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In-situ observation of hydrophobic micron particle impaction on liquid surface

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ABSTRACT

Particle impaction on a droplet surface directly affects the particle capture by the droplet, and this phenomenon is the basic process of wet scrubbing and wet deposition. The experimental system is established to in-situ observe the behavior of micron particles impacting on the liquid surface. 50–200 μm hydrophobic PMMA and PS particles were used. The particles showed two types of motion behavior, namely, submergence and oscillation, after impaction onto the liquid surface. During particle sinking, the advancing contact angle remained constant. The shape of the liquid surface met the Young–Laplace equation under the quasi-static assumption. After the angle of the three-phase line reached the critical value, the liquid surface was closed, and the particle submerged. A small bubble formed, adhering to the particle trailing surface. If the particle velocity decreases to zero before the angle of the three-phase lines reaches the critical value, the particle will reverse the direction of its motion. When the particle moves to the horizontal liquid surface, the movement ceases. Reciprocating oscillation behavior was not observed. During particle reversion, the receding contact angle gradually decreased and then remained unchanged. The large contact angle hysteresis is the main cause of failure observation in rebound motion mode in the experiment. The changing rule of the critical submergence/oscillation velocity with the particle diameter and surface tension coefficient was studied. As the particle diameter increases, the critical submergence/oscillation velocity decreases. As the surface tension coefficient increases, the critical submergence/oscillation velocity increases. The observed critical submergence/oscillation velocity in this experiment demonstrated the accuracy of the proposed model.

1. Introduction

Particulate matter is a key pollutant in the atmospheric environment [1–2]. Wet scrubbing and wet deposition are efficient methods to remove particles from industrial flue gas and the atmosphere [3–4]. Particle capture by a single droplet is the foundation of these two processes. Studies on single-droplet capture are significant to develop industrial wet scrubbing technologies and to understand the capacity and mechanism of wet deposition in the atmospheric environment.

Particle capture by droplets undergoes two stages: movement to the droplet surface under the influence of external forces and impaction after colliding with the droplet surface [5–7]. After particles collide with the droplet surface, hydrophilic particles enter the droplets [8–9], whereas hydrophobic particles may enter the droplets, remain on the surface of the droplets, or rebound under the action of surface tension [10]. The ratio of particles remaining on the surface or entering the droplet to the total making in contact with the droplet surface refers to the attachment efficiency [11]. The attachment efficiency affects the total capture efficiency and changes the surface and internal characteristics of the droplets, thereby affecting the subsequent capture process. Although accurate methods have been developed to predict collision efficiency [12–14], the attachment efficiency is assumed to be 1 for the simplified calculation of droplet capture efficiency. Mikhailov [15] measured the total number concentration of the mixture of 1.5 μm atomizing droplets and 0.8 μm hydrophobic solid particles after coalescence. They found that the total number concentration of the mixture decreased after hydrophilic treatments. Thus, Mikhailov supposed that rebound occurred when hydrophobic solid particles and droplets collided. Particles emitted from industrial plants are mainly hydrophobic [16]; approximately 60% of the particles larger than 1 μm in the atmospheric aerosols are hydrophobic [17]. Therefore, the behavior of hydrophobic particles impacting the droplet surface should be elucidated.

The diameters of micron-sized particles are usually hundreds of times smaller than those of a scrubbing droplet. An impaction between a micron-sized particle and a scrubbing droplet is similar to that between a micron particle and a flat liquid surface [18]. Research on the impaction behavior of particles after collision with a liquid surface mainly focused on millimeter particles because of the limited observation methods and demands from military fields and bionics [19,20].

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Lee [10] observed that millimeter-sized hydrophobic particles exhibit three types of motion behavior, namely, submergence, oscillation, and rebound. Aristoff [21] studied the interaction between millimeter-sized particles and liquid surfaces and found that the shape of the liquid surface around a moving particle is identical to that of a stationary one if $We < 10$. The impaction behavior of millimeter-sized particles is determined by the overall action of surface tension, drag force, gravity, buoyancy, and additional inertia force. The magnitudes of the different forces change with the decreasing particle size [10,22]. When the particle size is reduced to below 0.1 mm, the surface tension becomes dominant during impaction. Moreover, the shape of the liquid surface is different from that of millimeter-sized particle impaction, which will change the impaction mode. Thus, the research results of millimeter-sized particle impaction cannot be directly applied to micron-sized particle impaction.

To date, micron-sized particle impaction is limited to theoretical analysis [23]. Numerical simulation showed three types of motion behavior, similar as millimeter-sized particles. On the basis of the relationship among particle displacement, force, and work, the criteria of the critical velocity were proposed to distinguish the submergence, rebound, and oscillation after impaction. The criteria indicated that surface tension coefficient, contact angle, and particle diameter are the key parameters affecting the critical velocities.

Experimental research on hydrophobic micron-sized particle impaction on a liquid surface should be developed to obtain further information regarding this process and to verify the abovementioned criterion. The experimental system that can be used to determine the in situ behavior of micron-sized particles impacting the liquid surface is established. Particles and liquids with different properties are selected to perform the experiment. The characteristics of impaction behavior are observed. The influence of the contact angle and surface tension coefficient on the impaction behavior was also analyzed. The accuracy of the analytic model for impaction was verified by comparing the results of the experiments and the analytic model.

2. Experiment

2.1. Experimental setup and materials

The experimental apparatus consisted of gas paths, a particle generator, an impactor, a high-speed camera, and a background light source, as shown in Fig. 1(a). The particle generator produces particles by vibration, and the detailed operating principle was described by Wu [24]. In this experiment, the particle number is controlled to ensure the impaction onto the liquid surface of particles without disturbing each other. The distance between impaction positions of each particleis more than 10 particle diameter. The liquid surface will not be influence by the other particles which stay on the liquid surface far away. The time interval of particles is more than 5 times of oscillation time. The liquid surface always keeps calm before the next particle impacts. Fig. 1(b) shows the diagram of the impactor structure, which consisted of the accelerating jet and impaction void. The inner diameters of the upper and lower parts of the accelerating jet are 20 and 2 mm, respectively. Below the accelerating jet, the four gas flow exits exhibit a diameter of 4 mm each. The maximum velocity can reach 5 m/s under the carrying of gas flow in the accelerating jet. When the gas and particles flow out of the accelerating jet, the gas flows out of the impactor from four exits, whereas the particles deviate from the flow line and enter the impaction void because of its inertia. The impaction void is a cuboid with a size of 60 mm × 50 mm × 20 mm. Half of the void is filled with liquid and forms the horizontal liquid–gas interface. The 5 mm-long hole with a diameter of 1 mm on top of the void ensures that the particle vertically impacts onto the gas–liquid interface. Two rectangular windows were opened in two sides of the impaction void, with two embedded optical glasses. A LED light source (Kaiwei Optical Company: KW-B50F-HW) with a power of 5 W was installed on one side of the rectangular window as a background light source. The high-speed camera placed on the other side of the rectangular window was also fixed on the optical bench to shoot the impaction process on the gas–liquid interface in the void through the optical glass. The high-speed camera (Photron: FASTCAM SA-Z) has a resolution of 1024 × 1024 pixels at a shooting speed of 20,000 ftp. The camera lens magnification ranged from 2.8 to 18.0.

The motion of gas flow and particles in the impactor was simulated by the commercial CFD software Fluent. The flow is simulated by the laminar model. The particles are tracked by the discrete particle model. The results show that particles with a diameter of 50 μm vertically impacted the gas–liquid interface. The velocity of the particles can be controlled by changing the inlet gas flow rate.

The 50–200 μm PMMA (Polymethylmethacrylate) and PS (Polystyrene) particles with densities of 1.18 and 1.08 kg/m^3, respectively, were used in this work. Deionized water and aqueous ethanol solutions of different mass concentrations were used for the variation

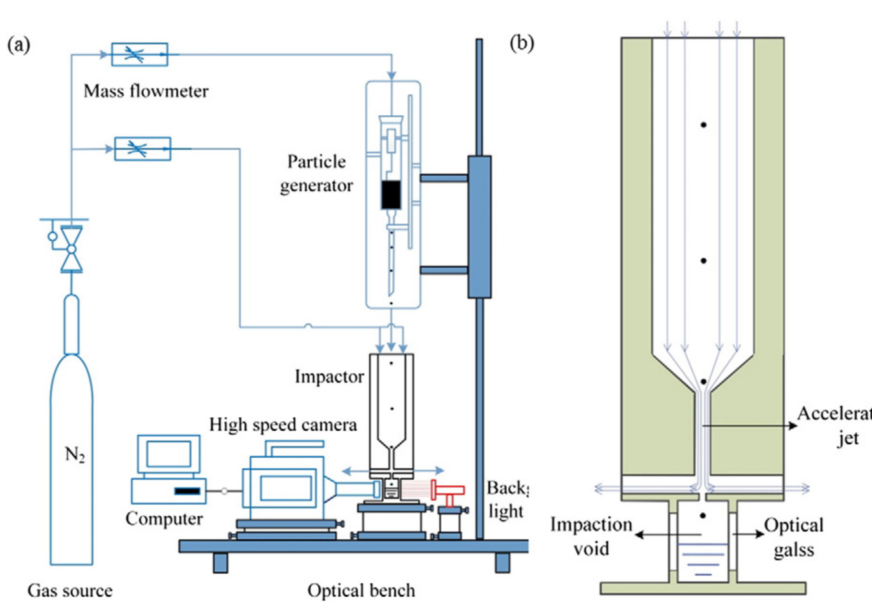

Fig. 1. Schematic diagram of the experimental system and the impactor.