2018

Accelerating-particle-deposition Method for Quickly Evaluating Long-term Performance of Fin-and-tube Heat Exchangers

Dawei Zhuang
Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China, zdw3108@sjtu.edu.cn

Guoliang Ding
Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, China, People's Republic of, glding@sjtu.edu.cn

Yifei Yang
Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China, wushi@sjtu.edu.cn

Feil Zhan
Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China, zhanfl@163.com

Yifeng Gao
International Copper Association, Shanghai 200020, China, frank.gao@copperalliance.asia

See next page for additional authors

Authors
Dawei Zhuang, Guoliang Ding, Yifei Yang, Feil Zhan, Yifeng Gao, Jun Shen, and Ji Song

Accelerating-particle-deposition Method for Quickly Evaluating Long-term Performance of Fin-and-tube Heat Exchangers

Dawei ZHUANG[1], Guoliang DING[1*], Yifei YANG[1], Feilong ZHAN[1], Yifeng GAO[2], Jun SHEN[2], Ji SONG[2]

[1] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University,
Shanghai, China
[2] International Copper Association,
Shanghai, China
* Corresponding Author
Tel: 86-21-34206378; Fax: 86-21-34206814; E-mail: glding@sjtu.edu.cn

ABSTRACT

Fin-and-tube heat exchanger is the most commonly used heat exchanger type in air-conditioning systems. In the actual operation of air-conditioning systems, the dust particles involved in the air may partly deposit and form particulate fouling on fins and tubes when the dusty air flows through the heat exchangers. The deposited particles may gradually block the passageway of air flow and occupy the heat transfer area, which results in the continuous increase of air side thermal resistance and the significant deterioration of the heat transfer capacity of heat exchangers during the long-term operation. In order to quickly evaluate the long-term performance of fin-and-tube heat exchangers, an accelerating-particle-deposition method, which is capable of implementing the particle deposition process on the long-running heat exchangers in a short time, is proposed in this study.

The idea of the accelerating-particle-deposition method is to employ high concentration dusty air flow through heat exchangers in the accelerated test, and to quickly form the particulate fouling with the same weight as that on long-running heat exchangers under the actual operating environment with low particle concentration. The accelerating factor, which is defined as the ratio of the actual running time to the accelerated testing time, is calculated based on the deposition weight of dust particles. The deposition weight is calculated by the relationship of the impact frequency and deposition probability of dust particles with the dust feed rate of dusty air.

An experimental apparatus for accelerating the particle deposition process and testing the heat transfer capacity of fin-and-tube heat exchangers is designed. The accelerating factor is fitted by the experimental data, and the mean deviation of the accelerating factor is 16.3%.

1. INTRODUCTION

Fin-and-tube heat exchangers are widely used in air conditioners and refrigeration systems (Wang et al., 1996, Zhu et al., 2015, Wu et al, 2017). The heat exchanger in air-conditioner outdoor unit is exposed to the environment for a long time (He et al., 2012, Zhan et al., 2016, Liu et al, 2012). The air of the environment contains dust particles, these particles will hit the heat exchanger surface during long time operation (Wu et al., 2017, Liu et al., 2012). Some of the dust particles will be deposited on the heat exchanger surface and form the fouling layer.

The long-term performance of the heat exchanger will be decreased due to the fouling layer on the surface (Bell et al., 2011, Ma et al, 2009). The fouling layer on the surface has high thermal resistance and leads to the decrease of heat transfer performance of heat exchanger. The thickness of fouling layer will increase and the space between fins will decrease. The smaller fin space will cause higher pressure drop on the air side (Pak et al., 2005, Waring et al., 2008, Ahn et al, 2003). For an air conditioner with 7 years of operation, the cooling capacity of the whole air conditioner will be decreased by 10-15%, and the pressure drop will be increase by 44%, which are both caused by the fouling layer (Ahn et al, 2003).

The forming of fouling layer on the heat exchanger surface is affected by the deposition objective and airflow characteristics. For the deposition objective, the geometry structure including row number, fin space and fin types will influence the fouling layer. Research results showed that the differences of heat transfer capacity and pressure drop between one row and two rows before and after deposition are 4%~12% and 22%~37%, separately (Wu et al, 2007). When the fin space increase from 1.2mm to 1.8mm, the deposition rate on the heat exchanger will decrease 63.1% (Zhan et al, 2016). For the airflow characteristics, various air velocity, particle diameter and dust concentration can affect the formation of fouling layer, which will deteriorate the performance of heat exchanger under deposition condition. When the air relative humidity increases, there will be more condensed water droplets on the fin surface, which can easily catch lots of particles. The study by Kaiser et al. (2002) showed that the deposition quantity under wet condition is 6.7 times larger than under dry condition.

Based on the dust deposition research, the dust concentration has a big effect on the deposition rate of heat exchanger. When the air conditioner is working in a heavy polluted area, its heat exchanger has more particle deposition. The higher the dust concentration is, the stronger the particle collision is. The collision between particles will change the original motion of particles, and the deposition rate increases due to the growth of collision frequency. In order to evaluate the long-term performance of heat exchanger, the experimental method is usually used to test the heat transfer and pressure drop performance. During experiment, the temperature and relative humidity are kept constant in all experimental conditions, same as actual operating condition. However, for the particle concentration on the air inlet, it is timely impossible to use the real concentration in the experiment. Because the real particle concentration needs several years of particle deposition, which is unpractical for an experiment. Therefore, enhancing the particle concentration on the air flow inlet is the common way to accelerate experiment.

In current researches, part of them set constant particle concentration as inlet condition, others focus on the effect of various particle concentration on the performance by experimental method. Abd-Elhady et al. (2004) found the proper inlet air velocity for particle deposition on the fin surface, and the inlet particle concentration is set to $2g/m^3$. Bell et al. (2011) measured the heat transfer performance and pressure drop of heat exchanger before and after particle deposition, and in their experiment, a total mass of 300g dust is passed through the heat exchanger. Bott et al. (1983) studied the friction factor of heat exchanger after particle deposition with various particle concentration and inlet air velocity, and the ranges of particle concentration and air velocity are from 0.65 $g/m^3$to $1.5g/m^3$ and from 2.4m/s to 5.8m/s, separately. Zhan et al. (2016) observed the fouling layer on the heat exchanger for three different inlet particle concentration, and the results showed that the concentration has little effect on the final deposition rate. However, all above researches did not discuss about how to determine the various particle concentrations in the experiment. It is therefore hard to set the proper particle concentration in the experiment to predict the actual operation.

In this study, an accelerating-particle-deposition method, which is capable of implementing the particle deposition process on the long-running heat exchangers in a short time, is proposed. The method can be used to precisely calculate the dust concentration at inlet to minimize the influence of acceleration of dust concentration on experimental results.

2. RESEARCH OBJECTIVE

A fin-and-tube heat exchanger can be severely fouled by particles after long-term operation, as shown in Fig. 1(a). The formation of particle fouling is due to the coupling effects of particle deposition and particle removal. At the beginning of fouling forming process, the particle depositing speed is larger than the removing speed and the fouling weight increases with deposition time. But after some deposition time the particle depositing speed decreases until it is equal to the particle removing speed, then the fouling forming process ends and the fouling weight reaches a critical point. During the fouling forming process, the rate of fouling weight increase is determined by the particle concentration of inlet dusty air. For a certain deposition time T_h, higher particle concentration leads to a larger fouling weight, as shown in Fig. 1(b) and 1(c). When the fouling weight reaches the critical value M_f, the ratio of total deposition time under low particle concertation t_l and high particle concertation t_h is defined as the accelerating factor α, as shown in Fig. 1(d).

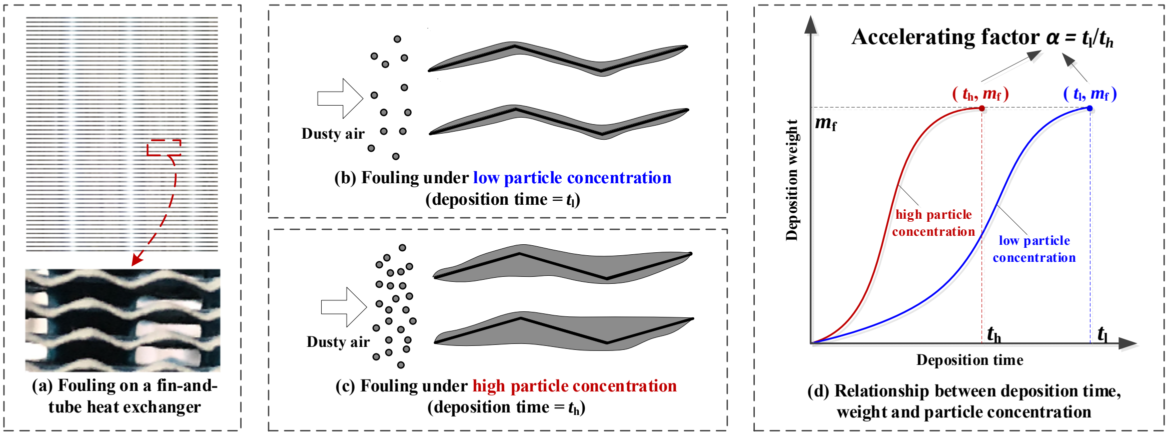


Figure 1: Fouling formation process in the fin-and-tube heat exchanger under low/high particle concentration of dusty air

3. EXPERIMENTAL METHOD

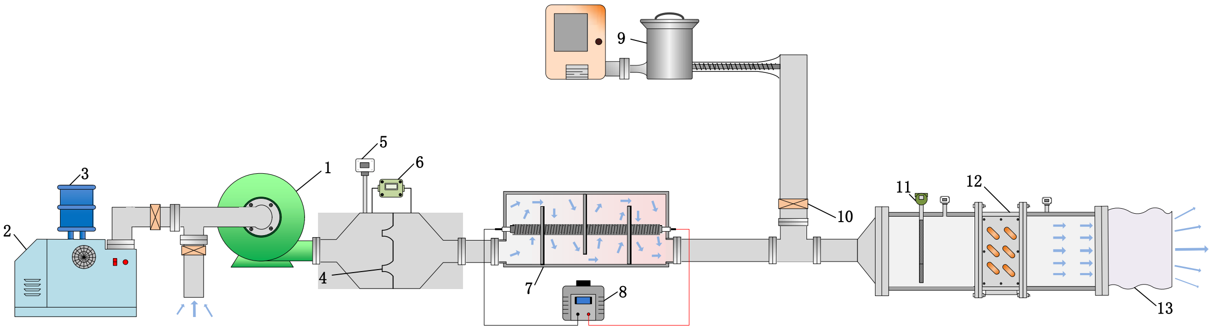
3.1 Experimental apparatus

The experimental apparatus includes three parts: (1) the air supply device for providing dry/wet air to air flow channel; (2) the dust supply device for providing constant concentration particles; (3) the test section for measuring the performance of experimental samples. Fig. 2 shows the rig of experimental apparatus.

The air supply device consists of variable frequency fan, ultrasonic humidifier, water tank, stop valve, control valve, air volume measuring device and heater. The dry air is drawn into the system by variable frequency fan, and mixes with the water vapor produced by ultrasonic humidifier to form the moist air with specific relative humidity. The heater is used to provide the constant temperature of the air flow. The range of variable frequency fan is 20-200m3/h, the maximum capacity of humidification is 6kg/h, the accuracy of air volume measuring device is 0.1 m3/h, and the maximum power of heater is 5kW.

The dust supply device consists of screw feeder and stop valve. The screw feeder pushes the dust into the air flow channel by screw. The dust concentration can be controlled by adjusted the speed of the screw with the motor. The ratio of high concentration and low concentration equals to that of high dust feed rate and low dust feed rate. The range of dust feed rate of the screw feeder is 20-200g/h.

The test section consists of stainless flow channel, dust concentration sensor, temperature and humidity sensor, pressure difference sensor, tray and cleaner bag. The accuracies of dust concentration sensor, temperature sensor, humidity sensor and pressure difference sensor are ±5%, 0.2K, ±2% and ±5%, separately. Two temperature and humidity sensors are settled at the inlet and outlet of the experimental sample to measure the temperature and humidity difference. The pressure difference sensor is used to measure the pressure drop of the experimental sample with dust on the surface.



1-Variable frequency fan, 2-Ultrasonic humidifier, 3-Water tank, 4-Nozzle, 5-Temperature and humidity sensor, 6-Pressure difference sensor, 7-Heater, 8-DC power, 9-Screw feeder, 10-Valve, 11-Dust concentration sensor, 12-experimental sample, 13-Cleaner bag

(a) The rig of the experimental apparatus

(b) The real photo of experimental apparatus

Figure 2: The experimental apparatus

3.2 Experimental condition and test samples

1) Experimental condition

The experimental condition is listed in Table 1. The inlet air temperature and relative humidity is chosen as 27℃ and 50%, which is referred to the National standard in China (GB-T7725-2004). The inlet air velocity is set as 2m/s. Six different values of inlet dust feed rate are selected in the experiment, ranging from 25-150g/h, which is fitted with the screw feed machine. Fin type is chosen as wavy fin, which is commonly used in the air conditioners.

Table 1: Experimental conditions for accelerating experiment

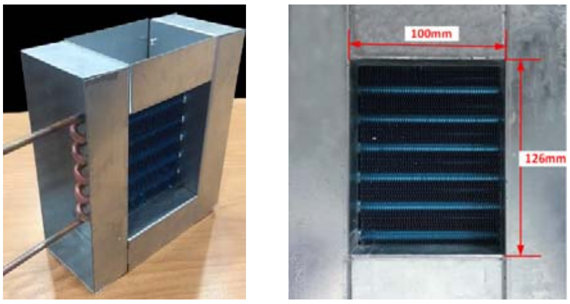
Inlet air temperature, *T*	**Inlet air relative humidity, *RH***	**Inlet air velocity, *v***	**Inlet dust feed rate, *n***	**Fin type**
27℃	50%	2m/s	25, 50, 75, 100, 125, 150g/h	Wavy fin

2) Test samples

Figure 3 shows the picture of test samples. The test sample includes two parts: the heat exchanger and the outer frame. The size of the whole heat exchanger is remarked in Figure 3(b). The length and width of the heat exchanger are 100mm and 126mm, respectively, which is fitted with the air flow channel.

The Table 2 listed the parameters of the heat exchanger in test samples. The tube diameter is 7mm, which is usually used in air conditioner. And the fin type is chosen as wavy fin. And the row number of the test sample is 2, which is wildly used in air conditioner.

Moreover, synthetic dust particles are adopted as the experimental dust particles in the present study, and the mass composition of this experimental dust is 75% silicon dioxide and 25% carbon black powder, which is similar to the components of ASHRAE standard dust. The mean diameter of silicon dioxide particles in the present study is 10 µm, and the density is 2.2×10^3 kg m^{-3}.



(a) test sample structure rig (b) size of heat exchanger in test sample

Figure 3: The picture of test sample

Table 2: Parameters of test samples

Tube diameter	Row number	Fin types	Fin pitch
7mm	2	Wavy fin	1.6mm

3.3 Data reduction and uncertainty analysis

Three key parameters are mentioned in this research, including the inlet air mass flow rate, the inlet dust feed rate and the pressure drop of test sample on air-side. For the inlet air mass flow rate, it can be measured by air volume measuring device. The calculation formula of the air flow rate is shown in eq.(1).

$$V = CA_n\sqrt{2\Delta P \rho_{a,in}} \quad (1)$$

where C is constant as 0.97, A_n represents the section area of nozzle throat, ΔP represents the pressure drop, $\rho_{a,in}$ represents the air density at the inlet of nozzle.

For the inlet dust feed rate, it can be obtained by the average of the value measured by concentration sensor and the value calculated by feeding speed of the screw feed. The dust feed rate can be calculated by feeding speed of the screw feed with eq.(2).

$$n = \frac{15\pi\left(d_b^2 - d_s^2\right)\rho_p r s \theta}{V} \quad (2)$$

where d_b is the diameter of screw blade, d_s is the diameter of screw spindle, ρ_p is the particle density, r is the speed of screw rotation, s is the screw pitch, θ is the filling coefficient, which is 0.95 in this experiment.

For the pressure drop of test sample can be obtained by pressure difference sensor directly. Based on the Moffat (1998) analytical method, the uncertainty of indirect parameters can be calculated, and the uncertainty results are listed in Table 3.

Table 3: Uncertainties of experimental parameters

Parameter	Min. (%)	Max. (%)
v	±1.0%	±10.0%
ΔP	±1.0%	±5.0%

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Definition of accelerated factor

The accelerating factor α is defined as the ratio of low particle concentration deposition time and high particle concentration deposition time, which can be written as:

$$\alpha = \frac{t_l}{t_h} \tag{3}$$

During the acceleration of particle concentration, the mass quantity of particles deposited on the heat exchanger must be equal.

$$m_l = m_h \tag{4}$$

The mass quantity deposited on the heat exchanger surface can be calculated by eq.(5) and (6).

$$m = f \cdot \xi \cdot t \cdot K \tag{5}$$

$$f = (n \cdot Z)/2 \tag{6}$$

where m is the particle deposition mass quantity, f is the collision frequency between particle and heat exchanger surface, ξ is the deposition probability of one particle on surface after impaction, t is the deposition time, K is the volume of air flow channel, n is the particle weight per cubic meter, Z is the contact frequency between a single particle and heat exchanger surface.

Assuming that the deposition probability of one particle on surface after collision has no relevance with the particle concentration, which means $\xi_l = \xi_h$. The value of collision frequency f need to be obtained for the calculation of accelerating factor. To quantify the collision frequency f, two extreme cases are considered:

a) If the collision between particles is ignored, there is no relevance between the contact frequency Z and dust feed rate n. In this condition, $f \propto n$;
b) If the collision between particles is considered with the assumption that frequencies of the collision between particles and the collision between particles and heat exchanger surface are equal. The contact frequency Z' between one particle and other particles can be written as eq.(7), which is derived according to molecular dynamics theory. The collision frequency between particles as well as particles and heat exchanger surface is shown in eq.(8).

$$Z' = \sqrt{2} n \cdot v \cdot \pi d^2 \tag{7}$$

$$f = \frac{\sqrt{2}}{2} \cdot n^2 \cdot v \cdot \pi d^2 \tag{8}$$

The actual situation is something between a) and b). Part of the particles will not contact the heat exchanger surface even after its collision with other particles. Therefore, the relationship between collision frequency and dust feed rate is shown in eq.(9).

$$f = \frac{\sqrt{2}}{2} \cdot n^a \cdot v \cdot \pi d^2 \tag{9}$$

where a is the concentration coefficient ranging from 1 to 2. Combining eqs.(3)-(5) and (9), the concentration factor can be expressed by eq.(10). In this study the value of a is fitted by the experimental data.

$$\alpha = \left(\frac{n_h}{n_l}\right)^a \tag{10}$$

4.2 Experimental results

Figure 4 shows the deposition weight with deposition time for various dust feed rate. For the high dust feed rate, the deposition weight reaches the steady state rapidly. For the low dust feed rate, the deposition weight increases slowly with the time. While at the final steady state, the deposition weights under various dust feed rate are equal to a constant. Figure 5 shows the total deposition time under various inlet dust feed rate. It can be seen that the total deposition time decrease with the increase of inlet dust feed rate. The total deposition time under dust feed rate of 25 g/h is almost 9.1 times that under dust feed rate of 150 g/h, and the rate of total deposition times is obviously larger than the rate of inlet dust feed rates.

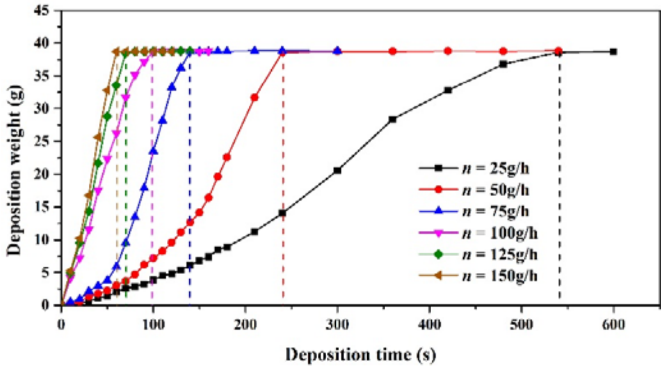


Figure 4: The deposition weight with deposition time for various dust feed rate

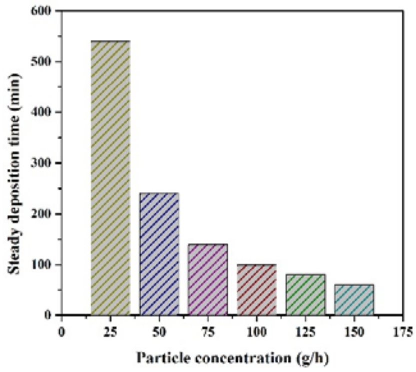


Figure 5: The total deposition time under various inlet dust feed rate

4.3 Development of the accelerating factor

Based on the experimental results, the concentration coefficient a can be developed as eq.(11).

$$a = \frac{\sum_{i=1}^{i=N}\left[\log_{\left(\frac{n_{i+1}}{n_i}\right)}\left(\frac{t_i}{t_{i+1}}\right)\right]}{N} \tag{11}$$

where N is the experimental condition total number, which equals to 6 in this research. Based on eq.(11), the average value of concentration coefficient a is 1.249. And the mean deviation is 16.3%.

The correlation of accelerating factor can be obtained by substituted the value of concentration coefficient to eq.(10). And the correlation of accelerating factor is shown as eq.(12).

$$\alpha = \left(\frac{n_h}{n_l}\right)^{1.249} \tag{12}$$

5. CONCLUSIONS

- In the current study, an accelerating-particle-deposition method, which is capable of implementing the particle deposition process on the long-running heat exchangers in a short time, is proposed. The method can be used to calculate the dust concentration on the inlet, which decrease the influence of experimental results by dust concentration.
- An experimental apparatus for accelerating the particle deposition process and testing the pressure drop of fin-and-tube heat exchangers is designed.
- Different values of dust feed rate are considered in the experiment, and the results show that dust feed rate has little effect on the final deposition weight, but obvious effect on the settling time of deposition.

- The accelerating factor is fitted by the experimental data, and the mean deviation of the accelerating factor is 16.3%.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

a	concentration coefficient	(-)
A_n	section area	(m^2)
C	air flow volume coefficient	(-)
d	diameter	(m)
f	impact frequency	($kg \cdot number \cdot s^{-1} \cdot m^{-3}$)
K	volume of flow channel	(m^3)
m	deposition weight	(kg)
n	dust feed rate	($kg \cdot m^{-3}$)
N	experimental condition number	(-)
ΔP	pressure drop	(Pa)
r	rotation speed	(r/s)
RH	relative humidity	(-)
s	screw pitch	(m)
t	deposition time	(s)
T	temperature	(K)
v	air flow velocity	(m/s)
Z	contact frequency	(-)
Greek symbol		
α	accelerating factor	(-)
θ	filling coefficient	(-)
ρ	density	($kg \cdot m^{-3}$)

Subscript

h	high particle concentration
l	low particle concentration

REFERENCES

Abd-Elhady, M. S., Rindt, C. C. M. & Wijers, J. G. (2004). Minimum gas speed in heat exchangers to avoid particulate fouling. *International Journal of Heat and Mass Transfer*, *47*(17-18): 3943-3955.

Ahn, Y. C., Cho, J. M., Shin, H. S., Hwang, Y. J., Lee, C. G., Lee, J. K., Lee, H. U. & Kang, T. W. (2003). An experimental study of the air-side particulate fouling in fin-and-tube heat exchangers of air conditioners. *Korean Journal of Chemical Engineering*, *20*(5): 873–877.

Bell, I. H., Groll, E. A. & Konig, H. (2011). Experimental analysis of the effects of particulate fouling on heat exchanger heat transfer and air-Side pressure drop for a hybrid dry cooler. *Heat Transfer Engineering*, *32*(3-4): 264-271.

Bell, I. H. & Groll, E. A. (2011). Air-side particulate fouling of microchannel heat exchangers: Experimental comparison of air-side pressure drop and heat transfer with plate-fin heat exchanger. *Applied Thermal Engineering*, *31*(5): 742–749.

Bott, T. R. & Bemrose, C. R. (1983). Particulate fouling on the gas- side of finned tube heat exchangers. *Journal of Heat Transfer*, *105*: 178-183.

He, Y. L., Han, H., Tao, W. Q. & Zhang, Y. W. (2012). Numerical study of heat-transfer enhancement by punched winglet-type vortex generator arrays in fin-and-tube heat exchanger. *International Journal of Heat and Mass Transfer*, *55*(21): 5449–5458.

Kaiser, S., Antonijevic, D. & Tsotsas, E. (2002). Formation of fouling layers on a heat exchanger element exposed to warm, humid and solid loaded air streams. *Experimental Thermal & Fluid Science*, *26*(2): 291–297.

Liu, D., Zhao, F. Y., Wang, H. Q. & Rank, E. (2012). Turbulent transport of airborne pollutants in a residential room with a novel air conditioning unit. *International Journal of Refrigeration*, *35*(5): 1455–1472.

Ma, X. K., Ding, G. L., Zhang, Y. M. & Wang, K. J. (2009). Airside characteristics of heat, mass transfer and pressure drop for heat exchangers of tube-in hydrophilic coating wavy fin under dehumidifying conditions. *International Journal of Heat & Mass Transfer*, *52*(19): 4358–4370.
Moffat R. J. (1998). Describing the uncertainties in experimental results. *Experimental Thermal & Fluid Science*, *1*(1): 3-17.
Pak, B. C., Groll, E. A. & Braun, J. E. (2005) Impact of fouling and cleaning on plate fin and spine fin heat exchanger performance. *ASHRAE Transactions*, *111*: 496–504.
Wang, C. & Chang, Y. (1996). Sensible heat and friction characteristics of plate fin-and-tube heat exchangers having plane fins. *International Journal of Refrigeration*, *19*(4), 223–230.
Waring, M. S. & Siegel, J. A. (2008). Particle loading rates for HVAC filters, heat exchangers, and ducts. *Indoor Air*, *18*(3): 209–224.
Wu, F., Jacobs, D. & Mitchell, C. (2007). Improving indoor environmental quality for public health: impediments and policy recommendations. *Environmental Health Perspectives*, *115*(6):953–7.
Wu, X. M., Ma, Q. & Chu, F. Q. (2017). Numerical simulation of frosting on fin-and-tube heat exchanger surfaces. *Journal of Thermal Science and Engineering Applications*, *9*(3): 031007.
Zhan, F. L., Tang, J. J., Ding, G. L. & Zhuang, D. W. (2016). Experimental investigation on particle deposition characteristics of wavy fin-and-tube heat exchangers. *Applied Thermal Engineering*, *99*: 1039–1047.
Zhan, F. L., Zhuang, D. W., Ding, G. L. & Tang, J. J. (2016). Numerical model of particle deposition on fin surface of heat exchanger. *International Journal of Refrigeration*, *72*: 27-40.
Zhu, Y., Wu, X. M. & Wei, Z. F. (2015). Heat transfer characteristics and correlation for CO2/propane mixtures flow evaporation in a smooth mini tube. *Applied Thermal Engineering*, *81*, 253-261.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the supports from the National Nature Science Foundation of China (Grant No. 51606119), the Foundation for Innovative Research Groups of the National Natural Science Foundation of China (Grant No. 51521004), the Program of Shanghai Academic Research Leader (Grant No. 16XD1401500).