1487 (1995).