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Efficient atomization of brine at atmospheric pressure

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ABSTRACT

An efficient and reliable technique to generate fine aerosols at atmospheric pressure is crucial in many engineering applications. Particularly, the development of a reliable continuous generation of fine aerosols from brine at atmospheric pressure is an essential step towards the future development of a portable thermal desalination system. In this study, we demonstrate the performance of a *without*-nozzle technique, which consists of a piezoelectric transducer coupled with a focusing tip, to rapidly destabilize the liquid-air interface, leading to the generation of fine aerosols. Unlike the conventional *with*-nozzle technique, which suffers a substantial decrease in aerosol generation rate after two hours of continuous operation, no significant change in aerosol generation rate in the *without*-nozzle technique. Nonetheless, increasing salt concentration in the solutions reduces the aerosol generation rate, which can be attributed to the increase in the surface tension, viscosity, as well as the density of the solutions. A reduction of aerosol generation rate of up to 60% when salt concentration is increased from 10% to 30%. Concomitantly, the aerosol size is also reduced at higher salt concentration. To further improve the efficiency of the technique, we also examine the effect of signal amplitude modulation and burst modulation. At a fixed power, up to 15% and 26% increase in aerosol generation rate can be obtained by using amplitude and burst modulation, respectively. For the amplitude modulation, the aerosol generation rate can be increased by increasing the modulation index, whereas, for the burst modulation, the aerosol generation can be increased when the number of *trigger*-cycle is larger than 60% of the number of total-cycle.

1. Introduction

The ability to generate fine aerosols of diameter in the micro to nanometer order is essential in many engineering applications. One of the significant advantages of using fine aerosols is the increment of the surface to volume ratio of the aerosols. Therefore, these fine aerosols have been employed in different fields such as engine combustion (Park, Kim, & Lee, 2006; Park, Youn, Lim, & Lee, 2013), evaporative cooling (Ang, Yeo, Friend, Hung, & Tan, 2015; Wang & Mamishev, 2012), ink-jet printing (Duraisamy, Muhammad, Kim, Jo, & Choi, 2012), spray coating (Anzai, Watanabe, & Sakamoto, 2012; Jeng, Su, Feng, Peng, & Chien, 2009) and many others. Additionally, fine aerosols are also crucial in applications such as food processing (Mulhem, Schulte, & Fritsching, 2006) and biomedical applications, which include pulmonary drug delivery (Qi, Yeo, & Friend, 2008) and DNA microarray printing (Basaran, 2002).

There are several common techniques that can be used to generate fine aerosols, such as the those that rely on applied pressure (Jeng et al., 2009; Jeng, Tu, Feng, Su, & Peng, 2007), electric field (Jaworek, 2007; Kikuchi et al., 2017; Wang & Mamishev, 2012), and high-frequency vibration (Fu et al., 2017; Goodridge, Shi, Hentschel, & Lathrop, 1997; Ju, Yamagata, Ohmori, & Higuchi, 2008;

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Qi et al., 2008; Vukasinovic, Smith, & Glezer, 2004; Vukasinovic, Smith, & Glezer, 2007). These techniques, in general, can be classified into two distinct types: *with*- and *without*-nozzle. For instance, one of the techniques that can be categorized as the *with*-nozzle type is via an oscillating pressure exerted on the liquid, resulting in the highly pressurized liquid being repeatedly forced through a small nozzle and subsequently produced individual droplets (Jeng et al., 2007, 2009; Xu et al., 2012). The size of the droplets generated from this type of atomizer is mainly defined by the diameter of the nozzle (Zhang et al., 2014), i.e., the droplet size is slightly larger than the nozzle diameter (Friend & Yeo, 2011). This technique can generate fine aerosols at higher rates. Nevertheless, one of the main drawbacks is the clogging or plugging within the nozzle due to impurities present in the solutions, which can hinder the flow of solution over an extended time of operation (Chen & Basaran, 2002; Georgieva, Dijkstra, Fricke, & Willenbacher, 2010), and subsequently deteriorate the nozzle quality (Chen & Basaran, 2002).

Another technique that also can be categorized as the *with*-nozzle type is electrospray. This technique relies on liquid surface destabilization under the influence of externally applied force, i.e., electric field. As such, the magnitude of the externally applied force and fluid properties such as surface tension, viscosity, and electric conductivity are the important factors that can affect the rate of aerosol generation. Electrospray utilizes electric field, wherein the droplets generation is based on the strong electric field applied between the nozzle and the target (Ganan-Calvo, 1997; Jaworek, 2007; Wang & Mamishev, 2012). Although electrospray can generate monodispersed droplets ranging from 3 nm to 700 µm, however, for efficient generation of aerosols, the surface tension of the solution may not be higher than 50×10^{-3} N/m. The solution conductivity should be in the range of 10^{-4} to 10^{-8} S/m (Chen & Basaran, 2002; Ganan-Calvo, 1997; Jaworek, 2007) and the maximum solution flowrate around 30 mℓ/h (Jaworek, 2007). More recently, Agostinho, Yurteri, Fuchs, and Marijnissen (2012), Agostinho (2013) employed electrospray to generate fine aerosols, from water with surface tension approximately 70×10^{-3} N/m, for thermal desalination application. Nonetheless, we note that a mechanical pump was used in their system to pump the liquid through the needle at a sufficiently high flow rate that was able to generate liquid jets even without the electric field. Therefore, this technique may not be suitable for a portable system due to the requirements of high electric field and the mechanical pump.

On the other hand, one of the techniques that can be categorized as the *without*-nozzle type is via high-frequency vibration of a substrate to generate fine aerosols from a liquid film. The piezoelectric transducer (Vukasinovic et al., 2004, 2007) or surface acoustic wave device (Chono, Shimizu, Matsui, Kondoh, & Shiokawa, 2004; Collins et al., 2012; Qi et al., 2008; Rajapaksa, Qi, Yeo, Coppel, & Friend, 2014) can be used to generate high-frequency mechanical vibration, which then transmits into the liquid atop the transducer. The transmitted acoustic energy in the liquid inducing capillary wave at the liquid-air interface, destabilizing it at a sufficiently high acceleration and leading to the generation of fine aerosols. One of the major advantages of the *without*-nozzle type is the ability to generate aerosols from contaminated solutions without having clogging issue as it does not involve any tiny nozzles (Rajapaksa et al., 2014; Vukasinovic et al., 2004) and the rate of aerosol generation is comparable to that *with*-nozzle type, i.e., approximately 10 m ℓ/s (Rajapaksa et al., 2014).

In this study, the focus is on the experimental investigation of an efficient technique to generate fine aerosols using brine, i.e., solutions with a high concentration of salt, at ambient atmospheric pressure. We note that the generation of fine aerosols, which can promote rapid heat transfer and evaporation due to the large surface to volume ratio, is an essential step in thermal-based desalination processes. Additionally, the ability to generate fine aerosols at ambient atmospheric pressure is important for the future development of an efficient portable desalination system. Therefore, the *without*-nozzle type, which uses the mechanical vibration to generate fine aerosols, is proposed here. The setup is relatively simple; the piezoelectric transducer is connected to a focusing tip, and upon application of a sinusoidal electrical wave, it generates a mechanical vibration that propagates along the tip and transmits into the brine, leading to a rapid generation of fine aerosols. We quantify the rate of aerosol generation at different power inputs and different concentrations of salt. Most importantly, continuous generation of fine aerosols using the brine for an extended period is conducted to ensure the reliability of this technique.

2. Experiment

Fig. 1(a) illustrates the experimental setup. The piezoelectric transducer (AE0505D18F, Thorlabs, United State) was bonded to the aluminum focusing tip using high-temperature epoxy resin (UHTE-S320, Incure, Singapore) and cured at 90 °C for two hours. For the transducer actuation, a sinusoidal electric signal generated from a function generator (TG5011, TTi, UK) was amplified using an amplifier (SN066801303, Mini-Circuits, USA) and subsequently applied to the piezoelectric transducer. The frequency of the signal was set to match the resonance frequency of the piezoelectric transducer, which was $f_e = 89.5$ kHz. The aluminum focusing tip was fabricated with a base diameter of 7 mm and a cylindrical tip of 1 mm in diameter at the top, with an overall height of 30 mm, as shown in Fig. 1(b). The 1 mm diameter cylindrical part of the focusing tip was inserted through a 1.5 mm hole in the aluminum supporting plate (with 1 mm protrusion) to provide a clearance between the tip and the sidewall. The mechanical vibration generated from piezoelectric transducer was focused to the top of the tip and subsequently transmitted into liquid surrounding the focusing tip. Cleanroom paper (porous media) (WIP-100DLE, Sourec, Malaysia) was used to deliver deionized (DI) water from the liquid reservoir to the vibrating tip through capillary effect. A thin liquid film was formed around the vibrating tip, where the fine aerosols were generated. Total input power, P_e, to the transducer was quantified using $P_e = V_{rms} I_{rms}$, where V_{rms} was the rms values of input voltage and I_{rms} was the rms values of the input current. The rms voltage and current were measured using voltage probe (Tektronix TPP 0201) and AC current probe (Tektronix P6022), respectively, and these probes were connected to an oscilloscope (Tektronix TDS 2012C).