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Scavenging of micron-scale particles using a combination of fog and a cylindrical ultrasonic standing wave field

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ABSTRACT

An experimental study is presented wherein a cylindrical ultrasonic standing wave field is used to increase the scavenging of micron-scale particles by water fog in an air stream. The cylindrical standing wave field was generated with a cylindrical resonator composed of a metal tube driven by three ultrasonic transducers. The nodes in the resonator took the form of concentric cylinders extending the length of the tube. Experiments conducted with the resonator yielded maximum scavenging coefficients over four times that obtained previously with a disk shaped geometry. The effect of both air flow rate and input power are investigated, and insights are presented on the mechanism of particle removal by drops in the presence of a standing wave field.

1. Introduction

It is estimated that the United States produces 8000 Mg/year of fine particulate matter pollution, defined as particles less than 2.5 μm in diameter ($PM_{2.5}$), a significant portion coming from the burning of fossil fuels (Tucker, 2000). If inhaled, $PM_{2.5}$ can have particularly deleterious effects on the pulmonary health of humans (Cohen, 2000; Fann et al., 2012; Johnson, 2004; Seaton, MacNee, Donaldson, & Godden, 1995;). This is because inhaled $PM_{2.5}$ can penetrate deep into the lungs where it has a particularly high deposition rate (Heyder, Gebhart, Rudolf, Schiller, & Stahlhofen, 1986). The health effects caused by exposure to $PM_{2.5}$ can lead to death, as studies have shown that mortality rates correlate to local $PM_{2.5}$ concentration in the atmosphere (Pope et al., 1995; Schwartz, Laden, & Zanobetti, 2002). Traditional methods for removing particles, such as wet scrubbers, electrostatic precipitators, and baghouses, generally do well over a large range of particle diameters, but perform poorly at particle diameters on the order of a micron (Kim, Jung, Oh, & Lee, 2001; Kim & Lee, 1999; Lee & Liu, 1980). As such, improvements are needed to increase the collection efficiency of micron-scale particles.

A commonly used technology for removal of particulate pollutants from exhaust streams is the wet scrubber which has several advantages, including robustness, an ability to work on particles regardless of their chemical composition, and an ability to also remove gases. However, like many particle removal technologies, wet scrubbers perform poorly on particles having an effective diameter on the order of a micron. In an effort to improve upon the effectiveness of the wet scrubber, researchers have studied the use of acoustic waves to enhance particle-drop interactions in such devices. Ran, Saylor, and Holt (2014) and Ran and Saylor (2015) demonstrated the ability to scavenge micron-scale particles from an air stream using a combination of an ultrasonic standing wave field and water drops. These researchers used a disk shaped transducer to excite an ultrasonic standing wave field in which particles and water drops combined in the nodes of the field, as shown in Fig. 1. As particles and drops combined they grew into much larger particle-laden drops which eventually fell from the system, thus removing particles in the process. The practical application of the above approach was limited by modest particle collection and relatively low air flow rates. For example, the maximum particle

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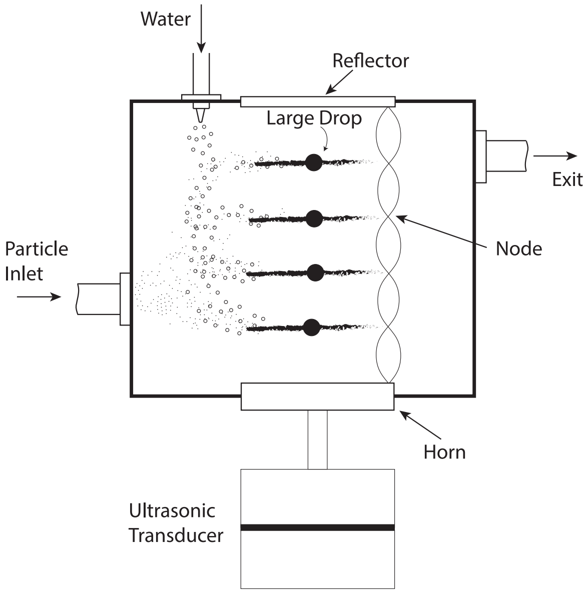

Fig. 1. Illustration of the setup used by Ran et al. (2014) to remove micron sized particles from an air flow.

collection reported by the authors was ~20% at an air flow rate of 12 L/min. Increasing both the percentage of particles collected and the air flow rate would facilitate practical application of the described approach in wet scrubbers. This need for an increase in particle removal and operating air flow rate is an important motivation for the present study.

A major constraint of the setup used in Ran et al. (2014) and Ran and Saylor (2015) was the relatively short residence time for particles and drops as they traveled through the ultrasonic standing wave field, which is roughly equal to the diameter of the disk-shaped transducer divided by the flow velocity. Scavenging of particles would be increased by increasing the residence time, however doing so requires either a reduction in the flow rate, which is not desired, or an increase in the size of the disk-shaped transducer. Commercially available disk-shaped ultrasonic transducers are currently limited to diameters on the order of an inch, leaving little room for improvement on this disk-shaped transducer approach.

An alternative approach to the work of Ran et al. (2014) and Ran and Saylor (2015) would be to use a cylindrical geometry like that shown in Fig. 2. If such a cylinder could be excited to oscillate in the breathing mode (axially symmetric expansion and contraction of the tube diameter), forming a cylindrical resonator, then an ultrasonic standing wave field could be created within the cylinder where the nodes would take the form of concentric cylinders extending the length of the cylinder. In such a geometry the residence time for a given flow rate could be increased simply by making the tube longer and would therefore be essentially unlimited (of course the acoustic power delivered to the standing wave field would still be limited to the total power delivered to the cylindrical resonator). An increased residence time would allow more time for drops and particles to combine in the nodes. Furthermore, even if the cylindrical resonator shown in Fig. 2 were modest in length, as long as most of the particles and drops had migrated to the nodal regions at the resonator exit, these regions of high particle/drop concentration could be maintained if a passive tube was connected to the cylinder exit. The passive tube concept is shown in Fig. 3. Thus, once particles and drops are moved by the acoustic radiation force to nodes, they should then remain in approximately the same radial location, allowing more time for particle/drop combinations to occur. The passive tube could potentially be much longer than the cylindrical resonator itself, thus greatly enhancing the overall residence time and subsequently the number of particle/drop combinations. Such a possibility does not exist for the disk setup (Fig. 1), where drops and particles are in close proximity as they flow through the nodes, but the nodal structure of high particle/drop

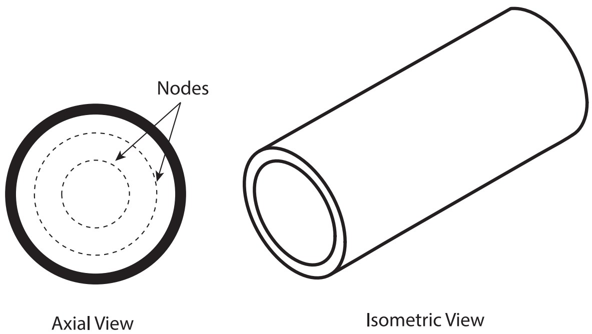

Fig. 2. Schematic of a cylindrical resonator showing the cylindrical nodes that would result should the tube be oscillated in the breathing mode.