Experimental study on size and velocity of charged droplets

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Abstract

A kind of twin-fluid sprayer with annular and needle combined electrode is developed and droplets are generated out of the chamber, where gas and liquid mixing together and finish the energy exchanging. Much important geometrical and physical information are obtained in this paper. Droplets diameter and velocity distribution in electrostatic spray flow field are measured by PDPA. The spray characteristics including droplets size and velocity under different electrostatic voltages are investigated systematically and analyzed. The experimental results demonstrate that the droplets diameter and velocity distribution are affected apparently by electrical field. The droplets would produce secondary atomization in spray plume due to maintaining droplets stable conditions which are called as Rayleigh and Taylor instability respectively. In addition, droplets movement is dominated by gas in twin-fluid spray, while the electrostatic force is crucial to the droplets movement in the case of that droplets diameter is very small. Droplets velocity in uncharged spray is as similar as in charged spray with different voltages. Meanwhile, droplets turbulent pulsating intensity is obtained by analyzing the data. Turbulent pulsating intensity is dominated by fluid force, and the electrostatic force could assuredly affect the movement characteristics for small size droplets.

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1. Introductions

Spray characteristics including droplets size and velocity in electrostatic spray are of great importance in many industries and agricultures such as crop-dusting, painting, film preparation, fuel spray and combustion, particles

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conglomeration, et al.[1-4]. Although significant progresses have been made in studying electrostatic spray flow, much more important information is still scarce because of the inherent complexity of measurements process in droplets size and velocity. With the development of fluid flow measurements techniques such as laser Doppler velocimeter (LDV), particle image velocimetry (PIV), phase Doppler particle analyzer (PDPA), there are increasingly advanced measurements skills and methods applied into research of electrostatic spray [5]. Since 1970s, many researchers have been focused on the spray characteristics of various types of nozzle and liquid. In 1980s, the technique used in droplets size measurements can be classified into three kinds which are mechanical, electrical, and optical methods. Mcdonell V.G. [6] measured the droplets diameter and velocity of aerodynamic nozzle adopting PDPA in 1988. Particles flow behavior in gas-solid separator with a guide baffle and separation baffles was investigated by Du L. [7] in 2005. Phase Doppler anemometry was used to determine the droplets size and velocity distributions by Tang K Q in 1995[8]. Over the last several decades, since the techniques have been developed to be more sophisticated and detailed with important information obtained from the electrostatic spray, it makes optimization of the spray parameters possible to researchers.

2. Experiments

Experimental equipment is made up of electrostatic spray setting, supplying system, and measurements system. Gas supplying includes air compressor, air buffer tank flowmeter, valve, and manometer. Water supply includes water tank, pump, water buffer tank, flowmeter, valve, and manometer. Measurements system includes PDPA, displacement machine, and computer, et al. The detailed information of PDPA is in Ref. [5]. Experimental device is showed as Fig.1. The typical twin-fluid nozzle is adopted in this work [5].

![Fig.1. Experimental device of electrostatic spray](image1)

In an electrostatically-assisted twin-fluid atomization, much high viscosity liquid such as some slurry, heavy oil, and pesticide could be easily atomized into droplets and even some droplets can break into much more finer droplets with application of electrostatic voltage. In this experiment, the droplets are generated in the twin-fluid sprayer by mixing of water and gas, and then fine and uniform-dispersed droplets are produced in electrostatic field. In order to produce effective charge on the droplets, a kind of annular electrode combined needles which can form a strong electrical field was introduced and high speed fluid could be easily charged. The vertical distance between electrode of sprayer and nozzle is key factor effecting on droplets charge in charged process and is set to 20mm, where can obtain a satisfying charge to mass ratio that is parameter expressing charge on the droplets [5].

The charging system which is connected with high voltage electrostatic generator (HVEG) could supply negative high voltage with range from 0 to 30kV. The liquid is tap water in Zhenjiang (The conductivity of water is 325μs/cm in our experiment). The aperture of nozzle is 1.5mm. When flow rate is given, the droplets velocity and diameter in the spray flow under charging voltage of 0kV, 5.0kV, 10kV, 15kV and 18kV are measured by PDPA. The electrostatic spray is an axial symmetry flow because the charged spray is assumed to be a conical shape. The droplets velocity and diameter distribution are also axial symmetrical. The droplets information in the section which
is through the axes of the nozzle is behave of the whole spray flow. In this paper, the measurements points are set to be 15, and they are located the same horizontal plane where the distance is 300mm to nozzle, and is found in Ref.[5].

3. Results and discussions

When the experiment is carried out, a stable spray flow could be obtained with the condition that the pressure of gas and liquid is both 0.24MPa, the gas flow rate is 8.2mL/s and the limewater flow rate is 10.8mL/s (The operation conditions are measured by bellows pressure gauge, float flowmeter, and vortex flowmeter respectively). The droplets mean-diameter is showed in Fig. 2 in electrostatic spray plume. It could be also found that the droplets mean diameter is obviously influenced by electrostatic voltage. The droplets mean diameter is decreasing with electrostatic voltage increasing, and tendency of size decreasing become slowly, and droplets diameter trend to be uniform.

3.1. Droplets size

Figure 2 shows mean-diameter and Sauter mean-diameter distribution under different voltages. It could be found clearly that droplet diameter continuously reduced with high voltages increasing. In twin-fluid atomization, the initial energy to form droplets is gas kinetic energy, while the secondary atomization depends on electrostatic force which could overcome the droplets surface tension. When droplets generated from nozzle due to gas kinetic energy pass through the electrostatic field which the electrodes induce, the charged droplets surface tensions drop down under the effect of the strong electrical field intensity[9]. According to Weber similarity criterion, the decrease of surface tension means the increase of Weber number. When the Weber number is bigger than critical value, droplets would generate the secondary atomization due to electrostatic and fluid shearing forces. The weakening of surface tension reached the single droplets unstable condition which could cause a droplet breakup into many fine droplets. According to the Rayleigh Instability, the stable condition of spatial charged droplet surface is

\[ E_s \leq (n+2) \frac{2\sigma}{\varepsilon_0 d_p} \]  

(1)

In Eq. (1), \( E_s \) is droplets surface field intensity, \( \sigma \) is droplets surface tension, \( d_p \) is droplets diameter, and \( n \) is integer (>2). When the droplet surface field intensity is certain under the effect of electrostatic force, and droplets surface tension changes to be small value, the balance of Eq.(1) would be destroyed. The decrease of droplets diameter can guarantee the balance, and meet the requirement of the Rayleigh stable condition.

Simultaneity, Taylor proposed that the isolated droplet without charge or much less charge also has the surface stability limit under the effect of outside electrical field. A droplet would change into a flat long ellipsoid under the influence of the strong electrical field. According to Taylor Instability, when the major axis is 1.9 times of the minor axis, the droplet would produce further disintegration. The stable condition of spatial charged droplet is expressed as

\[ E_T^2 = 77 \times \frac{\sigma}{2 \pi \varepsilon_0 d_p} \]  

(2)

\( E_T \) is space field intensity, \( \varepsilon_0 \) is vacuum permittivity. In Eq.(2), when the charges are applied onto the droplets surface, droplets surface tension changes to small value. In order to ensure the stable condition, the droplets diameter would decrease. In other words, the droplets would continue to breakup and form the more fine droplets to maintain the Taylor Limit.

The Sauter mean diameter of charged droplets is about 72.3 percent of uncharged droplets under the voltage of 18.0kV. Simultaneously, the strong electrical field not is within the Rayleigh Limit and Taylor Limit of droplets, but also could maintain the droplet diameter under the small range and uniform size. Droplets distribution is narrowed and tends to be a uniform value. In addition, when droplets surface tensions continually fall with the high voltages increasing, the tiny fine droplets could coagulate owing to some special electrical pull forces. The breakup and coagulation of small droplets could make droplets distribution more uniform.
3.2. Droplets velocity

In order to investigate the effect of electrostatic forces on droplets velocity, the specific 15 points are selected to measure mean velocity of droplets, where the distance is set to 300 mm to nozzle. Figure 3 shows the results of droplets velocity distribution under different voltages. The experimental data indicates that droplets velocity either along axial or radial direction is almost unchanged under different voltages. In twin-fluid atomization system, the gas kinetic energy is a crucial factor that determines moving direction value of velocity. Although the electrostatic forces could reduce the liquid surface tension and viscosity, the droplets velocity might be accelerated in some extent. The change of droplets velocity is very little and could be ignored, since the droplets process certain kinetic energy. The mean velocity is pulsating, and relation between droplets velocity and voltage is unclear. On the other hand, the droplets movement is influenced by the electrostatic force, when the droplets diameter is smaller than a specific size. This ratio is a non-dimensional number described as $\gamma$.

$$\gamma = \frac{3E_0 \beta E_{max}^2}{\rho g} \cdot \frac{1}{d_p}$$  \hspace{1cm} (3)

In Eq. (3), $E_{max}$ is space field intensity, $\rho$ is liquid intensity, $\beta$ is constant number, $g$ is acceleration of gravity.

Some researchers pointed out that when $\gamma \geq 10.0$, the electrostatic force could control the droplets movement. When the droplets pass through electrical field, the biggest electrical field intensity is approximately $3.8 \times 10^5$ V/m. Taking $\beta=1/3$ into the Eq.(3) to calculate the droplet diameter, diameter of the biggest droplets that is under controlled by electrostatic force is around 17.2 $\mu$m.

Fig. 3. Droplets velocity distribution under different voltages  a) axial direction; b) radial direction

In a majority of electrostatic spray, there is less effect on the droplets movement due to real electrical field intensity is much smaller than the critical value. Nearby the electrode, fine droplets fly onto the electrode due to orientation force and polarization force, while some droplets accumulate to form larger size droplets, and the drop from the electrode. Convolution flow near electrostatic spray nozzle is special phenomenon.

3.3. Droplets Turbulent Pulsating Intensity

In this paper, the droplets turbulent pulsating intensity could not be directly obtained by PDPA measurements. It could be described by of Root Mean Square (RMS) velocity[5]. Figure 4 shows the droplets turbulent pulsating intensity distribution along with axial and radial direction in uncharged spray and charged spray under different voltages. It could be found clearly that droplets turbulent pulsating intensity is in accordance with droplets velocity. When droplets velocity is big, droplets turbulent pulsating intensity is strong. In other words, droplets velocity nonuniformity is higher than any other areas near the nozzle in charged spray. The effect which could be imposed on droplets by high voltage is little, because the charged droplets velocity and turbulent pulsating intensity is dominated by aerodynamic force. On the other hand, Although electrostatic force is small, it can not be ignored. The droplets movement characteristic including velocity and turbulent pulsating intensity is influenced by electrostatic force.
4. Conclusions

A kind of twin-fluid sprayer with annular and needle combined electrode is developed. Droplets diameter and velocity distribution in charged spray flow field are gained. The result shows that the droplets diameter and velocity distribution is affected apparently by electrical field. The droplets would produce breakup in the spray plume in order to maintain droplets stable conditions based on Rayleigh and Taylor Limit respectively. In addition, droplets movement is dominated by gas flow in the spraying flow, while the electrostatic force is crucial to the droplets movement in the case that droplets diameter is very small. Droplets velocity in uncharged spray is as similar as in charged spray. Turbulent pulsating intensity is also dominated by aerodynamic force, but the electrostatic force could assuredly affect the movement characteristics in some extent.

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References