Theoretical and experimental study on the effective area of water film and dust removal efficiency

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Abstract

Breaking through the bottleneck of low resistance and high efficiency in mine exhaust dust control has been a hot issue in the industry. Aiming at the key problems of wet vibrating string grille dust removal, based on the multiphase flow theory and capillary mechanics, the dimensionless bond number expression of the influence of vibrating wire spacing on droplet spreading is derived. Furthermore, a liquid film formed by spreading droplets based on Kelvin correlation, young Laplace formula and Hagen Poiseuille theory, a formula for calculating the thickness and height of liquid film is established with temperature, relative humidity and molar volume of liquid phase as independent variables. Then, the dust removal efficiency calculation model of vibrating wire group is established between the liquid film thickness, height, wire diameter, effective water film area and vortex shedding frequency. Finally, on the experimental platform, the influence of the effective area of water film on the dust removal efficiency of wet vibrating wire grille plate is measured, and the above calculation model is verified. Moreover, the optimized combination of wet vibrating string spacing ratio 1.14, wind speed 3m/s and spray pressure 0.7 MPa is found, which provides important reference for engineering application.

Keywords: vibrating string grille; wetting mechanism; capillary action; effective water film area; dust removal efficiency
Introduction

In the process of mining, a large amount of dust is produced, which comes to the airshaft with the underground air flow and then discharged, which pollutes the atmospheric environment. With the country paying more and more attention to environmental protection, the dust emission standard of exhaust airshaft is improved. In order to meet the emission requirements and not affect the normal production of the mine, the dust removal technology with high efficiency and low resistance is the first choice. In the current high efficiency and low resistance dust removal technology, it is suitable for the exhaust airshaft, which is a limited space with large air volume and high pollution. The wet vibrating string grille dust removal technology is a kind of filtering dust removal technology. The droplet group ejected from the nozzle collides with the surface of the string grille, and the droplets are capillary wetted on the surface of the string grille due to the capillary effect. Under the pneumatic disturbance of the dust laden air flow, a downward flowing water film is formed in the longitudinal fine string grille gap. When the dust laden air passes through the water film, it is captured by the water film and flows downward with the water flow under the action of the flow, the fracture is generated and new water film is generated continuously under the action of continuous spray droplet group. During this process, the wet string grille dynamic water film dust removal mainly depends on the effective water film area, which directly affects the dedusting efficiency of vibrating wire grille plates.

In terms of wet dust removal, Zhou [1,2] and Zhou [3] were studied on the basis of spray pressure. The spray dedusting technology was optimized, not only the engineering application was carried out, but the dust removal efficiency was high. Further, Wang [4,5] analyzed the relationship between the atomization characteristics of the atomizing nozzle and the dust removal efficiency. However, in the aspect of theory and experiment, having research of string grille dust removal, for example, Fairs [6] discovered the existence of a liquid film by studying the formation of a sulfuric acid vinegar fog on four kinds of fibers with different properties. Using a continuous spray of water mist on the fiber, Agranovski [7] designed a method to form a water film after a few minutes. Theoretical and experimental studies show that the water film thickness increases with fiber equivalent diameter and differs along different heights of the fiber grille. In the case of equilibrium saturation, Jakub [8,9] and Ryan [10] observed uneven liquid coverage on the fiber and studied the efficiency of filter-trapping aerosol. Gong [11] studied the dominant mechanism of water film formation on the fiber grille and pointed out the capillary effect of the fiber spacing. Jiang [12] and Jin [13] theoretically analyzed the dedusting mechanism of water films and assumed that dust particles that are difficult to moisten tend to penetrate into the water film. Li [14] and Wu [15] indirectly explained dust removal efficiency from the aspect of fiber grille gap, material, and grille, as well as nozzle spacing according to water films observed in experiments. However, most of these studies analyzed the existence of water films from a macro and indirect perspective and there remains a lack of systematic analysis of the physical mechanism in water film formation and fragmentation processes, which makes the relationship between water film state and dust removal efficiency poorly understood.

During wet vibrating string grille dust removal, the water film between the vibrating wire directly affects dedusting efficiency and resistance. Quantification of how the water film affects dust removal efficiency requires information regarding the interaction between the vibrating wire structure and fog droplets. In this study, we perform experiments and theoretical analyses of the dynamic water film dedusting process using a vibrating wire grille plate. The state of the water film on the vibrating wire grille plate is monitored during the experiments using a high-speed camera, and the influence of spray pressure, wind speed, and vibrating wire grille
structure on the effective area of the water film is analyzed. A mathematical expression of
effective water film area and dedusting efficiency is established according to the experimental
results, which provides a reference for theoretical and engineering applications of string grille
dust removal.

**Materials and Methods**

**Water film formation mechanism**

The water mist contacts the two adjacent wires and forms a water film owing to surface
adhesion forces and capillary action. The Bond number is used to describe the capillary
phenomenon in surface mechanics [16] and is the relative magnitude of static water mist
gravity and surface tension:

\[
Bo = \frac{\rho g \lambda_c^2}{\delta_{lv}}
\]  

(1)

where \( \lambda_c \) is capillary length, which is considered here to be half of the vibrating wire spacing
\( d_0 \) (mm), \( \rho \) is the water mist density (kg/m\(^3\)), \( g \) is gravitational acceleration (N/kg), and \( \delta_{lv} \)
is the liquid gas surface tension (N/m). When the Bond number is large, surface tension
produced by static water mist under capillary pressure can be ignored. A small Bond number
(<0.1) shows that the surface tension strongly affects the hydrostatic gravity.

In the film formation test, the water is 20 °C, \( \delta_{lv} = 7.3 \times 10^{-3} \text{N/m} \), \( g = 9.8 \text{N/kg} \), \( \rho = 994 \text{g/m}^3 \),
combined with reasonable reference values [17] and \( Bo = 0.0036 \). From Eq. (1), it can be
calculated that: the distance between the vibrating wires is calculated from the equations above
to be less than 0.34 mm. The water mist generates a capillary phenomenon between the
vibrating wires.

**Basic physical parameters of the chord gate**

The diameter of the vibrating wire is a particularly important physical parameter. The vibrating
wire is cylindrical in shape and uniformly distributed in the wire grille with equal spacing. In
order to facilitate the formation of capillary water film on the gate and improve the dust removal
efficiency of the vibrating chord gate, the diameter of resonating string grille is 0.23 mm, the
spacing is 0.26 mm, and the distance diameter ratio is 1.14. According to analysis of the
filtering mechanism of the vibrating string grille, the vibrating wire is uniformly distributed on
the rectangular string grille and parallel to the airflow direction. The percentage of the steel
wire area to the whole vibrating wire grille area prior to wetting is expressed by \( \beta_s \). The wire-
filling rate is determined during production and can be calculated according to Eq. (2). Voidage
\( \varepsilon_s \) is obtained according to Eq. (3).

\[
\beta_s = \frac{\text{Area of vibrating wire}}{\text{Total area of grid plate}} \times 100\%
\]  

(2)

\[
\varepsilon_s = 1 - \beta_s
\]  

(3)

When the airflow carries water mist through the vibrating string grille, the filling rate of the
wet vibrating wire includes the water mist attached to the vibrating wire and the residual water
film after the film ruptures. The filling rate of the string grille is therefore composed of the
filling rates of the unwetted wire and water:
where $\beta_{ws}$ and $\beta_w$ are the filling rates of the wet wire and water, respectively (dimensionless). The liquid holding capacity of the steel wire is measured and calculated experimentally and $\varepsilon$ represents the gate voidage (dimensionless).

### Calculation of water film thickness and height on a vibrating wire grille plate

When the water mist and vibrating wire meet conditions of film formation, a liquid film force is produced, also known as a liquid bridge force [18,19]. Capillary action theory can be used to analyze the liquid film force. The left and right sides of the water film between the vibrating string steel wires are connected owing to adhesion. On the other hand, there is surface tension on the upper and lower film surfaces, which forms a concave water film surface in the arc (Fig. 1) and leads to a pressure difference between the gas and body side of the water film (i.e. pressure outside the water film is greater than that inside). This negative pressure on the film itself has a pulling effect, which is essentially the liquid film force.

![Fig. 1 Concave water film surface](image1)

![Fig. 2 Radius of the concave liquid surface](image2)

(1) Derivation and calculation of water film thickness

During the tests, water mist is sprayed continuously on the vibrating wire grille plate with a small gap between the wires, and a water film forms under capillary action. The outer outline of the water film between the wires is a circular arc concave surface owing to the influence of the water film force (Fig. 2). Let $d_0$ represent the distance between the two adjacent vibrating wires. The average curvature radius of the water film side surface is $r$, $r_1$ and $r_2$ are the curvature radius of the curved surface perpendicular and parallel to the steel wire, respectively, and the surface tension of the water film is $\delta$. According to the Young-Laplace [20] equation, the negative pressure difference of the water film between the vibrating wire is:

$$\Delta p = \frac{2\delta}{r} = \delta \left( \frac{1}{r_1} + \frac{1}{r_2} \right)$$

In a humid environment, when the water mist and parallel body of the wettable vibrating wire are close to one another, the vibrating surface absorbs the water mist molecules to form a water film. According to the physical and mechanical knowledge of surfaces and interfaces, the separation pressure $P_0$ in the water film is expressed as:
\[
P_o = \frac{H}{6\pi L^2}
\]
where \( H \) is the Hamaker constant (J) and \( L \) is the water film thickness (mm).

Under mechanical equilibrium conditions, the negative pressure of the water film between the wires is equal to the separation pressure in the water film. Combined with the relationship between the curvature radius of the water film surface and relative humidity in the continuous spray environment, the Kelvin equation [21] shows:

\[
r_k = \left( \frac{1}{r_1} + \frac{1}{r_2} \right)^{-1} = \frac{\partial V_m \cos \theta}{R_0 T \ln(p_g / p_l)}
\]

where \( r_k \) is the kelvin radius (m), \( V_m \) is the molar volume of the water mist (m\(^3\)/mol), \( \theta \) is the angle, taken here as 0°, \( R_0 \) is the universal gas constant (J·K\(^{-1}\)·mol\(^{-1}\)), \( T \) is the absolute temperature (K), \( p_g \) is the gas vapor pressure (Pa), \( p_l \) is the saturated vapor pressure of the water mist (Pa), and \( p_g / p_l \) is the relative humidity (dimensionless).

The negative pressure difference of the water membrane and the separation pressure are a pair of equilibrium forces, combined with Eqs. (6)–(8):

\[
\delta \frac{R_0 T \ln(p_g / p_l)}{\partial V_m} = \frac{H}{6\pi L^2}
\]

The thickness of the available water film is:

\[
L = \left[ \frac{H}{6\pi} \frac{V_m}{R_0 T \ln(p_g / p_l)} \right]^{1/3}
\]

Under continuous spraying at 20 °C, the molar volume of water fog is \( V_m = 1.8 \times 10^5 \) m\(^3\)/mol, the universal gas constant \( R_0 = 8.31 \) J·K\(^{-1}\)·mol\(^{-1}\), the absolute temperature \( T = 293 \) K, and the Hamack constant of water mist \( H = 3.72 \times 10^{-20} \) J.

(2) Derivation and calculation of water film height

Water mist between the wires forms a water film under capillary action and presents a circular concave liquid surface under magnification. The height of the concave water film is affected by the total capillary force (negative pressure difference of the total water film) \( F_m \), adjacent vibrating wire viscosity force \( F_v \), and water mist gravity \( F_g \).

According to the Young-Laplace equation [20], the capillary force (negative pressure difference of the water film) can be written as follows:

\[
\Delta p = \frac{2\delta}{r_2}
\]

As can be seen in Fig. 2,

\[
r_2 = \frac{r}{\cos \theta}
\]

If the distance between the vibrating wire and steel wire is \( d_0 = 2r \), the total capillary force is as follows:

\[
F_m = 2\pi r \delta \cos \theta
\]

The capillary motion of the water mist between vibrating wire is unsteady and satisfies the Navier-Stokes equation. To simplify the calculation, the flow of water mist between the vibrating wire is regarded as steady flow, the radial and circumferential direction components
of the flow velocity is set to 0, and the flow is symmetrically distributed. The Navier-Stokes equation [22] can therefore be expressed by the special Hagen-Poiseuille equation [23]. The viscous force between vibrating wires can be obtained by the internal friction law of a Newtonian viscous fluid and the Hagen-Poiseuille equation. The constitutive equations of Newtonian viscous fluid are as follows:

\[
\tau = \mu \frac{dv}{dr} \bigg|_{r=0} 
\]

(14)

where \( \tau \) is the internal friction force on the wall of the vibrating wire (Pa), \( \mu \) is the viscosity of water mist (Pa·S), \( v \) is the incoming flow velocity (m/s), and \( r_0 \) is the radial coordinates (m). The above formulations show that the viscous internal friction force of the water mist on the surface of the wire is linearly related to the velocity gradient, and the distribution law of the flow rate under the wind action is similar to that in a circular tube. Hagen-Poiseuille equation can be used to express [23]:

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{dv}{dr} \right) = \frac{1}{\mu} \frac{\partial p}{\partial z} 
\]

(15)

where \( p \) is the water mist pressure (Pa) and \( z \) is the capillary tube length direction coordinate (m). Taking into account the uniform change of the water film force between the vibrating wire, \( \frac{\partial p}{\partial z} = \frac{\Delta p}{h^1} \), \( h^1 \) is the height of the water film (mm) when it does not reach equilibrium. Integration of Eq. (15) with boundary conditions of \( r_0 = r \), \( v = 0 \) (m/s), the distribution of water mist velocity on the cross section of vibrating wire is as follows, The derivation can be obtained:

\[
\frac{dv}{dr_0} = \frac{r_0}{2\mu} \frac{\Delta p}{h^1} 
\]

(16)

Based on the Hagen-Poiseuille theory and its derivation, at \( r_0 = r \) :

\[
\frac{dv}{dr_0} \bigg|_{r_0=0} = \frac{r}{2\mu} \frac{8\mu \bar{v}}{r^2} = \frac{4\bar{v}}{r} 
\]

(17)

The internal friction force on the surface of vibrating wire can be obtained by replacing Eq. (17) with the Newtonian viscous fluid constitutive equation (14):

\[
\tau = \mu \cdot \frac{4\bar{v}}{r} 
\]

(18)

The viscous force of the adjacent vibrating wire is:

\[
F_v = 2\pi h \cdot \frac{4\mu \bar{v}}{r} = 8\pi \mu \bar{v}h 
\]

(19)

The gravity of the water mist between vibrating wires can be expressed as:

\[
F_g = mg = \rho \pi r^2 hg 
\]

(20)

where \( h \) is the rising water film height in the vibrating wire clearance (mm) and \( \rho \) is the water mist density (kg/m³).

Capillary action of the water film between the vibrating and steel wires is the result of the above three forces, according to the action direction of the force, namely:
\[ F_m = F_v + F_g \]  
\[ 2\pi r \delta \cos \theta = 8\pi \mu h + \rho g \pi^2 h \]  
The height of the capillary action of the water film in the gap of the vibrating wire is as follows:

\[ h = \frac{2r\delta \cos \theta}{8\mu v + \rho g r^2} \]  

From Eq. (23), the rising height of water film capillarity depends on the distance between adjacent vibrating wires, contact angle between the water film and wire, surface tension of water film, and average flow velocity.

**Results and Discussion**

**Relationship between effective area of a water film on a vibrating wire and dust removal efficiency**

The dust filtration efficiency of a vibrating string grille depends on the uniform filling rate of the steel wire (Fig. 3). The filtered area (height × width) of the vibrating wire grille plate used in the experiments is 590 mm × 550 mm, the cylindrical steel wire diameter \( d_f \) is 0.23 mm, the steel wire spacing \( d_0 \) is 0.26 mm, the filling rate \( \beta_s \) is 46.70%, and the total length of the double vibrating wire diameter is:

\[ L_s = \frac{8\beta_s ab}{\pi d_f} \]  

where \( L_s \) is the total diameter and length of the double vibrating wire (mm), \( a \) is the height of single layer vibrating wire (mm), and \( b \) is the width of the single layer vibrating wire (mm).

![Fig. 3 Filling rate of the curvature of the vibrating string grille](image-url)

The working parameters are as follows: dust gas flow \( Q \) (m\(^3\)/s), dust concentration \( C_0 \) (kg/m\(^3\)) in front of the dust flow through the plate, dust concentration \( C_1 \) (kg/m\(^3\)) after dust flow through the plate, the dimensionless filtering efficiency \( \eta_1 \), the incoming flow velocity of the filtered gas is the velocity \( \nu \) (m/s) of the wind flow at an infinite distance from the vibrating wire, and the velocity \( \tilde{\nu} \) (m/s) at the vibrating wire is shown in Eq. (25). The amount of dust collected
by the vibrating wire per unit length \( \phi \) (g) is shown in Eq. (26).

\[
\frac{v}{1 - \beta_f} = \frac{Q}{ab(1 - \beta_f)} \tag{25}
\]

\[
\phi = C \eta_1 d_f \tag{26}
\]

According to reference [24], the filtration efficiency of each vibrating wire can be expressed as:

\[
\eta_1 = R + (0.25 + 0.4R)(S_{ik} + 2R) - 0.0263(S_{ik} + 2R)^2 \left[ 0.16 + 10.9\beta_i - 17\beta_i^2 \right] \tag{27}
\]

where \( R \) is the low interception settlement, dimensionless, as shown in Eq. (28), \( S_{ik} \) is the Stokes number, dimensionless, as shown in Eq. (29).

\[
R = \frac{d_p}{d_f} \tag{28}
\]

\[
S_{ik} = \frac{\rho_p d_p^2 \nu C_\mu}{9\mu_s d_f} \tag{29}
\]

where \( d_p \) is the dust particle size (mm), \( \rho_p \) is the true density of dust particles (kg/m\(^3\)), \( C_\mu \) is the Cunningham correction coefficient, often taken as 1, and \( \mu_s \) is the viscosity of air (Pa·S).

For a vibrating wire dust catcher that is uniformly distributed in the vibrating wire grille, a unit filter \( dx \) is assumed on the vibrating wire surface, and the dust concentration entering the unit is \( C \) (%). In a unit time, through the vibrating wire with a filter area of \( a \times b \) (m\(^2\)), the layer thickness can be regarded as water film thickness \( L \) (mm), the total number of dust particles in the filter unit is \( \beta_f d_f L \pi \frac{dx}{4 d_f^3} \). Therefore, the amount of dust particles captured by the filter unit per unit time is:

\[
-Q dC = \beta_f \cdot \frac{d_f L}{\pi} \cdot C \cdot \eta_1 \tag{30}
\]

When Eq. (29) is substituted into Eq. (30), the following simplification and integral can be made:

\[
-\frac{1}{C_\eta_1} \frac{dC}{C_\eta_1} = \int_0^{L} \frac{4\beta_f \eta_1}{\pi(1 - \beta_f) d_f} dx \tag{31}
\]

The dust capture efficiency of simplified vibrating wire is:

\[
\eta_f = 1 - \exp \left[ -\frac{4\beta_f L}{\pi(1 - \beta_f) d_f} \eta_1 \right] \tag{32}
\]

For a vibrating wire under spray wetting condition, the trapping of dust particles by the steel wire and water film occurring between the strings is included in the process of dust particle capture. Under spraying conditions, the effective water film area between the vibrating wire can purify the dust. According to the formation process, the effective area of water film can be divided into effective areas of primary and secondary film formation. The effective area of primary film formation is that in which the water mist ejected from the nozzle forms between the wires. The effective area of secondary film formation forms under the combined action of turbulent buffeting and vortex shedding excitation. The secondary film-forming frequency is twice the fiber vibration frequency [25]. The experimental data show that the vibration frequency of the wire is the sum of the turbulent buffeting frequency and vortex shedding.
excitation frequency. The turbulence buffeting frequency can be expressed by dimensionless empirical Eq. (33) of unit time turbulent buffeting frequency. As studied by Webster [26]. Under turbulent conditions, the relationship between the dimensionless vortex shedding frequency and vibrating wire Reynolds number is as Eq. (34):

$$f = \frac{vd_f}{td} \left[ 3.05 \left( 1 - \frac{d_f}{d} \right)^2 + 0.28 \right]$$  \hspace{1cm} (33)$$

where \( t \) is the distance between two layers of vibrating wire grille (mm).

$$Sr = 0.198 \left( 1 - \frac{19.7}{Re} \right)$$  \hspace{1cm} (34)$$

Assuming that the thickness of the effective water film between the vibrating string steel wires is equal to the diameter of the vibrating string steel wire, the effective area function of the water film is expressed by the effective saturation of the water mist.

$$A_v = \left[ 1 + 2(f + Sr) \right] (1 - \beta_{sw})S_{we,ab}$$  \hspace{1cm} (35)$$

where \( f \) is the dimensionless turbulent buffeting frequency per unit time, \( Sr \) is the dimensionless vortex shedding frequency, and \( S_{we} \) is the effective saturation of the water on the plate (dimensionless).

The effective saturation of water on the plate refers to water flowing in the gap, accounts for the volume of the entire plate gap, and is calculated as follows:

$$S_{we} = \frac{S_u - S_{w0}}{1 - S_{w0}}$$  \hspace{1cm} (36)$$

where \( S_u \) is the water saturation, which refers to the degree to which the grille gap is filled by water mist, is the water-to-void volume ratio and is related to spray pressure. Water saturation can be obtained from the experimental data concerning spray pressure, where \( S_{w0} \) is the irreducible saturation of water, part of the water in the gap does not flow owing to adsorption forces. This part of the water is called irreducible water. The irreducible water-to-void volume ratio is the irreducible saturation of water, which can be calculated by the static liquid holding capacity of the wire. Combined Eq. (35) with Eq. (32), the dedusting efficiency of the double-layer wet vibrating string steel wire is calculated as follows:

$$\eta_{ef} = 1 - \exp \left[ -\frac{4\beta L}{\pi(1 - \beta)vd_f} - \eta_t \right] + \left[ 1 + 2(f + Sr) \right] (1 - \beta_{sw})S_{we}$$  \hspace{1cm} (37)$$

Experimental determination and analysis of dust removal efficiency

Eq. (37) shows that the dedusting efficiency increases proportionally to the effective area of the water film. In order to determine the relationship between the effective area of water film and the efficiency of dust removal, wet vibrating string grille dust removal experimental platform was built in the laboratory simulation return-air roadway. The dust removal efficiency was mainly measured through the platform. The composition of the system is shown in Fig. 4, which mainly includes dust, ventilation, spray, vibrating string grille dust removal, and drainage. The vibrating string grille dust removal subsystem located in the middle of the apparatus is mainly composed of the vibrating string steel wire, water mist, and water film attached to the wire. In order to measure the dust removal efficiency of the dust removal process, the dust sampling points are selected at the central position of the junction between the front and rear measurement sections and the wet string grille filter dust removal section. The dust removal efficiency can be calculated according to the change of the filter membrane dust at the front and rear sampling points. The roadway model is made of 10-mm-thick high-strength plexiglass to facilitate observation.
In the experiment, municipal tap water was used as the working medium. The equipment pressurizes the water to five pressure conditions commonly found in mines: 0.3, 0.5, 0.7, 0.9, and 1.1 MPa. The wind speed is determined according to the common wind speed of mine return-air roadway, which is 3 m/s. Under the same wind speed and different water pressure conditions, the wet vibrating string grille dust removal efficiency with string grille distance ratio of 1.14 and filling rate of 46.70% is measured. The measuring points are arranged one by one with the geometric center of resonance string grille as the coordinate origin (points A and B in Fig. 4). In addition, in order to reduce the measurement error, each point is tested three times and the average value is taken. The process and photos of the experiment is shown in Fig. 5. The effective area of water film can be obtained by using the above Eq. (35), the theoretical dust removal efficiency can be obtained from Eq. (37), and the experimental dust removal efficiency can be obtained by actual measurement. The specific data are shown in Table 1, and the specific change trend is shown in Figure 6.

| Spray pressure (MPa) | Effective area of water film/m² | Experimental dust removal efficiency/% |
|----------------------|---------------------------------|-----------------------------------------|
| 0.3                  | 0.19                            | 86.30                                   |
| 0.5                  | 0.25                            | 89.20                                   |
| 0.7                  | 0.28                            | 92.69                                   |
| 0.9                  | 0.27                            | 90.00                                   |
| 1.1                  | 0.24                            | 89.12                                   |

Table 1  Experimental data of effective water film area and dedusting efficiency
The theoretical value is consistent with the experimental measurements and shows that the dedusting efficiency is proportional to the effective water film area. A larger effective water film area is associated with higher dedusting efficiency. When the spray pressure changes from 0.5 to 0.7 MPa, the variation range of the dedusting efficiency is substantially larger than that of the effective water film area. When the water pressure is >0.7 MPa, the effective water film area continues to increase whereas the dedusting efficiency decreases slightly, which shows that higher spray pressure is preferable but that there exists an optimal spray pressure. When the optimal spray pressure is obtained, it enhances water film formation, however, the film breaks more easily, which is not conducive to the improvement of dedusting efficiency.

Conclusion

(1) The adjacent steel wire is subjected to adhesion forces between the water mist and wire surface, resulting in the formation of a water film. Based on the Bond number, the water film formation conditions include wire spacing of <0.34 mm. According to mechanical equilibrium conditions, the film thickness can be derived from the Kelvin equation. Combined with the Navier-Stokes equation and Hagen-Poiseuille law. The expression of the height of the capillary action of the water film in the gap of vibrating wire is constructed.

(2) Assuming that the water film between vibrating wires fills the gap of vibrating wire evenly. The effective area function of the water film is expressed by the effective saturation of the water mist, and the dedusting efficiency of double-layer wet vibrating wire is calculated.

(3) From the expression of dedusting efficiency and experimental data, we conclude that the dedusting efficiency is proportional to the effective water film area. Larger effective water film area is associated with higher dedusting efficiency. When the dedusting wind speed is 3 m/s, the chord-grille distance ratio is 1.14, the filling rate $\beta_s$ is 46.70%, the optimum spray pressure is 0.7 MPa, the corresponding effective area of water film is 0.28 m$^2$, and the dedusting efficiency is 92.69%.

Nomenclature

- $a$ height of single layer vibrating wire (mm)
- $b$ width of the single layer vibrating wire (mm)
- $A$ filter area ($m^2$)
- $A_w$ effective area function of the water film($m^2$)
- $B_O$ Bond number
- $C$ dust concentration entering the unit (%)
- $C_0$ dust concentration in front of the dust flow through the plate (kg/m$^3$)
- $C_1$ dust concentration after dust flow through the plate (kg/m$^3$)
- $C_o$ Cunningham correction coefficient
- $d_o$ distance between the two adjacent vibrating wires(mm)
- $d_e$ unit filter, dimensionless
- $d_f$ steel wire diameter (mm)
- $d_p$ dust particle size (mm)
- $f$ turbulent buffeting frequency
- $F_g$ water mist gravity(Pa)
- $F_m$ negative pressure difference of the total water film(Pa)
- $F_v$ adjacent vibrating wire viscosity force(Pa)
- $g$ gravitational acceleration (N/kg)
- $h^t$ height of the water film (mm) when it does not reach equilibrium(mm)
- $h$ rising water film height in the vibrating wire clearance (mm)
- $H$ Hamaker constant (J)
$L$  water film thickness (mm)
$L_d$ total length of the double vibrating wire diameter (mm)
$p$ water mist pressure (Pa)
$P_0$ separation pressure in the water film(Pa)
$p_g$ gas vapor pressure (Pa)
$p_l$ saturated vapor pressure of the water mist (Pa)
$Q$ dust gas flow (m³/s)
$r_0$ radial coordinates (m)
$r$ average curvature radius(mm)
$r_1$ curvature radius of the water film side curved surface perpendicular(mm)
$r_2$ curvature radius of the water film side curved surface parallel(mm)
$r_k$ Kelvin radius (m)
$R$ low interception settlement, dimensionless
$R_0$ universal gas constant (J·K⁻¹·mol⁻¹)
$Re$ Reynolds number
$S_r$ dimensionless vortex shedding frequency
$S_{st}$ Stokes number
$S_{we}$ effective saturation of the water on the plate
$S_w$ water saturation
$S_{w0}$ irreducible saturation of water
$t$ distance between two layers of vibrating wire grille (mm)
$T$ absolute temperature (K)
$V_m$ molar volume of the water mist (m³/mol)
$z$ capillary tube length direction coordinate (m)

Greek Symbols

$\beta_s$ wire-filling rate (%)
$\beta_{ws}$ filling rates of the wire and water(%)
$\beta_w$ filling rate of water on vibrating wire(%)
$\delta$ surface tension of the water film (N/m)
$\delta_{lv}$ liquid gas surface tension (N/m)
$\Delta p$ negative pressure difference(Pa)
$\varepsilon$ gate voidage(%) 
$\varepsilon_s$ voidage(%) 
$\eta_i$ filtration efficiency of each vibrating wire (%) 
$\eta_f$ dust capture efficiency of simplified vibrating wire(%) 
$\eta_{wf}$ dedusting efficiency of the double-layer wet vibrating string steel wire(%) 
$\theta$ angle(°)
$\lambda_c$ capillary length(mm)
$\mu$ viscosity of water mist (Pa·S)
$\mu_g$ viscosity of air(Pa·S)
$v$ incoming flow velocity (m/s)
$\overline{v}$ average velocity(m/s)
$\rho$ water mist density (kg/m³)
$\rho_p$ true density of dust particles (kg/m³)
$\tau$ internal friction force on the wall of the vibrating wire (Pa)
$\phi$ dust collected by the vibrating wire per unit length(g)
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