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A mechanistic explanation of the increase in particle scavenging in the ultrasonic scrubber

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ABSTRACT

Ran et al., 2014 developed the ultrasonic scrubber, a device which combines an ultrasonic standing wave field and a water spray to eliminate particles from a gas flow. This device, which is essentially a wet scrubber enhanced by ultrasound, was shown to significantly improve the scavenging of micron-scale particles compared to the use of a water spray alone. Herein a simulation of trajectories of the particles and spray drops in the ultrasonic scrubber are presented. These simulations and an associated model of the process are used to provide a mechanistic understanding of the enhanced scavenging observed in the ultrasonic scrubber.

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1. Introduction

Emission from fossil fuel combustion in the transportation and industrial sectors is one of the main sources of particulate air pollution (Tucker, 2000). These particulate pollutants have significant deleterious effects on pulmonary health (Cohen, 2000; Docker & Pope, 1994; Pope et al., 1995; Pope et al., 2002; Schikowski et al., 2005; Schwartz et al., 1993; Seaton et al., 1995), cardiovascular disease (Johnson, 2004; Pope et al., 2004; Suwa et al., 2002; Verrier, Mittleman & Stone, 2002), and increased mortality (Schwartz & Dockery, 1992; Schwartz, Laden & Zanobetti, 2002). Particles with aerodynamic diameter less than 2.5 μm (PM2.5) are believed to pose the greatest health risks (Davis, Bell & Fletcher, 2002; Schwartz et al., 1993).

Several methods exist for reducing particulate pollution from combustion sources. One example is the wet scrubber which has several advantages, including its ability to operate at high temperatures and to simultaneously remove gaseous and particulate pollutants. In a typical wet scrubber configuration, water is sprayed downward into an upward flowing stream of pollutant laden gas, and the pollutants are removed by the falling droplets which are collected at the bottom of the wet scrubber. The performance of a wet scrubber can be quantified by the scavenging coefficient:

$$E = \frac{n_s}{n_T} \tag{1}$$

where n_s is the number of particles removed by the scrubber, and n_T is the total number of particles entering the scrubber.

While generally effective, experimental and theoretical studies of wet scrubbers show that they perform poorly in the removal of micron-scale particles (Gemci & Ebert, 1992, Raj Mohan, Jain & Meikap, 2008). Plots of E versus particle diameter d_p for wet scrubbers typically show a minimum in the micron scale region. For example, Kim, Jung, Oh & Lee (2001) present

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a plot of E versus d_p showing a minimum at (almost exactly) $d_p = 1$ μm. This minimum is due to the basic physics of particle collection which can be understood as follows. When a large particle approaches a droplet, its inertia prevents it from following the flow streamlines around the drop and the particle impacts the drop and is removed. For very small drops, this inertial effect vanishes, but Brownian motion causes these particles to deviate from their streamlines effectively diffusing to the drop. Inertial effects increase with d_p while Brownian motion decreases with d_p. Accordingly, there is a range of d_p falling between the inertially-dominant and diffusive-dominant regimes, where neither the inertial nor diffusive mechanisms are effective, resulting in a minimum in E, often referred to as the “Greenfield gap” (Greenfield, 1957). This minimum falls, again, within 0.1 μm$\lesssim d_p \lesssim$10 μm as reported by several researchers (Gemci & Ebert, 1992; Kim et al., 2001; Lai, Dayan & Kerker, 1978; Lim, Lee & Park, 2006; Raj Mohan et al., 2008). Summarizing, the micron scale particle diameters that are most harmful to human lungs are the least effectively removed by wet scrubbers. Hence, there is a strong motivation to improve upon the current ability of wet scrubbers to remove micron scale particles from pollution streams.

Ran, Saylor, and Holt (Ran et al., 2014), referred to hereinafter as RSH, demonstrated that micron-scale particles could be more effectively removed when an ultrasonic standing wave field was added to the wet scrubber, a device which we term the “ultrasonic scrubber”. An ultrasonic standing wave field can be created by an ultrasonic transducer and a reflector (typically a flat metal disk), with the two separated by an integer number of half wavelengths. An example of such a setup is presented in Fig. 1 which shows a fine water mist being introduced into the standing wave field. The small drops are forced toward the pressure-nodal region by the acoustic radiation force, F_{ar} (see below), forming “accretion disks”. RSH hypothesized that particles in the vicinity of the standing wave field would also be driven to the accretion disks just as the fine water droplets are in Fig. 1 and that particles and drops would then come into close proximity with each other, increasing the chance for a drop to scavenge a particle, thereby increasing E. To test this hypothesis RSH used the small scale ultrasonic scrubber shown in Fig. 2, where air laden with fine particles was flowed into the scrubber. The particle concentrations of the inlet and outlet of the scrubber were measured to compute the scavenging coefficient E. Experiments conducted with and without the ultrasonic standing wave field showed an increase of as much as 140% due to the ultrasonics.

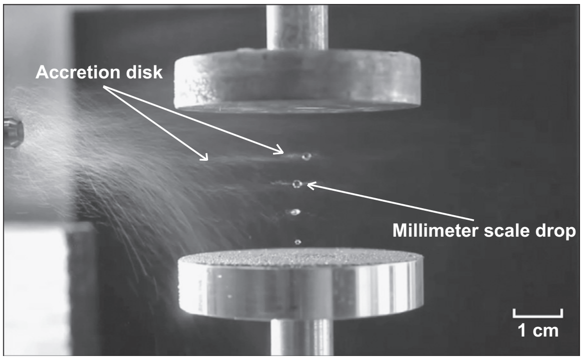

Fig. 1. Droplets accumulate in the accretion disks of a ultrasonic standing wave field. The ultrasonic horn is the lower circular aluminum piece and the reflector is the upper circular aluminum piece. A nebulizer can be seen on the left hand side, which introduces a fine water mist into the vicinity of the standing wave field. The large drops located in the center were formed by the agglomeration of these fine water mist drops.

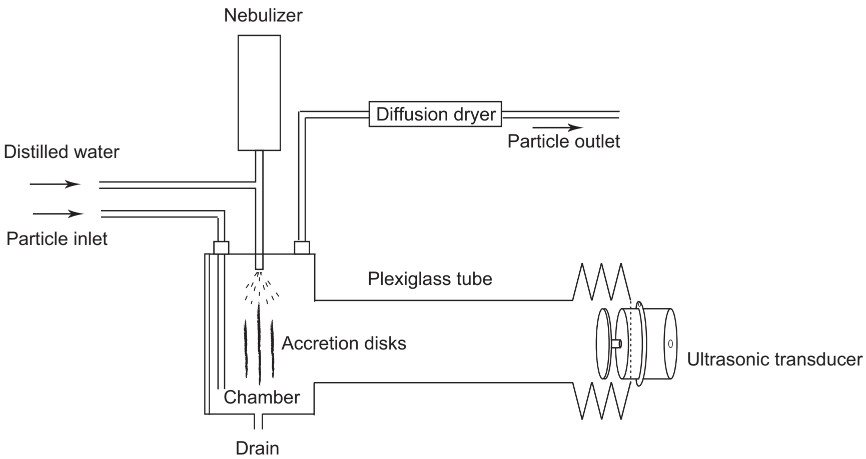

Fig. 2. Ultrasonic scrubber used by RSH. The scavenging chamber is the rectangular portion where the accretion disks are located and is presented in greater detail in Fig. 3. Note that the ultrasonic standing wave field is rotated 90° from that shown in Fig. 1. The diameter of the exit to the nebulizer at the top of the chamber is 2 mm.

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