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# THE IMPACT OF FOULING ON THE PERFORMANCE OF FILTER-EVAPORATOR COMBINATIONS

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## ABSTRACT

This paper presents results of experiments performed on 6 different combinations of filters and evaporator coils under clean and fouled conditions. The fouled conditions were obtained after injection of 600 grams of dust upstream of the filter/coil combination, which was meant to simulate a year of operation in the field. The airside pressure drops of the coils and filters and airside effective heat transfer coefficients of the coils were determined from the measurements under the clean and fouled conditions. Depending upon the filter and coil, the coil pressure drops increased in the range of 6%-30% for an air velocity of 2.54 m/s (500 fpm). The impact was significantly greater for tests performed without a filter. The largest relative effect of fouling on pressure drop occurs for coils with fewer rows, primarily due to higher fin densities. The impact of fouling on airside effective heat transfer coefficients was found to be relatively small. In some cases, heat transfer was actually enhanced due to additional turbulence caused by the presence of dust.

## 1. INTRODUCTION

Fouling of evaporator coils affects the heat transfer coefficient, increases pressure drop, reduces system air flow rate, and leads to a loss in cooling capacity, increased energy consumption and increased service costs. Filters are often employed upstream of evaporators to reduce these effects and improve indoor air quality in the building. This project investigated the role of filtration in maintaining clean evaporator coils. Four different coils were studied in connection with 6 different levels of filtration (MERV 14, 11, 8, 6, 4, and no filter). The coils and filters were representative of those generally used in residential and commercial applications.

Most of the fouling studies in the literature have focused on liquid-side fouling. Only a few studies were found to focus on air-side fouling. A review of developments in air-side fouling was presented by Manner (1990). Six classifications (precipitation fouling, particulate fouling, chemical reaction fouling/corrosion fouling, biological fouling and solidification fouling) for fouling and five main fouling mechanisms (initiation of fouling, transport to the surface, attachment to the surface, removal from the surface, aging of the deposit) were provided in this paper. Analytical models were presented to predict the various gas-side fouling processes.

Siegel and Nazaroff (2003) built a model for fouling of fin-and-tube heat exchanger to estimate the overall deposition fraction that was related to the penetration factors of impaction on fins edges, impaction on refrigerant tubes, gravitational setting, air turbulence and Brownian diffusion. The paper predicted that less than 2% of submicron particles (<1 μ m) would deposit on heat exchangers while for supermicron particles, deposition increases quickly with particle size. Higher airflow rate led to increased deposition by impaction on fin edges, tubes and by air turbulence, while lower airflow rate increased deposition by Brownian diffusion and gravitational settling. Larger fin density caused increased deposition for all mechanisms except for impaction on tubes.

There were a few studies on airside fouling in heat exchangers through experiments by Mort (1966), Marner (1990), Bott and Bemrose (1983), Zhang, Bott and Bemrose (1990). Some general conclusions resulted from these experiments: (1) The effect of gas-side fouling on pressure drop is more pronounced than on heat transfer. (2) Fouling rate is directly proportional to particulate bulk concentrations and after an initiation period there is a rapid fouling process. (3) Small size particles seem to increase fouling compared to the larger particles. (4) Fouling is enhanced by higher air velocities. (5) The surfaces that are least susceptible to fouling are those with the largest values of hydraulic diameter (lowest fin density) of the basic orifices in the front face.

The present study aimed to characterize, experimentally, the effect of dust loading on coil performance when employing different filter-coil combinations.

## 2. EXPERIMENTAL STUDY

### 2.1 Test Facility

An existing Purdue Air Coil Test (PACT) facility was employed for the experiments. The general layouts of the equipment are shown in Figure 1 (wind tunnel) and Figure 2 (water loop). The cross-sectional of the main air duct is 0.61m×0.61m (24 inch×24 inch). The test section includes a dust injector, an upstream test filter, a test coil and a downstream filter. Four coils with different geographies and five types of upstream filters of different efficiencies were used for the test. The details of the coils and filters are presented in Table 1 and Table 2. The water system included a chilled water loop and a cooling water loop. The main components of the water system included a chiller, a pump, a mass flow meter, and a surge tank.

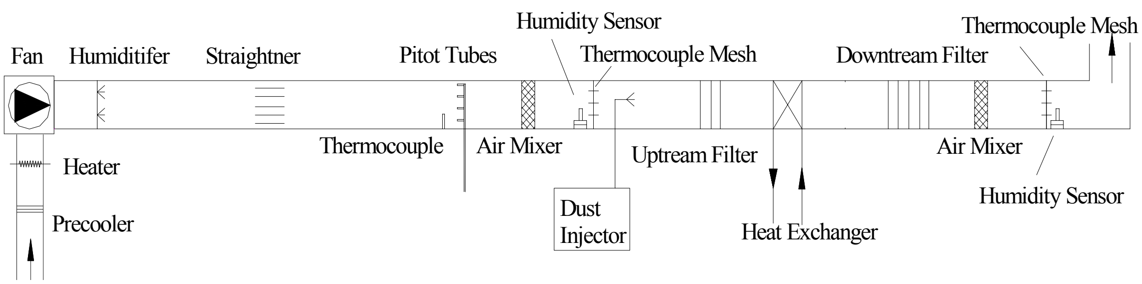


Figure 1: Schematic of experimental wind tunnel

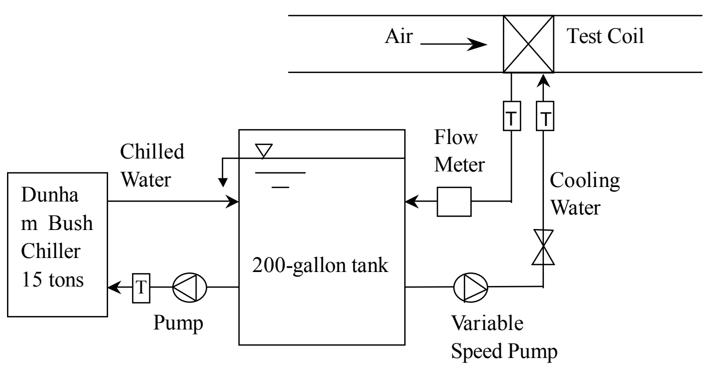


Figure 2: Schematic of experimental water loop

The dust feeder was manufactured according to ASHRAE specifications (ASHRAE Standard 52.1). The ASHRAE synthetic arrestance dust used in the experiment meets specifications set forth in the standard. The compounded dust consists by weight of:

(1) 72% of standardized air cleaner test dust. It is predominantly silica and has a mass-mean diameter of approximately 7.7 micrometers.
(2) 23% of powdered carbon
(3) 5% of cotton linter

Table 1: Test coil descriptions

| Coil No. | Fin Geometries | Tube Geometries (cm) | No. of Rows | Fin Density (fin/cm) |
|---|---|---|---|---|
| HX2L | Lanced | 0.95 (3/8 in) | 2 | 5.51 (14 fin/inch) |
| HX4L | Lanced | 1.27 (1/2 in) | 4 | 4.72 (12 fin/inch) |
| HX8W | Wavy | 1.27 (1/2 in) | 8 | 3.15 (8 fin/inch) |
| HX8L | Lanced | 1.27 (1/2 in) | 8 | 3.15 (8 fin/inch) |

Table 2: Test filter descriptions

| Filter No. | MERV4 | MERV6 | MERV8 | MERV11 | MERV14 |
|---|---|---|---|---|---|
| Filter Type | Fiberglass Media | Pleated Filters | Pleated Filter | Mini-Pleat Filter | Mini-Pleat Filter |
| Arrestance | 75-80% | 90-95% | 95% | 99% | 99% |
| Clean Pressure Drop at 2.54 m/s | 59.8 Pa (0.24 in$H_2O$) | 79.7 Pa (0.32 in$H_2O$) | 59.8 Pa (0.24 in$H_2O$) | 93.4 Pa (0.38 in$H_2O$) | 190.6 Pa (0.77 in$H_2O$) |
| Replacement Pressure Drop at 2.54 m/s | 124.6 Pa (0.5 in$H_2O$) | 249.1 Pa (1.0 in$H_2O$) | 249.1 Pa (1.0 in$H_2O$) | 373.7 Pa (1.5 in$H_2O$) | 373.7 Pa (1.5 in$H_2O$) |

## 2.2 Test Conditions and Procedure

The tests that were conducted are shown in Table 3. Most of the tests were performed at wet conditions. However, two tests were carried out at dry conditions to understand the impact of moisture condensation on fouling. The conditions were set as:

(1) Air velocity: 1.52, 2.03, 2.54, 3.05 m/s (300, 400, 500, 600 fpm)
(2) Air inlet dry-bulb temperature: $T_{a,i}$=26.7$^o$ C (80$^o$ F)
(3) Air inlet relative humidity: $RH_i$=61% (for wet conditions) <20% (for dry conditions)
(4) Water inlet temperature: $T_{w,i}$=3$^o$ C (37.4$^o$ F)
(5) Water flow rate: 0.5 kg/s (8 gal/min, for 8-row coil test), 0.35 kg/s (5.5 gal/min, for 4-row coil test), 0.25 kg/s (4 gal/min, for 2-row coil test)

Table 3: Test matrix

| Wet | Clean | No Filter | | HX8L | HX8W | HX4L | HX2L |
|---|---|---|---|---|---|---|---|
| | | | | X | X | X | X |
| | Fouling | Filter | MERV4 | X | X | X | X |
| | | | MERV6 | X | X | -- | X |
| | | | MERV8 | X | X | X | X |
| | | | MERV11 | X | X | -- | X |
| | | | MERV14 | X | X | -- | X |
| | | No Filter | | X | X | X | X |
| Dry | Clean | No Filter | | X | -- | -- | -- |
| | Fouling | MERV11 | | X | -- | -- | -- |

The following general procedures were followed for obtaining clean and fouled test results:
(1) At clean or original conditions, the coil was tested without any upstream filer and without dust feeding at four air velocities.
(2) To create fouled conditions, the coil was loaded with 600 grams of dust with an upstream filter (or no filter for nofilter case) at an air velocity of 2.54 m/s (500 fpm).
(3) After dust loading, the coil was tested without an upstream filter at four air velocities.
(4) After the fouling tests, the coil was cleaned with an evaporator cleaner to return it to its original condition.

# 3. DATA REDUCTION

The outputs of voltages and amperes of the instrumentation were collected by a Hewlett Packard Model 75000 Series B data acquisition system and converted to digital signals. The data acquisition software HP VEE (Visual Engineering Environment) was used to read the signals from the PC. MicroSoft Excel and EES (Engineering Equation Solver) were applied for further calculations to deduce the coil air-side pressure drop and effective heat transfer coefficient.

## 3.1 Coil Airside Pressure Drop

Pressure drop correlations were determined for the coils under clean and fouled conditions using:

$$\Delta P_c = a_c V^{b_c} \text{ or } \Delta P_f = a_f V^{b_f} \quad (1)$$

where $\Delta P_c$ is the coil air-side pressure drop at clean conditions and $\Delta P_f$ is the coil air-side pressure drop at fouling conditions. The coefficients $a_c$, $b_c$, $a_f$, $b_f$ were determined using regression for each coil and set of tests. The pressure drop fouling factor $f_{dp}$ was defined as:

$$f_{dp} = \frac{100(\Delta P_f - \Delta P_c)}{\Delta P_c}\% \quad (2)$$

## 3.2 Coil Air-side Effective Heat Transfer Coefficient

The coil airside effective heat transfer coefficient was defined as the product of coil airside heat transfer coefficient and fin effectiveness. The coil waterside heat transfer coefficient was assumed to be known and the air-side effective heat transfer coefficients for the coils were deduced from the data using the model given in the ASHRAE Handbook: "2000 HVAC Systems and Equipment", Chapter 21. The coil air-side effective heat transfer coefficients under clean and fouled conditions were correlated using the following forms:

$$h_c = c_c V^{d_c} \text{ or } h_f = c_f V^{d_f} \quad (3)$$

where $h_c$ is the coil air-side effective heat transfer coefficient at clean conditions and $h_f$ is the coil air-side effective heat transfer coefficient at fouling conditions. The heat transfer coefficient fouling factor $f_h$ was defined as:

$$f_h = \frac{100(h_f - h_c)}{h_c}\% \quad (4)$$

# 4. TEST RESULTS

## 4.1 Coil Baseline Performance

The baseline is defined as the performance of the test coil without and upstream filter at clean conditions (and wet conditions for most of tests). Six baselines were obtained for each test coil relative to six fouling tests with different filter combinations except HX4L (only three fouled cases were tested for HX4L). However, since the coils were cleaned very well and the baselines had very small differences, an average baseline is presented. Figures 3 and 4 show the four average baselines for the four test coils. The coil pressure drops and effective heat transfer coefficients are presented as a function of air velocity. The pressure drop increases nonlinearly with air velocity for a given coil and is higher for coils having greater depths. The effective heat transfer coefficient also increases with air velocity, but differences between different coils are relatively small. Generally, greater fin density and greater coil depth can increase the effective heat transfer coefficient, but the effect of fin density is relatively small compared to the effect of coil depth when the number of rows is larger than four (C. C. Wang, K. Y. Chi (1999)). Therefore, the effective heat transfer coefficient for HX4L is a little lower than that for HX8L. The highest effective heat transfer coefficient occurred for HX2L, possibly because of the tighter fin spacing and a somewhat different fin and tube geometry. The manufacturer for HX2L was different than the manufacturer for HX8L, HX8W and HX4L, so that there might be greater difference between the performance of HX2L and other coils.

## 4.2 Coil Fouling Factors

The coil air-side pressure drop and effective heat transfer coefficient fouling factors for all filter-coil cases at an air velocity of 2.54 m/s (500 fpm) are presented in Figures 5 and 6, respectively.

For each coil, from MERV14 to no-filter cases, the quantity of dust deposited increased. Thus, from Figure 9, it can be seen that the pressure drop fouling factor increased as the level of filtration was decreased. For each filter type, the differences in $f_{dp}$ among the four coils were small. However, for the no-filter case, $f_{dp}$ for HX4L (equal to 108%) was more than two times $f_{dp}$ for HX8L and HX8W, and $f_{dp}$ for HX2L (equal to 201%) was two times $f_{dp}$ for HX4L.

In general, coils with fewer rows are more affected by fouling. This is due to the following two reasons:

(1) Dust is mainly deposited on the front of coil. This situation was clearly observed for the test coils; especially the eight-row coils. For deep coils, the pressure drop at the frontal face is a smaller percentage of the total coil pressure drop than for a shallow coil.
(2) Coils with fewer rows generally have greater fin density. The fin densities were 3.15 fin/cm, 4.72 fin/cm, and 5.51 fin/cm (8 fin/inch, 12 fin/inch and 14 fin/inch) for 8-row, 4-row and 2-row coils, respectively. Greater fin density leads to greater dust capture on the coil surfaces.

Figure 6 shows $f_h$ for all coil-filter combination cases at an air velocity of 2.54 m/s (500 ft/min). For most fouling cases, heat transfer was decreased but for a few cases it was enhanced. $f_h$ ranged from –14% to 4%, which was very small compared to $f_{dp}$ (ranged from 10% to 200%). In many cases with filters, the heat transfer impact was less than the uncertainty in the measurements (approximately 4% to 5%) and the trends were inconsistent. However, it appears that a moderate amount of dust could actually enhance heat transfer for HX8W. The enhancement could be due to additional turbulence caused by the dust. This was apparent for the HX8W which uses a wavy fin and has less turbulence than the lanced fin. However, the dust also acts as insulation and creates an uneven air velocity distribution, which decreases the heat transfer. Therefore, with large dust deposits, heat transfer is degraded.

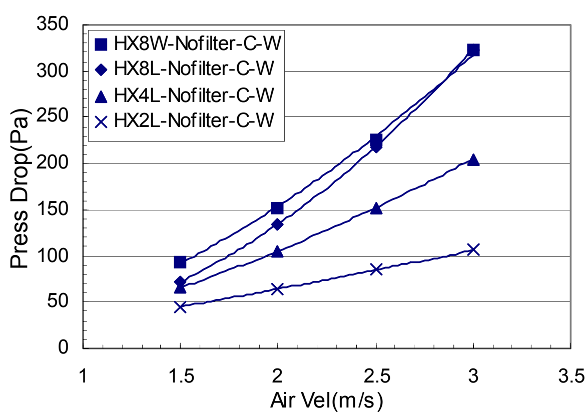


Figure 3: Baseline pressure drop vs air velocity for four test coils

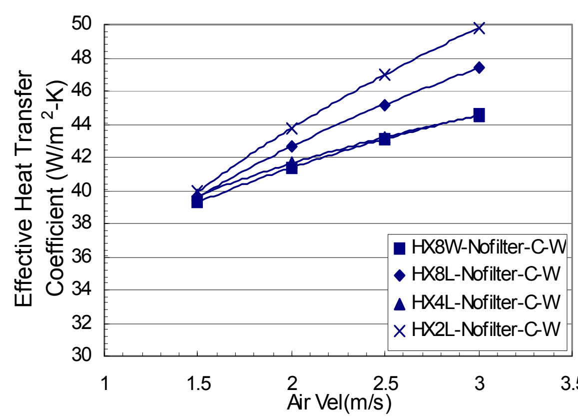


Figure 4: Baseline effective heat transfer coefficient vs air velocity for four test coils

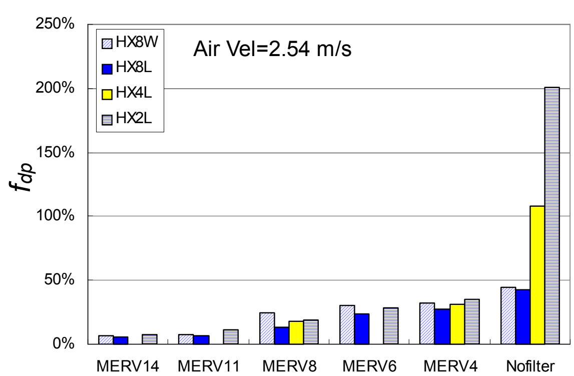


Figure 5: Pressure drop fouling factors for all wet cases at an air velocity of 2.54 m/s

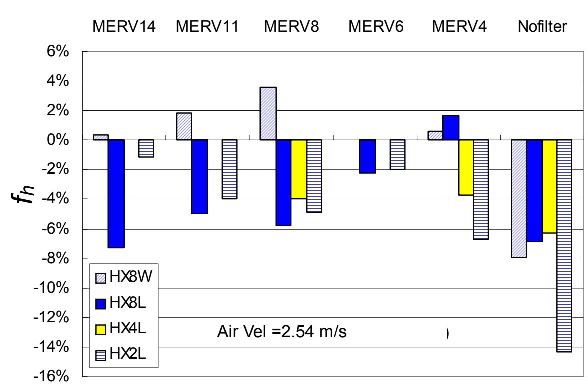


Figure 6: Effective heat transfer coefficient fouling factors for all wet cases at an air velocity of 2.54 m/s

### 4.3 Comparisons Between Dry and Wet Conditions

Limited tests were performed at dry and wet conditions to understand the impact of condensation on fouling. They were: HX8L-Nofilter-C-D, HX8L-Nofilter-C-W, HX8L-MERV11-F-D and HX8L-MERV11-F-W.

Figure 7 shows baseline coil pressure drops for the two clean cases. It can be seen that the coil air-side pressure drop at wet conditions was 24% to 59% higher than the pressure drop at dry conditions, because the condensation on the coil surface reduced the air flow area and increased the turbulence. Figure 8 shows the pressure drop fouling factors for the two fouled cases. It was found that when the coil was fouled, the pressure drop increased 2% to 8% after fouling for wet conditions while it increased 17% to 25% for dry conditions. Fouling had a greater impact on the pressure drop of the dry coil than the pressure drop of the wet coil. Possibly, the condensation helps to wash some of the dust off the coil and reduce the amount of dust acccumulation. Unfortunately, the coil dust deposits were not determined for the dry tests. More tests are needed to understand the differences between fouling at wet and dry conditions.

Figure 9 shows the coil air-side effective heat transfer coefficients for the two clean cases. It can be seen that the coil air-side effective heat transfer coefficient for wet conditions was 9% higher than the effective heat transfer coefficient for dry conditions at an air velocity of 1.52 m/s (300 ft/min). When the air velocity increased, the difference became smaller. Figure 10 shows the effective heat transfer coefficient fouling factors for the two fouled cases. Fouling made the effective heat transfer coefficient for wet conditions decrease within a range of 5%, but it had a less effect on the dry condition results. Those effects may be due to experimental error. The overall effect is so small that it is difficult to identity reasons for these trends.

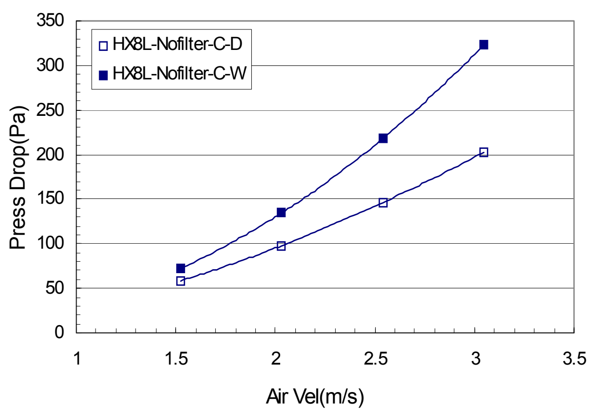


Figure 7: Pressure drop vs air velocity of HX8L-Nofilter-C at dry and wet conditions

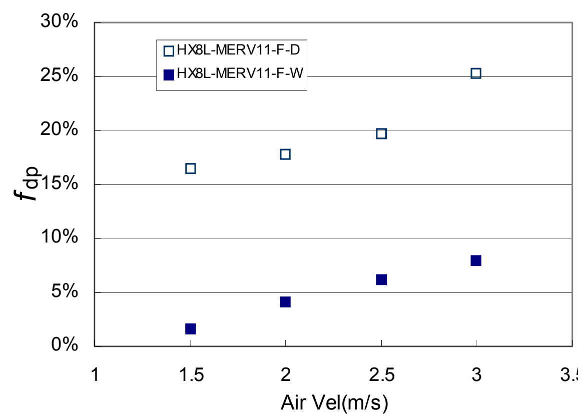


Figure 8: Effective heat transfer coefficient vs air velocity of HX8L-Nofilter-C at dry and wet conditions

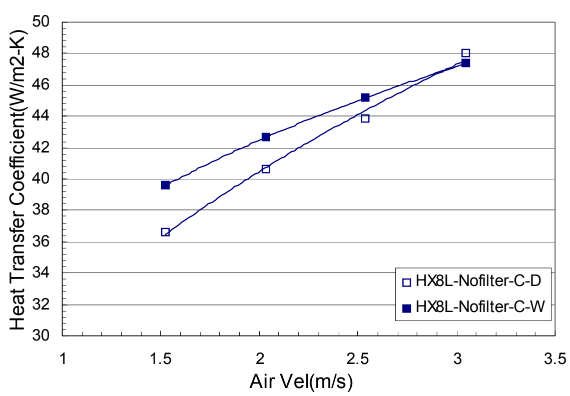


Figure 9: Pressure drop fouling factor for HX8L-MERV11 at dry and wet conditions

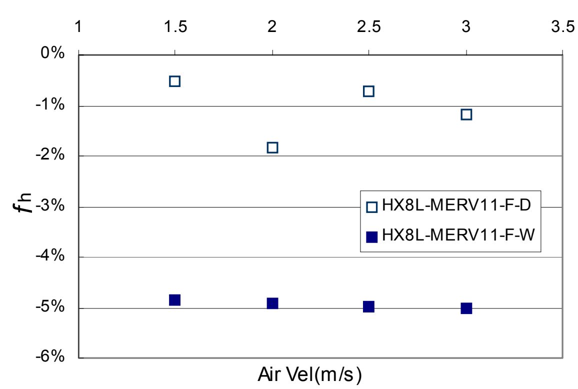


Figure 10: Effective heat transfer coefficient fouling factor for HX8L-MERV11 at dry and wet conditions

### 4.4 Dust Quantities Deposited on the Coils

A total of 600 grams of ASHRAE standard dust was injected into the air stream during the fouling tests. Most of dust was captured by the upstream filter (when installed) and the rest was deposited on the coil, downstream filter, inside of the duct, drain pan and some flowed away with condensation. The quantity of dust on the test coil is shown in Figure 11. The mass of dust captured by the coil ranged from approximately 4 grams to 50 grams for all the cases with filters and it was approximately 300 grams for no-filter cases. There appears to be little correlation between the depth of the coil and the amount of dust deposited on the coil. In fact, the two-row coil had slightly greater dust deposits than the deeper coils in many cases. This may be due to the higher fin density used for the shallower coils.

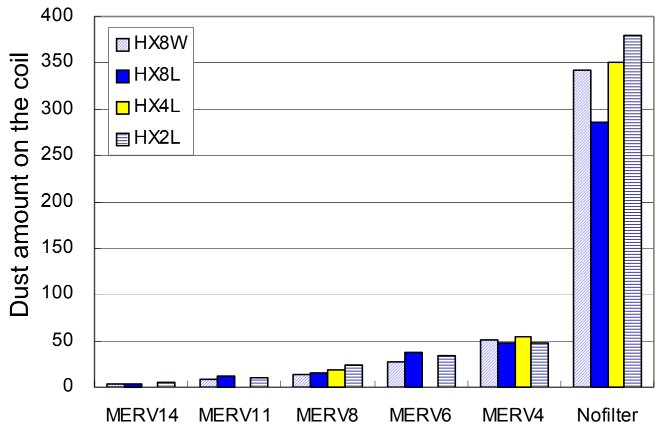


Figure 11: Dust quantities deposited on the coils for all test cases

## 5. CONCLUSIONS

Depending on the quantity of dust deposited, heat transfer coefficients can increase or decrease with fouling for a fixed air velocity. The enhancement is due to increased turbulence. The experiments showed a maximum of approximately 4% increase in effective heat transfer coefficient after fouling, whereas the maximum penalty for a year's worth of dust deposits with no filter was approximately 14% at an air velocity of 2.54 m/s (500 ft/min).

Fouling has a greater effect on coil air-side pressure drop than heat transfer coefficient. When loading dust, the pressure drop fouling factor increases continuously. For the highest efficiency filter the pressure drop increased by approximately 6%, whereas for no filter the increase was approximately 200% at an air velocity of 2.54 m/s (500 ft/min).

Fouling has less effect on coil air pressure drop for deeper coils. This probably because deeper coils used in medium to large commercial applications generally have larger fin spacings than shallower coils used in residential and small commercial. Most of the dust was captured by the leading edges of coil. It was observed that the rear of the coil was very clean compared to the front for the coil. When coils were tested without an upstream filter, the pressure drop fouling factor was approximately 45% for the eight-row coil, 100% for four-row coil and 200% for two-row coil.

Fouling had a greater impact on the pressure drop of the dry coil than the pressure drop of the wet coil, possibly because the condensation washed some of the dust off the coil and reduced the amount of dust accumulation. However, the effect of fouling on heat transfer was so small that it is difficult to obtain any conclusion regarding differences between fouling effects for wet and dry conditions.

There were relatively small differences in the results for lanced and wavy fins for the 8-row coils (HX8L and HX8W). However, differences could be greater for coils having tighter fin spacings. It would interesting to independent study the impact of coil depth, fin spacing, and fin type on fouling effects.

ASHRAE standard dust was used in the study, which was made of coarse particles. Smaller particles should be employed in future work so that the whole size range of ambient particles is considered.

## NOMENCLATURE

| | |
|---|---|
| $a$ | coil pressure drop factor, $Pa \cdot s^{b_{c(f)}} / m^{b_{c(f)}}$ |
| $b$ | coil pressure drop exponent |
| $f$ | fouling factor |
| $h$ | effective heat transfer coefficient, W/m$^2$-K |
| $RH$ | relative humidity |
| $T$ | temperature, ºC |
| $V$ | air velocity, m/s |
| $\Delta P$ | pressure drop, Pa |
| **Subscripts** | |
| $a$ | air or airside |
| $c$ | coil or clean |
| $d$ | dry |
| $dp$ | pressure drop |
| $h$ | effective heat transfer coefficient |

## REFERENCES

Bott, T. R., Bemrose, C. R., "Particulate Fouling on the Gas-side of Finned Tube Heat Exchangers", Journal of Heat Transfer, Vol. 105, p. 178-183 (1983).

Wang, C.C., Chi, K.Y., "Heat Transfer and Friction Characteristics of Plain Fin-and-Tube Heat Exchangers, Part I: New Experimental Data", International Journal of Heat and Mass Transfer, Vol. 43, Issue 15, p. 2681-2891 (2000).

Marner, W. J., "Progress in Gas-Side Fouling of Heat-Transfer Surfaces", Appl Mech Rev, Vol. 43, No. 3, p.35-66, (1990).

Miller, J. A., "Mechanisms of gas turbine regenerator fouling", Paper No. 67-LGT-26, ASME, New York, (1967).

Mort, C. B., "Research on exhaust gas effects on heat exchangers", Technical Report SEG-TR-66-30, Wright-Patterson Air Force Base, O.H. (1966).

Siegel, J. A., Nazaroff, W. W., "Predicting particle deposition on HVAC heat exchangers", Atmospheric Environment, Vol. 37, Issues 39-40, p. 5587-5596 (2003).

Thornburg, Don "Filter Testing and IAQ Control Move Forward", Heating, Piping, Air Conditioning, Vol. 71, No. 10, p.54-56 (1999).

Zhang, G., Bott, T. R., Bemrose, C. R., "Finned Tube Heat Exchanger Fouling by Particles", Heat Transfer, Proceedings of the Ninth International Heat Transfer Conf., p.115-120, (1990).

"ASHRAE STANDARD -- Gravimetric and Dust-Sport Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter", ANSI/ASHRAE 52.1 – 1992.

"ASHRAE STANDARD – Standard Methods for Laboratory Air-Flow Measurement", BSR/ASHRAE 41.2-1987.

"ASHRAE STANDARD – Standard Methods for Temperature Measurement", ANSI/ASHRAE 41.1-1986.

ASHRAE Handbook: "2000 HVAC Systems and Equipment", Chapter 21 "Air-cooling and dehumidifying coils".

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