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A Literature Review On Heat Exchanger Air Side Fouling In Heating, Ventilation And Air-conditioning (HVAC) Applications

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A Literature Review on Air Side Heat Exchanger Fouling in Heating, Ventilation and Air-Conditioning (HVAC) Applications

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ABSTRACT

This paper provides a review on the fouling mechanism and its effect onto the performance of finned tube heat exchangers in HVAC systems. Fouling tends to degrade the performance of heat exchangers by decreasing the heat transfer coefficient and increasing the air-side pressure drop across the heat exchangers. Air side fouling depends on a number of factors on the air side, including type and concentration of fouling matter, size of particles in the fouling matter, and air velocity. Additionally, it depends on the heat exchanger design, e.g. heat exchanger geometry, fin geometry, and fin spacing. Various studies indicate that the effect of fouling on air pressure drop is higher than its degrading effect on heat transfer coefficient. Studies on heat exchanger fouling in HVAC systems indicate that the actual effect of the fouling onto system efficiency additionally depends on the employed refrigerant.

1. INTRODUCTION

HVAC systems are extensively used in residential, commercial and industrial systems. Due to increased demand of water for both domestic and industrial purposes in the recent years, there has been an increased interest in the use of air cooled systems as an alternative to water cooled systems. Also, in locations, where it is not possible to find adequate water for cooling of condensers, air-cooled condensers might be the only option. Due to extensive use of air cooled heat exchangers in HVAC applications, it is important to analyze the fouling phenomenon in these systems.

Fouling, in general, may be defined as the accumulation and growth of particles on heat exchanger surface that tends to degrade its performance for conditions under which it is designed to operate. Fouling causes a decrease in heat transfer because thermal conductivity of fouling material is typically less as compared to heat exchanger surface material. Therefore, it acts as a resistance to heat transfer resulting in heat exchanger performance degradation. Fouling on the surface of heat exchanger additionally acts as a hindrance to the flow of air causing an increase in the pressure drop, resulting in reduced air flow, therefore decreasing the heat transfer indirectly. In addition, the increased pressure drop increases fan power, an additional contribution towards the fouling-caused reduction in system energy efficiency.

Awad (2011) studied the fouling of heat transfer surfaces in general. He found out that fouling agents can contain inorganic materials such as airborne dust and grit, waterborne mud and silt, as well as organic materials including biological substances and elemental carbon. Fouling of a specific heat exchanger is, besides from the fouling agent itself, additionally dependent on its design and particular process in which it is used.

Numerous studies have been conducted on the impact of fouling on heat exchanger performance in different applications. Haghighi-Khoshkhoo & McCluskey (2007) studied the air-side fouling of the compact heat exchangers for industrial vehicles. Marner (1990) observed the gas-side fouling of heat exchangers caused by unclean fluid streams in applications like heat recovery systems and boilers. Cremaschi *et al.* (2012) have studied the impact of water-side fouling on the performance of brazed plate heat exchangers for air conditioning applications.

Fouling occurs on both the evaporator and condenser side of air-to-air AC & HP systems. It varies in nature from textile fibers and mold compounds to airborne dust and particulate matter (Qureshi & Zubair, 2012).Various studies have been conducted to analyze the impact of fouling on the performance of heat exchangers in HVAC applications. These studies range from the fouling only on evaporator or condenser side to combined fouling on both sides. Ali &

Ismail (2008) studied the effect of heat exchanger performance for evaporator side fouling while Pak *et al.* (2005) performed the analysis for condenser side fouling. Qureshi & Zubair (2011) investigated the performance of the system for three cases on air-side: evaporator only fouling, condenser only fouling, and combined evaporator and condenser fouling.

In literature, different types of fouling matter have been used to investigate the effects of fouling onto the HVAC systems are extensively used in residential, commercial and industrial systems. Due to increased demand of water for both domestic and industrial purposes in the recent years, there has been an increased interest in the use of air cooled systems as an alternative to water cooled systems. Also, in locations, where it is not possible to find adequate water for cooling of condensers, air-cooled condensers might be the only option. Due to extensive use of air cooled heat exchangers in HVAC applications, it is important to analyze the fouling phenomenon in these systems.

2. FOULING PHENOMENON

Different types of fouling phenomena can occur depending on the particulate matter in the gas stream as well as the material and geometry of the heat exchanger. According to Awad (2011), these phenomena can be divided into:

- **Particulate fouling**, taking place due to the accumulation of suspended particles in the fluid stream on the surface of the heat exchanger. Particulate fouling can, according to Ahn et al. (2003) be further divided into turbulent diffusion, Brownian diffusion, gravitational settling, inertial impaction, thermophoresis, and electrophoresis.

- **Precipitate fouling,** occurring due to the presence of dissolved salts in the saturated solution. The crystallization of these saturated salts as a result of the change in temperature (solubility dependence on temperature) can result in the formation of precipitate fouling.

- **Chemical reaction fouling,** occurring due to the chemical reaction that takes place between the particles present in the fluid stream. The heat exchanger surface can act as a catalyst.

- **Corrosion fouling,** caused by electrochemical reactions that can take place between heat transfer surface and fluid stream. In contrast to other fouling types, corrosion fouling will cause permanent damage to heat exchangers.

- **Biological fouling,** occurring due to the presence of biological matter in the fluid stream which sticks to the heat transfer surface and allows microorganisms to grow on the surface of heat exchangers.

- **Freezing fouling/Frosting,** occurring due to the freezing of liquid on heat transfer surface like frosting in heat exchangers during winter.

For air cooled exchangers in HVAC applications, the main fouling mechanisms are particulate fouling, biological fouling and freezing fouling (Siegel & Nazaroff, 2003).

Fouling, in general, occurs as a net result of the two phenomena is shown in Figure 1 that take place simultaneously: a deposition process and a removal process, the net effect of which can be described by a fouling factor. The fouling factor is the difference between the deposition rate, Φ_d and the removal rate, Φ_r (Awad, 2011).

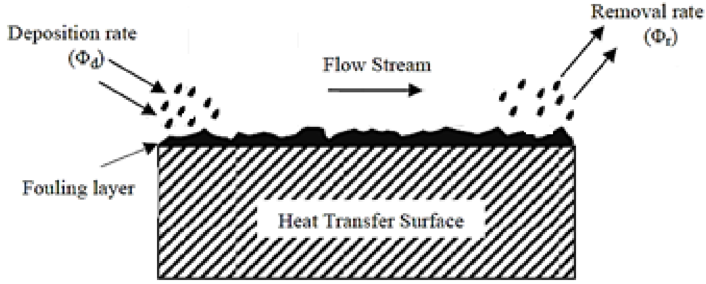


Figure 1: Fouling Process (Awad, 2011)

Siegel & Nazaroff (2003) developed a model for the deposition of particles onto heat transfer surfaces. They analyzed three major variables affecting the deposition process: particle size, air velocity, and fin spacing. The term deposition fraction was used in their study, representing the probability that fouling particle will deposit on the heat exchanger surface. They analyzed heat exchangers varying in fin pitch size, tube diameter, and number of tube rows. Since particulate fouling is a function of the size of particulate matter, monodisperse oil particles of different sizes were used for the experimental study. Previous studies were mainly focused on particles in the size range of 10 to 100 µm. However, they observed that submicron (0.01-1 µm) particles were in greater concentration in indoor air and supermicron particles (10-100 µm) were present in indoor dust.

They concluded that particle deposition takes place mainly by impaction on fin edges and tubes, gravitational settling on fin corrugations, impaction on fin walls due to turbulent motion and deposition by Brownian motion. The different deposition mechanisms were combined, assuming no cross dependence, to obtain the overall deposition fraction η:

$$\eta = 1 - P_{\text{fin}} \cdot P_{\text{tube}} \cdot P_{\text{G}} \cdot P_{\text{T}} \cdot P_{\text{D}}, \quad (1)$$

where:
P_{fin} = Fraction of particulate matter lost due to the impaction on the fin edges,
P_{tube} = Fraction of particles lost due to the deposition on the tube surface,
P_{G} = Penetration fraction representing losses due to the gravitational settling,
P_{T} = Penetration fraction accounting for losses due to deposition by turbulence, and
P_{D} = Fraction of particles representing losses due to Brownian motion.

The assumption that the effect of these mechanisms was independent of each other was justified by their dependence on different particle size ranges without any overlap.

They found out that deposition fraction was a strong function of particle size while a weak function of air velocity and fin spacing. Smallest particles (0.01-1 µm) were deposited mainly by the Brownian diffusion. Particles in the range of 1-10 µm were deposited by impaction on fin edges and particles greater than 10 µm were deposited by air turbulence, impaction on tubes and gravitational settling. For a given fin spacing, at higher velocities, tube impaction was the dominant phenomenon and for lower velocities, the dominant phenomenon was settling on fin surface. Directly proportional relationship was observed between the particle size and overall deposited mass on the coil.

It was found that with an increase in air velocity, inertial deposition increased while it decreased for Brownian diffusion and gravitational settling. In case of fin pitch, it was observed that greater fin pitch led to increased deposition by all mechanisms except by tube impaction.

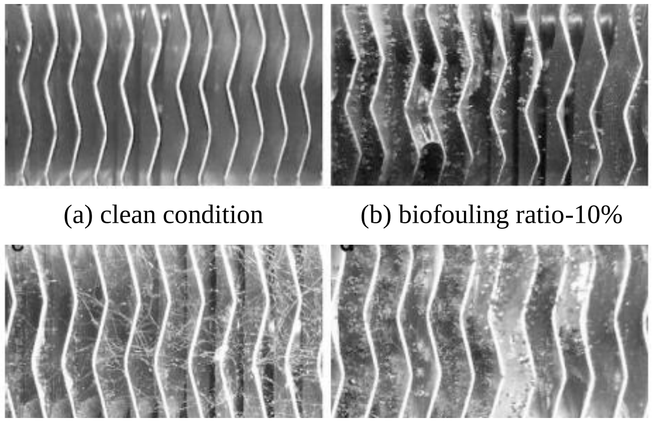
3. FOULING OF AIR COOLED HEAT EXCHANGERS

3.1 Biofouling

Two types of studies on the effects of fouling on heat exchangers performance can be found in literature: air dust deposition and biofouling. Biofouling or biological fouling takes place due to the presence of biological matter in the air stream and microorganisms nourished by the deposition matter in the prolonged presence of water on the surface of heat exchangers, such as air coolers and evaporators.

Effect of biofouling on the performance of the heat exchangers was studied by Pu *et al*. (2009). They analyzed biofouling for the heat exchangers with aluminum herringbone wavy fin with hydrophilic coating and copper as a tube material. Aspergillus niger (a fungus) was selected as a biological material to grow on heat transfer surface. This microorganism was selected because it grows quickly on evaporator surface. Figure 2 shows the heat exchangers with different biofouled area ratio.

Pu *et al*. (2009) found out that for a biofouled area ratio (fungus to air-side surface area ratio) of 60%, air-side pressure drop increased by 21.8 % and 43.1 % respectively for the air velocity of 0.5 m/s and 2 m/s. For an air velocity of 2 m/s, heat transfer coefficient decreased by 7.2% and 15.9 % for a biofouled area ratio of 10% and 60 % respectively. Due to air turbulence, heat transfer was increased for low biofouling area. Biofouling caused the hydrophilic coating on the surface of the heat exchanger to fail. As a result, condensed water remained on the heat exchanger surface, increasing the growth of fungus.



(a) clean condition (b) biofouling ratio-10%

(c) biofouling area ratio-30% (d) biofouling area ratio-60%

Figure 2: Heat exchangers during biofouling test with Aspergillus niger (Pu *et al*. 2009)

3.2 Air Dust Deposition Fouling

Various researchers studied the dust deposition fouling for different types of heat exchangers with different geometrical parameters, air flow rates and amount and type of dust as shown in Table 1.

Table 1: Heat exchanger type and dust used by different researchers

Source	Heat exchanger type	Dust type	Amount of injected dust	Heat exchanger face area
Ali & Ismail (2008)	Plate fin-and-tube	From used field installed evaporators	300 g	0.048 m^2
Ahn *et al.* (2003)	Fin and tube	Heat exchanger samples from field	Not applicable since field units were tested	No information given
Bell & Groll (2010)	Microchannel & Plate fin	ASHRAE standard dust & Arizona road test dust	300 g	0.2 m^2
Yang *et al.* (2007)	Wavy fin and Lanced fin	No dust (Strip of paper to simulate fouling)	Not Applicable	0.372 m^2
Pak *et al.* (2003)	Plate fin and Spine fin	ASHRAE standard dust	300 g	No information given
Qureshi & Zubair (2011)	Plate fin	Not applicable (model developed using EES)	Not applicable	No information given

Air-side fouling of heat exchangers depends on the number of factors on the heat exchanger (system) side and the air-side.

In HVAC systems, fin and tube heat exchanger are extensively used for residential, commercial, and industrial applications. Therefore, this paper is mainly focused on fin and tube heat exchangers. For the fin and tube exchangers, fouling is dependent on the following factors:

i. Fin type,
ii. Number of tube rows,
iii. Heat exchanger type,
iv. Fin spacing,
v. Refrigerant type, and
vi. Filters, if any.

Cowell & Cross (1980) investigated the performance of gas side fouling for automotive heat exchangers and found out that the dust is accumulated on the frontal face of the heat exchanger, and fouling is more severe on the front face as compared to the rear face. The same behavior was observed in HVAC systems, e.g. by Pak *et al.* (2005) and Ali & Ismail (2008).

On the frontal face, dust accumulates on the leading edges of the fin as seen in the example in Figure 3.

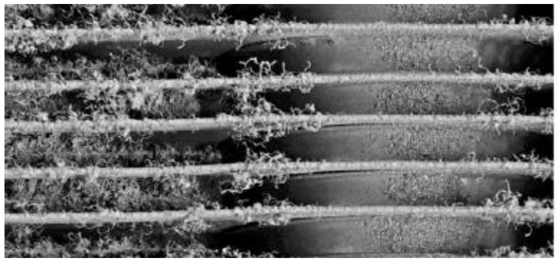


Figure 3: Front face of coil fouled with 600g of injected dust. (Bell *et al.*, 2011)

Pak *et al.* (2005) investigated the performance of heat exchangers on the basis of number of tube rows. They found that out of the total amount of dust injected, the amount of dust accumulated on single row condenser was 30-50%, while, for the double row condenser, it was 60-67%. However, they observed that the relative increase in pressure drop was almost identical for double and single row condensers because fouling matter was accumulated on the leading edges of the fins and as a result, the blockage was similar in both the condensers. However, heat transfer after and before fouling was better for the double row condenser than the single row condenser because of the greater depth in a double row condenser as compared to a single row condenser.

Bell & Groll (2010) investigated the performance of two different types of heat exchangers: plate and fin as well as microchannel. They experimentally observed that for the same type and amount of dust material, the performance of the microchannel heat exchanger was more severely affected as compared to the plate and fin exchangers.

Qureshi & Zubair (2011) analyzed the effect of fouling onto the system efficiency for different refrigerants, using a simulation model. They considered R134a, R407C, and R410A in one group (0°C evaporation temperature) while R717, R404A, and R290 were considered in a separate group (-25°C evaporation temperature). They conducted simulations with their model for 3 different cases: Condenser only fouling, evaporator only fouling, and combined evaporator and condenser fouling. They found that the Coefficient of performance (COP) of the condenser only fouling case was lower as compared to the evaporator only fouling. This was caused by an increased compressor power requirement for the condenser only fouling case. In case of evaporator only fouling, the cooling capacity was reduced but compressor power requirement was also reduced which led to a smaller decrease in COP[1]. For the combined case, the compressor power requirement was in between the condenser only and evaporator only fouling case. However, COP in the combined case was found lower as compared to the other two cases because the effect of fouling on both the evaporator and condenser side is to decrease COP by decreasing the capacity. Amongst the first set of refrigerants, according to the first law analysis standpoint, R134a performed the best except for the evaporator only fouling case while according to the second law analysis standpoint, R134a performed the best in all the cases. A similar behavior was observed for the refrigerant R717 amongst the second set of refrigerants.

Yang *et al.* (2007) analyzed the cooling efficiency of packaged air conditioners equipped with filters of different rated efficiencies, e.g. minimum efficiency reporting value (MERV) 4 to MERV 14. They concluded that the energy efficiency ratio (EER) of the system for both clean and fouled case is reduced significantly by high-efficiency filters due to the increased pressure drop on the air-side. The decrease in EER was more sensitive to the filter type for large equipment. However, better air quality was obtained when a higher efficiency filter was used. It was found that the amount of dust passing through the system with an MERV 4 filter is 30 times the amount found for MERV 14 filter.

[1] Qureshi & Zubair (2011) did not include fan power into the COP calculation, e.g. effect of increased fan power onto COP is not considered.

Siegel *et al*. (2002) analyzed the performance of residential evaporator coil by presenting a fin and tube heat exchanger fouling model. They studied the fouling time as a function of filter efficiency and indoor concentrations. They calculated the mass concentration distribution function m_c, which describes the amount of fouling material deposited on the coil surface as a function of particle diameter. It can be calculated as the fraction of fouling material removed by filtration and amount deposited in the return duct as:

$$m_{\mathrm{c}} = P_{\mathrm{d}}\,(1 - \eta_{\mathrm{f}} + \eta_{\mathrm{f}}\, b_{\mathrm{f}}) \cdot \eta_{\mathrm{c}} \cdot (1 - b_{\mathrm{c}}) \cdot m_{\mathrm{in}}\,, \tag{2}$$

where P_{d}, the fraction of particles not removed by deposition in the duct work is calculated from Sippola & Nazaroff (2002), η_{f} is the filter efficiency calculated as described in ASHRAE standard 52.2, b_{f} is the filter bypass calculated using anecdotal evidence and scaling analysis, η_{c} is the coil deposition fraction and calculated using Siegel & Nazaroff (2002), and m_{in}, the indoor particle distribution function is calculated using the functions from Riley *et al.* (2002), Schneider (1986), and Thatcher & Layton (1995).

Fouling time, τ_{foul} is the time taken to double the pressure drop across the heat exchanger coil for a given air flow rate and is calculated as:

$$\tau_{foul} = \frac{M_{foul}}{Q\ M_c DC}, \tag{3}$$

where M_{foul} is the deposited mass that causes the pressure drop of coil to double and is determined experimentally, Q is the air flow rate through the system, DC is the duty cycle of the air handler fan, and M_c is the total mass distribution that deposits in the coil and is calculated as:

$$M_c = \int_{d_p} m_c\, \mathrm{d}d_p, \tag{4}$$

where d_p is the particle diameter and ranges from .01-100 µm. Table 2 represents the estimated fouling time ratio which is the ratio of fouling time of a particular case in comparison to the base case. In Table 2, GM is the geometric mean and GSD is the geometric standard deviation.

Siegel et al. (2002) found that the average fouling time for the base case was 7.6 years. It can be observed from the above table that shifting from MERV 2 filter to MERV 12 filter increased the fouling time by 7 times . However, this time was found to be dependent on the interaction between the filter efficiency and filter bypass caused by the poor design of the filter housing. Using high-efficiency filter with increased filter bypass led to the deposition of particles on the heat exchanger coils that were larger than what should be filtered out according to the MERV rating.

Table 2: Fouling time ratios (Siegel *et al.* 2002)

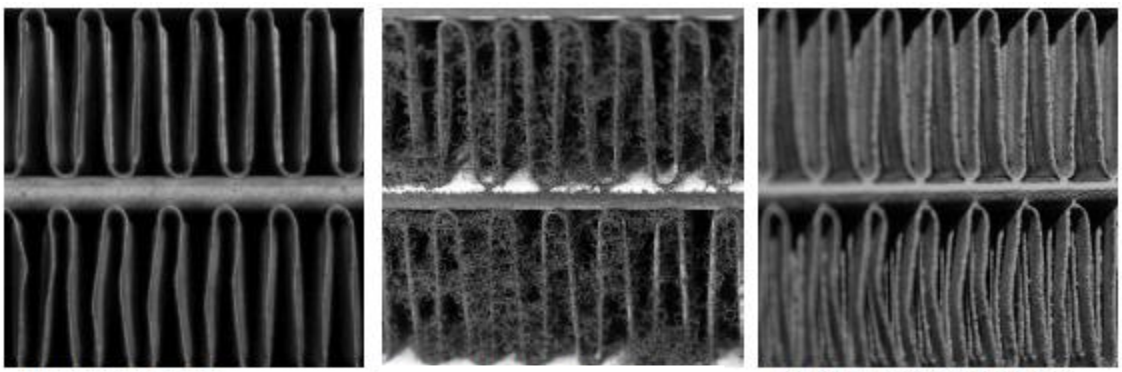
			Fouling Time Ratio		
Variable	**Base Case**	**Going to**	**Median**	**GM**	**GSD**
Filter Efficiency	MERV 2	MERV 6	1.39	1.39	1.08
		MERV 12	10.04	6.89	2.79
Indoor Concentration	Urban	Rural	0.43	0.45	1.23
	Cycling	CA	0.31	0.30	1.09
	Dirty	Clean	1.85	1.70	1.45
Coil Efficiency	4.7 fin/cm	2.4 fin/cm	1.82	1.90	1.11
		7.1 fin/cm	0.71	0.70	1.05
Filter Bypass	10%	None	1.81	1.12	2.26
		25%	0.73	0.86	1.38
Duct Penetration	Typical	Simple	0.99	0.99	1.01
		Complex	1.02	1.02	1.01

On the air-side, the dust fouling depends on the following factors:

(1) Type of dust or fouling material used
(2) Air flow rate

Bell & Groll (2010) investigated the performance of plate and fin as well as microchannel heat exchangers using two different types of dust: ASHRAE standard dust and A2 Arizona road test duct. ASHRAE standard dust is prepared using ASHRAE standard 52.1, which by mass contains 72 % A2 fine Arizona test dust, 23% of carbon black powder and 5% of milled cotton lint. A2 Arizona road test dust was used in the experimentation to demonstrate the fouling in the areas with little fibrous matter.

From Figure 4, it can be seen that the ASHRAE standard dust covered the front face of the exchanger. This is due to the presence of the fibrous content in the ASHRAE standard dust. However, for the Arizona road test dust, it was deposited over the entire heat transfer surface and did not block the front face. As a result, the pressure drop in case of heat exchanger fouled with ASHRAE test standard dust was larger as compared to Arizona test dust. However, heat transfer reduced more in case of Arizona test dust due to its low thermal conductivity and since it covered most of the heat transfer surface. Also, ASHRAE test dust has 23 % carbon which is a better conductor of heat as compared to the silicon oxide particles in Arizona road test dust and hence led to a better heat transfer as compared to the latter.



(a) (b) (c)

Figure 4: Heat exchanger (a) clean condition (b) fouled with 135g of ASHRAE test dust (c) fouled with 500g of Arizona Road test dust (Bell & Groll, 2010)

Ali & Ismail (2008) used fouling material collected from evaporators that were put in their actual application. They used sieve analysis to determine that the particles ranged in size from 0.01 to 200 µm. After injecting the fouling material, they found that fiber and non-dusty material were attached to fins on frontal face due to the presence of condensed water. After the injection of 100 g of fouling material, COP was found to be reduced to 67%, after 200 g to 63.4%, and after the injection of 300 g of fouling material to 43.6%. Air velocity was kept constant at 1.53 m/s.

The fouling rate is a strong function of air velocity. An increase in air velocity increases the thermal performance of the exchanger and decreases the fouling rate. Ali & Ismail (2008) analyzed the COP as a function of velocity for clean and fouled conditions. COP increased with the increase in air velocity in both the clean and fouled cases, due to the increase in the heat transfer coefficient. However, COP was found to be a weaker function of velocity in the fouled case.

Burmeister & Bortone (1995) found that the sensitivity of pressure drop to air velocity for fouled heat exchangers was larger than for clean heat exchangers.

4. CONCLUSION

This paper presented a literature review of fouling in heat exchangers focused on air conditioning applications. The review explains that fouling in heat exchangers depends on a number of factors on both the system as well as the air-side. The overall impact of fouling is degradation of the performance of heat exchangers. This includes a degradation of the heat transfer by accumulating on the heat transfer surface as well as an increase in pressure drop. Numerous studies found that for a different type of fouling material, fouling is more severe on the front face as compared to the rear face. The impact of fouling in increasing pressure drop for constant air flowrate is greater than the decrease in heat transfer especially at the initial phase of the fouling process and if fibrous materials are involved. Using high-efficiency filters before evaporators result in an increase in the fouling time but decreases the EER of the system due to the increased overall airside pressure drop. Increase in air velocity increases the COP of the system for both clean and fouled case, however, increase in COP with an increase in air velocity is not as significant in fouled case as in the clean case.

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