Contribution of air velocity to the particle deposition characteristics on the air side of air cooler exposed to warm, humid, and solid loaded air streams under deep coal mine

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Abstract: Refrigeration systems have been used for providing a reasonably comfortable environment, increase productivity, and maintain safety in mining sites. An air cooler, as the terminal device of refrigeration systems, was exposed to warm, humid, and solid loaded air streams, which lead to serious fouling on the air-side tubes. However, the particle deposition characteristics on the tubes in the hot, humid, and solid loaded environment were unclarified. Therefore, in this study, experimental and theoretical analyses were performed to clarify the results. The indicated the following. (1) Fouling mass and area increased when air velocity gradually increased, and the particles were observed to be easily accumulated on the first and fifth columns of tubes, whereas they were equally accumulated on the rows. (2) Particles larger than 100 μm in size tended to accumulate on the first column of the tubes when the air velocity was greater than 1.5 m/s. (3) The deposition of particles on the pipe surface in a hot and humid environment benefited from the air velocity, mass transfer, physical property of particles, and the structure parameters of the air cooler. These results would be beneficial to the optimization of cooling under deep coal mines.

Keywords: air cooler; air-side fouling distribution; condensation; coal mine; warm, humid, and solid loaded environment

1 Introduction
Coal is a major energy source in China. Owing to a decrease in the shallow resources and social demand for minerals, the depths of coal mines have increased. One consequence is an increase in the associated heat hazard. An increasing number of coal mines in China are suffering from high temperatures and moisture [Qiaoyun et al., 2019; Guo et al., 2017]. The safety of mine workers is threatened by their exposure to heat and humidity conditions as well as poor working conditions [Donoghue, 2004; Pule, 2011; Qiaoyun et al., 2019]. Thus, refrigeration systems are installed in deep underground mines to provide a reasonably comfortable ambient environment to increase productivity and maintain safety as a priority [Xiaojie et al., 2011; Sasmito et al., 2015; Guo et al., 2017]. As the terminal device of a cooling system [Xiaojie et al., 2011] and with its usage to improve air conditions, an air cooler is exposed to warm, humid, and solid loaded air streams at the mining working face. Consequently, people have been troubled by the air-side particle fouling, which increases air-side thermal resistance and causes a pressure drop as well as decreases the heat transfer rate [Bell et al., 2011; Ahn et al., 2003; Lankinen et al., 2003; Pak et al., 2003].

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Sufficient knowledge of fouling mechanisms in the warm, humid and solid loaded conditions of the air side of an air cooler is necessary to attain the optimal design and efficient operation of a cooling system in a deep coal mine. The fouling process on the air side of an air cooler is essentially the process in which particles in the air penetrating the air cooler are deposited on the tube wall; so, the air velocity is a crucial parameter that affects the fouling. Abd-Elhady et al. (2004) investigated the effect of flow velocity on the growth of a dirt layer on a heat exchanger. The experimental results showed that the surface area and thickness of the scale layer decreased as the flow velocity increased, and the average flow velocities through the heat exchanger in the experiment were 2.7, 3.8, and 5 m/s. Zhan et al. (2016) investigated the particle deposition characteristics of wavy fin-and-tube heat exchangers in air velocity in the range of 1–3 m/s. The observation results showed that the particles were mostly deposited on the leading edge of fins and the front part of tubes. Air velocity has a complicated effect on particle deposition: the maximum particle deposition weight per unit area increases by 6.8% and then decreases by 10.9% as air velocity increases. Fu et al. (2017) adopted a numerical model to predict the collision, adhesion, and rebound of fly ash particles on the surface of a flue gas heat exchanger. They determined that when the velocity range was 5–10 m/s, an increase in velocity could decrease the ash fouling, and the total deposition rate of larger particles (5 and 10 μm) decreased faster than that of small particles (1 μm). Pérez et al. (2017) simulated ash deposition trends and stated that faster flow inlet velocity resulted in higher values for both the deposition and arrival trends. Wang et al. (2018) discovered that the deposition number and mass of low-temperature bonding ash and loose ash decreased by 61% and 80%, respectively, when the velocity of flue gas increased from 5 to 10 m/s; the mass of the loose ash decreased much faster than the low-temperature bonding ash. Antonyuk et al. (2009) investigated the energy absorption of a liquid layer during the impact of particles. The results showed that the higher the viscosity and thickness of the liquid layer are, the greater the energy of the particles consumed during impact, and the smaller the critical thickness required for particle adhesion. Fu et al. (2004) investigated the impact deformation and rebound of wet particles and concluded that, at a relatively small impact velocity, approximately 97% of the impact kinetic energy of the particles dissipated. Subbarao et al. (2013) conducted impaction experiments in which particles hit a surface coated with a liquid film and dry surface to evaluate the limit parameters of particles that stuck to a surface without rebounding. They assumed that a particle would stick to a surface if the Stokes number was less than 5 and considered that the presence of the liquid layer enhanced the deposition process. In addition, Yun et al. (2009) discovered that the existence of condensate film on a surface would change the airflow conditions on the surface. Korte et al. (1997) examined the amount of condensate retention in finned tube heat exchangers and discovered that the airflow force did not significantly affect the retention of condensate when the fin spacing or wind speed was large for heat exchangers with hydrophilic coatings. Kaiser et al. (2002) stated that air humidity is a crucial factor influencing the growth of dirt layers on the surface of a heat exchange element under wet conditions. Zhan et al. (2018) investigated the influence of deposited wet particles on the air-side heat transfer and pressure drop of heat exchangers. Their experimental conditions covered the inlet air relative humidity (RH) of 50%–90%, inlet air velocity of 1.0–3.0 m/s, and particle concentration of 2.1–10.8 g/m³. Their results showed that the particle deposition weight increased with the inlet air RH. Nuntaphan et al. (2007) investigated the effect of fly ash deposit on the thermal performance of a cross-flow heat exchanger.
and determined that the fly ash deposit was proportional to the amount of condensate on the heat exchange surface. Li et al. (2012) presented a novel algorithm for predicting indoor suspension particle dispersion based on a $v^2-f$ model.

The air-side surface of an air cooler exposed in warm, humid, and solid loaded air streams during deep mining would be partially or fully wet since the fin temperature is commonly lower than the dew point temperature; then, the condensate water would form on the fins, which might cause more deposition. However, the fouling mechanisms of an air cooler in deep mines have not been clarified. Thus, in this study, experimental and theoretical analyses were performed to investigate the air-side fouling distribution of air coolers in warm, humid, and solid loaded environments.

2 Experimental system and scheme

2.1 Experimental system

A schematic of the experimental system, which employed a tunnel locating HEMS-II (air cooler) [Qiaoyun et al., 2019] of the Zhangshuanglou Coal Mine in China as the prototype (with a height of 2 m and width of 3 m, Figure 3), is shown in Figure 1. The system comprised three sections: (1) wind tunnel, (2) tested air cooler, and (3) data acquisition system. (1) The wind tunnel was used to simulate the warm, humid, and solid loaded mine environment. The height and width of the tunnel cross-section model are 390 and 560 mm, respectively. Heat and humidity were emitted from an inner wall surface of hollow interlayers (with a thickness of 40 mm and used to simulate the warm and humid walls of the tunnel [Qiaoyun et al., 2019]) on three sides of the roadway. Heating cables and temperature sensors were arranged in the interlayers (Figure 2). Air velocity was controlled using a centrifugal fan, whose maximum wind volume would reach 2,300 m$^3$/h. The dust generator comprised a German AG420 aerosol generator and an air compressor. The air compressor was connected to the aerosol generator to provide a conveying force [Wang et al., 2019], and the particles were sprayed from a nozzle. (2) The air cooler was located in a special tunnel of the Zhangshuanglou Coal Mine [Qiaoyun et al., 2019]. Hot air was guided into the tunnel to be cooled, and pure cool air was passed into the mining area [Qiaoyun et al., 2019]. The air cooler in the Zhangshuanglou Coal Mine is shown in Figure 3. The modeled air cooler (Figure 2 or 7) in this experiment and the onsite air cooler had the same parameters. The horizontal row spacing and column spacing of the air were 50 mm. The model had 30 red copper tubes with a 16-mm external diameter and a 0.8-mm wall thickness. The air cooler comprised 30 (6 rows × 5 columns) copper tubes. Chilled water that flowed in the air cooler was provided by a refrigeration device (see Figure 1). (3) The surface temperatures of the walls of the tunnel and roofs were measured using a wall temperature self-recording meter [Figure 4(a)], which could automatically collect the surface temperature. The temperature and RH of the air in the tunnel were measured using temperature and RH self-recording meters [Figure 4(b)] [Xing et al., 2019]. An air velocity self-recording meter was employed to measure the wet air velocity [Figure 4(c)]. All fouling morphologies on the air side of the air cooler were recorded using a Canon EOS 700D camera. The fouling on the tubes was collected and weighed by the AR224CN balance [Figure 4(d)], and the particle size was analyzed using an LS13320.
laser diffraction particle size analyzer [Figure 4(e)] produced by the American Beckman Coulter Company. The accuracy, measurement range, and sampling interval of these instruments are listed in Table 1.

![Figure 1 Schematic of the experimental system](image1)

![Figure 2 Interlayer used to simulate the warm and humid tunnel wall](image2)
Figure 3 Air cooler in the Zhangshuanglou Coal Mine

Table 1 Data monitoring and instrumentation

| Measuring device                  | Sampling interval | Measuring range      | Accuracy  |
|-----------------------------------|-------------------|----------------------|-----------|
| Wall temperature self-recording meter | 2 min             | −20°C to 80°C        | ±0.1°C    |
| Air temperature self-recording meter | 2 min             | −40°C to 100°C       | ±0.2°C    |
| RH self-recording meter           | 2 min             | 0%–100%              | ±0.1%     |
| Air velocity self-recording meter | 2 min             | 0.05–30 m/s          | 0.01 m/s  |
| Electronic balance                | –                 | 0–220 g              | 0.0001 g  |

Figure 4 Instrument and equipment for data acquisition: (a) wall temperature self-recording meter, (b) air temperature and RH self-recording meters, (c) air velocity self-recording meter (d) AR224CN electronic balance, and (e) LS 13320 laser diffraction particle size analyzer [Wang et al., 2019].

2.2 Experimental scheme

The air-side fouling distribution of the air cooler is related to the moisture content $d$, air temperature $T$, air velocity $v$, dust loading $q$, dust particle size $D$, and air cooler inlet water temperature $T_{in}$. In deep mines with warm, humid, and solid loaded environments, the condensate generated at the air-side tubes is critical to the air-side fouling. The condensation may be affected by the $T$, $d$, $v$, and $T_{in}$. During the experiment, $T$ with a value range of more than 30°C was applied to create a warm environment controlled by the inlet ambient air temperature, wall temperature, and amount of water mist provided by the humidifier. Table 2 shows the values of experimental parameters. The RH ranges from 95.2% to 96.7% throughout the experiment (series A), and experiments with the RH of 56.4%–57.8% were conducted as contrast experiments (series B). The particles in the experiments comprised pulverized coal separated from a 250 standard industrial sieve. The initial particle size composition is shown in Figure 11. According to the studies of Qin et al. (2011), Kong et al. (2008), Wang et al. (2019), the dust concentration in the tunnel would reach 300–400 mg/m$^3$, even in a dust-proof measured working environment. The dust concentration would be in this range when the dust loading $q$ in the experiment was set to 40 g/min. Our experiments comprised two stages (Figure 5). The first was the parameter stabilization stage, with a duration of at least 23 min. During this stage, a centrifugal fan, humidifier, and heater were turned on at the beginning of experiments and kept running throughout the
experiments. When the change rate of air temperature, air velocity, or RH was lower than 5%, the fluid flow would be considered stable (Figure 6). Then, the second stage (dust generation stage) began, and dust was loaded. In our experiments, the second stage began 30 min after experiment initialization.

![Figure 5 Air temperature and RH variations over time](image)

**Figure 5** Air temperature and RH variations over time

Experimental results were analyzed from three aspects: fouling morphology, distribution of mass, and particle size composition. Fouling morphology was presented through pictures captured by a camera. Mass of fouling on each tube was obtained via gauze and balance. A particle size analyzer was employed to measure the particle size composition of the dirt.

| Parameter    | A                  | B (Contrast experiment)       |
|--------------|--------------------|------------------------------|
| v (m/s)      | 0.5, 1, 1.5, 2     | 30.5–35.4                    |
| T (℃)        |                    | 32 ± 1                       |
| T_w (℃)      |                    | 10 ± 1                       |
| T_in (℃)     |                    | 40                            |
| q (g/min)    |                    | 95.2%–96.7%                  |
| Coal particles | IPC-2 (average size = 28.31 μm) | 56.4%–57.8%                  |
| RH           | 95.2%–96.7%        | 56.4%–57.8%                  |

### 3 Experimental results and discussion

#### 3.1 Dynamic particle depositional behavior on the air side of air cooler

Dynamic variation of particle depositional behavior was analyzed based on five experiments, with the experimental time of 40 min (30 and 10 min for the first and second stages, respectively), 50 min (30 and 20 min for the first and second stages, respectively), 60 min (30 min for each stage), 70 min (30 and 40 min for the first and second stages, respectively), and 80 min (30 and 50 min for the first and second stages, respectively). Air velocity during the experiments was 2 m/s. IPC-2 coal particles with an average size of 28.31 μm were used in the experiments.

The particles distributed at the surface of the tubes are recorded in Figure 6. All photos depict the
tubes in the same position. The dirt layers thickened with time. As shown in Figure 6, the fouling mass increased during the first 10 min of loading particles and then decreased until t = 50 min, when the mass reached a minimum. Deposition increased again with the deposition rate maintained at a constant level; thus, the experimental time of series A and B, which were used to investigate air velocity contribution to the particle deposition characteristics on the air side of the air cooler, was set to 60 min.

3.2 Contribution of air velocity to the particle deposition characteristics on the air side of air cooler

Experiments of series A were employed to investigate air velocity contribution to the particle deposition characteristics on the air side of the air cooler in a high humidity environment. As shown in Figure 7, when the air velocity was lower than 1.5 m/s, the surface of the tubes was not completely covered with fouling, and the fouling area increased when the air velocity gradually increased. The no dust areas were mainly distributed in the windward and upper parts of the tubes. Meanwhile, water drops mixed with particles appeared in the photos of v = 1 and 1.5 m/s. Condensation occurred when moist air passed over the cold tube surface. On the one hand, the airflow promoted condensation, and the particles were much easier to be caught by the surface, on the other hand, increasing air velocity blew off the deposit from the surface. Hence, the fouling mass on the air side of copper pipes with variation in air velocity was necessary to be recorded; the results are shown in Figure 8. Fouling mass accumulated with the increase in air velocity. The mass percentages on the rows and columns (Figures 9) of the air cooler were investigated to obtain the mass distribution of air-side fouling. When the air velocity was less than 1 m/s, the fouling mass distribution on each column of the tubes was almost the same, whereas the particles were inclined to be deposited in the fourth row of tubes. When the air velocity increased, the particles easily accumulated on the first and fifth columns of the tubes, and equally accumulated on each row.

The particle size distribution of the initial coal dust is shown in Figure 10. The size of most particles in the initial coal dust was less than 80 μm. Dust particles smaller than 10 μm accounted for the largest proportion of the total sample—approximately 35%. Moreover, few dust particles were greater than 200 μm. When the air cooler was subjected to a humid environment, compared with the initial particle size distribution, the proportion of particles with the size range 20–40 μm increased. The particles with sizes larger than 100 μm increased, particularly for particles with sizes larger than 200 μm. When the air velocity was greater than 1.5 m/s, large particles (larger than 100 μm) tended to accumulate on the first column of the tubes. In addition, the proportion of particles with a particle size less than 10 μm was much smaller than the initial coal dust on each column of tubes when the air velocity was greater than 0.5 m/s, which might be because dust with small-sized particles easily coagulated and caused a reduction in proportion. The particle size distribution indicated that the coalescence of particles had occurred on the tube surfaces, and the air velocity promoted the coalescence of particles.
Figure 6 Fouling morphology and mass on the tubes under different experiment time
Figure 7 Fouling morphology on the tubes when \( v = 0.5 \text{–} 2 \) m/s under experiments of series A

Figure 8 Fouling mass when \( v = 0.5 \text{–} 2 \) m/s under experiments of series A and B

\( v = 0.5 \text{ m/s} \)

\( v = 1 \text{ m/s} \)

\( v = 1.5 \text{ m/s} \)

\( v = 2 \text{ m/s} \)

\( v = 0.5 \text{ m/s} \)

\( v = 1 \text{ m/s} \)

\( v = 1.5 \text{ m/s} \)

\( v = 2 \text{ m/s} \)
Figure 9 Mass percentage of fouling in each column and row of tubes when \( v = 0.5–2 \text{ m/s} \) under experiments of series A

Figure 10 Particle size distribution of fouling under experiments of series A

The contrast experiments were performed to better reveal the influence of air velocity on the particle deposition characteristics. Unlike the results of series A, the dirt on the tubes was much more unconsolidated. With an increase in airspeed, unconsolidated dirt decreased and the fouling on the tubes became substantially clingier. As shown in Figure 11, almost all tubes were covered with fouling. The dripping of the condensed water from the upper columns of the tubes was less obvious. During experiments of series B, from 0.5 to 2.0 m/s, \( M \) increased by approximately 103%, compared with the 62% of \( \Delta M \) during experiments of series A. When the air velocity was 0.5 m/s, most foulants were distributed on the latter 4 columns [Figure 12(a)]. As air velocity increased, especially when the air velocity was greater than 1.5 m/s, the mass of foulant was more evenly distributed on each row and column (Figure 12). Compared with the initial size distribution, the proportion of particles in the size range of 20–40 \( \mu \text{m} \) increased. When the air velocity was below 1 m/s, particles larger than 100 \( \mu \text{m} \) significantly increased, especially particles larger than 200 \( \mu \text{m} \), which might be because large particles at low velocities were more likely to break away from the airflow, thus collided with the duct and were captured by the tube surface. Smaller particles (less than 60 \( \mu \text{m} \)) tended to accumulate in the third, fourth, and fifth columns, which might be because smaller particles would easily reach the back column ducts at lower velocities, resulting in a higher probability of particle deposition in the back column ducts. As the air velocity increased, small particles were easily retained in the tubes. At an air velocity of 0.5 m/s, particles larger than 60 \( \mu \text{m} \) tended to accumulate more in the first column. The results indicated that large particles were more likely to break away from the air at low velocities. A comparison of the particle size distribution at 1.5- and 2-m/s air velocity showed that the distributions were very similar at both velocities, and the results suggested that velocities above a certain value
insignificantly affected the particle size composition, which seemed to reflect the increased influence of the particles by the flow field.

![Images of tubes with fouling at different flow velocities](image1.png)

$v = 0.5 \text{ m/s}$  
$v = 1.0 \text{ m/s}$  
$v = 1.5 \text{ m/s}$  
$v = 2.0 \text{ m/s}$

**Figure 11** Fouling morphology on the tubes when $v$ ranges from 0.5 to 2 m/s of experiments of series B

![Graphs showing mass percentage of fouling](image2.png)

(a)  
(b)

**Figure 12** Mass percentage of fouling in each column and row of tubes when $v = 0.5$–2 m/s under experiments of series B
In all results shown in experiments of series A and B, the condensed water played a paramount role in the growth and removal of dirt on the air side of the air cooler. During the dirt formation, the growth and removal of dirt occurred simultaneously. Particles from the humid air first reached the pipe’s surface, where condensed water was present, and were captured by the condensed water, forming a layer of wet particles. However, too much condensed water on the pipeline would cause some of the previous dirt on the pipeline to be washed away, resulting in the removal of dirt. In addition, the dripping or splashing of condensate water from the upper pipe directly above would cause the dirt on the lower pipe to fall off, thereby enhancing the removal of dirt. Obviously, for the tube bundle heat exchanger used in this experiment, the dripping of condensed water from the upper pipe would be seen in Figure 7. Thus, the particle deposition on the wet wall surfaces and removal by condensate droplets were studied in this article.

3.3 Theoretical analysis of the particle deposition and removal on wet wall surfaces
3.3.1 Particle deposition on wet wall surfaces

Antonyuk et al. (2009) proposed the interaction between the particles and wall surfaces with a liquid film layer is divided into four stages. The first stage represents the process of particle penetration through the liquid layer and then contact with the solid surface, the second stage represents the process of elasto-plastic deformation of the particle and the wall, the third stage represents the process of the particle starting to bounce back to the upper surface of the liquid layer, and the fourth stage represents the process of formation and breakage of the liquid bridge. The particles are subjected to gravity, surface tension, buoyancy, traction, liquid bridge force, and particle-wall contact force in the above process.

When a particle flows vertically onto a surface with a liquid film, neglecting gravity, buoyancy, and surface forces, the energy equation could be expressed as follows:

\[ Q_k + Q_{A,a} = Q_{D,k} + Q_{vis} + Q_{cap} + Q_p + Q_{r,k} \]  

(1)

Where, where \( Q_k \) is the kinetic energy of the incident particle, \( Q_{A,a} \) is the surface adhesion energy due
to the attraction between the incident particles and wall surfaces, $Q_{D,l}$ is the energy expended by the particle to overcome the drag force during the movement of particles in the second and third stages, $Q_{vis}$ is the energy expended by the particle to overcome the liquid viscous force in the second and third stages, $Q_{cap}$ is the energy expended by the particle to overcome the liquid bridge force in the fourth stage, and $Q_{r,k}$ is the rebound kinetic energy of the particle to finally break away from the liquid film surface.

$F_{D,l}$, $F_{vis}$, and $F_{cap}$, the drag force, viscosity force, and dynamic liquid bridge force of water [Antonyuk et al., 2009; Lian et al., 2001; Lee et al., 2002] on the air side of tubes are, respectively, expressed as follows:

\[
F_{D,l} = \frac{1}{2} \rho_l C_{D,l} A_D v(t)^2 \tag{2}
\]

\[
F_{vis} = \frac{1.5 \pi \mu^2}{\delta - x} v(t) \tag{3}
\]

\[
F_{cap} = 6 \pi \eta a^2 \left(1 - \frac{H_2}{H_1}\right)^2 \frac{1}{H_2} v(t) \tag{4}
\]

where $\rho_l$ is the density of the liquid, $C_{D,l}$ is the drag coefficient, $A_D$ is the vertical projected area of the part of the particle immersed in the liquid film, $v(t)$ is the velocity of the particle with time, $\eta$ is the dynamic viscosity of the liquid, $a$ is the radius of the particle, $\delta$ is the thickness of the liquid film, $x$ denotes the size of the particle immersed in the liquid film, $H_1$ is the distance of the wetted part of the particle from the wall, and $H_2$ denotes the distance of the bottom of the particle from the wall.

When the particles were deposited on the surface of tubes, $Q_{r,k}$ would be 0. Therefore, the critical value of velocity would be expressed as Equation (5), and the deposition mass of particles $M_{p,d}$ per unit tube length on the gas side of the air cooler can be expressed as Equation (6).

\[
v_{w,c} = \sqrt{\frac{2(Q_{D,l}(F_{D,l}) + Q_{vis}(F_{vis}) + Q_k(F_{cap}) + Q_p - Q_{D,l})}{m_p}} \tag{5}
\]

\[
M_{p,d} = \sum_{i=1}^{N_i} m_{pi} = f(\delta, \eta, v_i, y) \tag{6}
\]

where $m_{pi}$ denotes the mass of the deposited particles, $N_i$ denotes the number of deposited particles, velocity of the particles satisfies $v_i \leq v_{w,c}$, and $y$ denotes other parameters that affect particle deposition, such as the physical parameters of the particles, and air velocity.

### 3.3.2 Analysis of particle sediment removal by condensate droplets

Water vapor in the hot and humid air condenses in large quantities on the cold wall surface of the pipeline. Condensate would be gathered at the bottom of the tubes under the action of gravity (Figure 8) and drop to the lower tubes when growing up to a certain extent. When droplets arrived at the lower tubes, one part would spread out on the tubes to form liquid film, and the other part would leave the tube surface due to splashing. In addition, particles on the tube surfaces would be washed away by the condensate. To obtain the particles that washed away by the condensate, some assumptions were made...
as follows.
(1) Subjection to the conservation of mass during the spreading of liquid film on the tube surface, i.e., no water separated from the wall and no new liquid joined in.
(2) The velocity of the liquid film at the bottom of the pipe was 0.
(3) During spreading, the movement of the liquid film was affected by gravity, the viscous shear of the fouling layer, and the resistance of the moved particles, ignoring the viscous force of the airflow on the liquid film.
(4) The splashed droplets would not carry particles out.
(5) Particles were removed only by condensate droplets.

The gravitational potential energy of condensate droplets from an upper pipe to a lower one would be converted partly into the kinetic energy $Q_{k1}$ for the liquid film moving (spreading) around the pipe and partly into the kinetic energy $Q_{k2}$ of the splashing condensate.

\[ Q_m = Q_{k1} + Q_{k2} + Q_{r1} \]  
\[ Q_{k1} + Q_{md} = Q_p + Q_v + Q_{r2} \]

where $Q_m$ is the gravitational potential energy when the droplet falls from the upper tubes to the lower, $Q_{md}$ is the gravitational potential energy of water decreasing from the top to the bottom of the pipe, $Q_{r2}$ is the energy lost before the droplet falls and spreads, $Q_p$ is the energy consumed by the movement of the particles within the area of action of the droplet, $Q_v$ is the energy consumed to overcome the viscous resistance during the spreading of the liquid film, and $Q_{r2}$ is the energy lost due to other factors during the spreading of the liquid film, such as the resistance of the airflow to the liquid film.

According to the mass transfer theory, the amount of condensed water $m_w$ per unit area of the pipe surface is expressed as follows:

\[ m_w = h_m (\rho_s - \rho_\infty) \]  

where $h_m$ is the average convective mass transfer coefficient, $\rho_s$ is the vapor concentration near the wall, kg/m$^3$, and $\rho_\infty$ is the vapor concentration of wet air, kg/m$^3$.

The distribution density $n$ of condensate droplets per unit tube length and the drop frequency $f$ were introduced. Assuming the amount of produced condensate was equal to the amount of condensate droplets, then the mass of condensation droplets ($m_d$) and $m_w$ are related as follows:

\[ \pi D m_w = nf m_d \]

Therefore,

\[ m_d = \frac{\pi D m_w}{nf} = \frac{\pi D h_m (\rho_s - \rho_\infty)}{nf} \]

Thus, the movement of particles on the tube surface was mainly affected by drag force $F_{Dp}$, gravity $F_g$, surface force $F_t$, buoyancy force $F_b$, viscous force $F_{vis}$, and the liquid bridge force $F_{cav}$. The motion of individual particles would be described as follows:
Assuming that the total number of particles affected by a single water drop was \( N \), and all moving particles will be separated from the wall, the energy \( Q_p \) consumed by a single water drop to remove the particles is given by

\[
m_p \frac{d^2 \vec{a}}{dt^2} = \vec{F}_g + \vec{F}_e + \vec{F}_b + \vec{F}_{pt} + \vec{F}_{vis} + \vec{F}_{cap} = \vec{F}
\]  

(12)

Moreover, the mass of particulate sediment \( M_{p,r} \) that just considers the influence of condensate droplets would be expressed as follows:

\[
M_{p,r} = \sum_{j=1}^{N_f} m_{p,j} = f(m_d, n, f, l, D, A, z)
\]  

(14)

where \( z \) indicates other parameters that affect particle removal.

Finally, the total mass of particles deposited on the pipe would be expressed as Equation (15). The deposition of particles on the pipe surface in a hot and humid environment benefited from the air velocity, mass transfer, physical property of particles, and the structure parameters of the air cooler.

\[
M_p = M_{p,d} - M_{p,r}
\]  

(15)

4 Conclusions

Experimental and theoretical analyses were performed to investigate the air-side fouling morphology, distribution of mass, and particle size of an air cooler in warm, humid, and solid loaded environments. The results of the analyses are summarized as follows.

1. Clingy dirt was visible on the surface of the air cooler, and the fouling area increased with an increase in air velocity.

2. With an increase in the air velocity, the total mass increased. In addition, when the air velocity was less than 1 m/s, the fouling mass distribution on each column of the tubes was almost the same, whereas the particles were inclined to be deposited in the fourth row of tubes. When the speed increased, the particles easily accumulated on the first and fifth columns of the tubes, whereas they were equally accumulated on the rows.

3. When the air velocity was greater than 1.5 m/s, particles larger than 100 μm in size tended to accumulate on the first column of the tubes. Moreover, the proportion of particles with a particle size less than 10 μm was much smaller than the initial coal dust on each column of tubes when the air velocity was greater than 0.5 m/s. The particles size distribution indicated that the coalescence of particles occurred on the tube surfaces, and the air velocity promoted the coalescence of particles.

4. The deposition of particles on the pipe surface in a hot and humid environment benefited from the air velocity, mass transfer, physical property of particles, and the structure parameters of the air cooler.

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