Journal of Aerosol Science 67 (2014) 104–118

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Improved particle scavenging by a combination of ultrasonics and water sprays

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ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
15 August 2013
Accepted 16 August 2013
Available online 11 September 2013

Keywords:
Particles
Drops
Sprays
Scavenging
Ultrasonics

ABSTRACT

The results of an experimental study are presented where an ultrasonic field was used to increase the scavenging of micron-scale particles by water sprays. Specifically, an ultrasonic standing wave field was set up between an ultrasonic transducer and a reflector, creating multiple pressure nodes. These nodes are locations where drops collect into what we call accretion disks. Significant increases in the scavenging coefficient were observed when these accretions disks were present. Experiments conducted in the presence of an ultrasonic standing wave field and a water spray yielded scavenging coefficients as large as 140% of those which were obtained using a spray alone. Also, experiments conducted with the ultrasonic field present, but detuned so that accretion disks did not form, showed no significant improvement over the case without ultrasonics at all. The scavenging coefficients are presented as a function of particle diameter and water flow rate.

1. Introduction

This work focuses on the use of water sprays to remove particles from a particle laden stream of air. This is a common situation encountered, for example, when particles are removed from a polluted air stream, such as a smokestack, using wet scrubbers, or in environments such as mines where sprays are used to reduce the high levels of coal dust or silica dust which renders the air dangerous to human health and can make the air explosive. Particulate pollutants negatively impact the health of humans in several ways, including increases in mortality in individuals with pre-existing lung conditions (Davis et al., 2002; Schwartz, 1994) via increased cardiovascular disease morbidity and mortality (Johnson, 2004; Pope et al., 2004; Suwa et al., 2002; Verrier et al., 2002), and via increased prevalence or exacerbation of lung ailments such as lung cancer (Cohen, 2000; Pope et al., 1995, 2002), chronic obstructive pulmonary disease (COPD) (Schikowski et al., 2005) and asthma (Docker & Pope, 1994; Schwartz et al., 1993; Seaton et al., 1995), among others. Studies of city populations show increases in mortality on days when particulate pollution levels are elevated (Schwartz & Dockery, 1992; Schwartz et al., 2002). In the mining industry, exposure to silica dust causes silicosis, and exposure to coal dust results in coal workers' pneumoconiosis (CWP) also known as black lung disease, diseases that continue to kill mine workers. The increased use of diesel engines in mines has raised concerns over exposure of mine workers to diesel particulate matter, presenting yet another potential threat to human health from particulate pollutants (NIOSH, 2002).

Sprays are commonly used to remove particles from air. This is the case, as noted above, in the use of wet scrubbers in smokestacks. Sprays are ubiquitous in the mining environment where they are used to prevent particles from entering the

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http://dx.doi.org/10.1016/j.jaerosci.2013.08.009

air, and also to reduce their levels once they have entered the air. Because sprays are used so often in particle scavenging, increasing their ability to scavenge particles would have a significant impact.

The ability of a drop or group of drops, such as a spray, to capture particles can be quantified by the scavenging coefficient:

$$E = \frac{n_s}{n_T} \times 100\% \tag{1}$$

where n_s is the number of particles scavenged by the drop (or collection of drops) and n_T is the total number of particles within the cylindrical volume swept out by the drop(s) as it travels through the particle laden air stream. The scavenging coefficient E is dependent on the complicated physics of particle–drop interactions, and is affected by many factors. These include the drop and particle densities, the diameters of the drop and particle, the charge on the drop and particle, the physical properties of the liquid such as surface tension and viscosity, and the airflow characteristics around the drop.

For a given drop diameter D, E is sensitively dependent on the particle diameter d. Specifically, plots of E versus d reveal a minimum in E which can be quite low. This minimum is the result of two competing trends. At large particle diameters, inertia plays a large role in particle scavenging since the particle, unable to follow the streamlines around the drop, impacts the drop. At very small particle diameters these inertial effects do not play a role, but Brownian motion enables a relatively large fraction of particles in the boundary layer near the drop to diffuse[1] toward the drop and thereby impact the drop in that fashion. These diffusive effects increase with decreasing d, while inertial effects increase with increasing d. Accordingly, there is a range of particle diameters that falls between the inertially-dominant and diffusive-dominant regimes where neither inertial or diffusive processes are effective, and where values of E are relatively low. This region where a minimum in E is observed is often referred to as the “Greenfield gap”, after Greenfield who analytically investigated the scavenging coefficients of particles in rainfall and was first to show the existence of this minimum (Greenfield, 1957). Significant research on rain/particle interactions has taken place since the time of Greenfield, excellent examples of which can be found in the work of Beard and co-workers, such as Beard & Grover (1974) and Beard (1974). A plot taken from Greenfield's paper is presented in Fig. 1 which shows reduced E for particle diameters ranging from ~ 0.1 μm to ~ 1.0 μm. This range will differ depending on the characteristics of the drop, the particle, and the airflow, among other factors. However, for applications relevant to the current work where water drops have diameters ranging from several tens of microns to a millimeter, the gap in scavenging coefficient corresponds roughly to that shown in Fig. 1. This was shown, for example, by Pranesha & Kamra (1996) who compiled the work of several authors, incorporating water drops where D ranged from 87 μm to 4.8 mm and particle densities ranged from 1000 kg/m^3 to 2500 kg/m^3. Although the location of the scavenging gap varied with experimental conditions, the minimum in E resided between 0.1 μm and 1.0 μm, with few exceptions.

The existence of a minimum in E for particle diameters, $d = 0.1$–1.0 μm is of particular concern for pulmonary illness. Alveolar deposition of particles peaks for d slightly larger than 1 μm, and significant alveolar deposition occurs for particles ranging in diameter from 0.01 μm to 10 μm (EPA, 1999; Heyder et al., 1986). Particles with $d < 2.5$ μm (often referred to as PM2.5) are believed to pose the greatest health risk (Schwartz et al., 2002). This means that the range in d that presents the greatest threat to pulmonary health overlaps the range in d where sprays are least effective in removing particles from air. Because sprays are used in the wet scrubbers of smokestacks and in particle control in mines, a method that could improve the scavenging coefficient of spray drops for particle diameters in the 0.1–1.0 μm range could lead to technologies that would significantly improve pulmonary health.

The goal of the work presented herein was to determine if ultrasonics could be used to improve the ability of sprays to scavenge micron-scale particles. Our hypothesis was that ultrasonics could be used in such a way that micron scale particles would be forced into contact with spray drops. Such an approach is theoretically possible, since a force is experienced by any object that scatters acoustic[2] waves in a medium, e.g. particles or drops. This acoustic radiation force F_{ar} has often been used to levitate objects in a standing wave field, a technique that has found application in many areas ranging from the study of fluid mechanics (Marston & Thiessen, 2004; Shi et al., 1995; Trinh et al., 1996) to containerless processing of materials (Weber et al., 1994) as well as in analytical chemistry applications (Santesson & Nilsson, 2004). In a typical application, acoustic levitation is achieved by placing an ultrasonic transducer oriented in the vertical direction, directly beneath a reflector (typically a flat metal disk), with the two separated by an integer number of half wavelengths to create a standing wave field. The acoustic radiation force should act to move particles and drops toward the nodes or anti-nodes (depending on the properties of the particles/drops and the ambient fluid) of the standing wave field (Crum, 1971; Marston & Thiessen, 2004).

An example of such a setup is presented in Fig. 2, which shows an ultrasonic transducer (below) and a reflector (above). A fine water spray has been introduced into the general vicinity of the field by a nebulizer (the tube on the upper left hand side of the image), and the fine spray drops have accumulated in the pressure nodes, forming what we call “accretion disks”. In the center of these disks, enough drops have agglomerated with each other to form relatively large drops. In the figure, these large drops in the center of the accretion disk have a weight less than the acoustic radiation force. However, as time

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[1] Here we are modeling Brownian motion as diffusion.

[2] Herein the words “acoustic” and “ultrasonic” are used interchangeably, though any practical device would have to use ultrasonics due to the auditory damage that would result should audible frequencies be employed.