International Journal of Multiphase Flow 88 (2017) 99–115

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Atomization of liquids by disintegrating thin liquid films using gas jets

Maksim Mezhericher[a,b,*], Izhak Ladizhensky[a], Isaac Etlin[a]

[a] Center for Energy and Numerical Simulations, Department of Mechanical Engineering, Shamoon College of Engineering, 56 Bialik Str., Beer-Sheva, 8410802, Israel

[b] Department of Mechanical and Aerospace Engineering, School of Engineering and Applied Science, Princeton University, Princeton, NJ 08540, USA

ARTICLE INFO

Article history:
Received 25 October 2015
Revised 20 June 2016
Accepted 18 July 2016
Available online 23 September 2016

Keywords:
Atomization
Bubble
Droplet formation
Froth
Gas jet
Thin liquid film
Micro-spray

ABSTRACT

Liquid atomization is useful in many applications, such as engineering, science, pharmaceutics, medicine, forensics and others. In the present research, an innovative methodology and a new device for atomization of liquids into mists of micron and submicron droplets have been developed. The new liquid-atomization method exploits the physical phenomenon of fragmentation of thin liquid films into fine micron and submicron droplets by gas jets. For several tested prototypes, the direct observations using a high-speed visualization technique have demonstrated that bubbles were generated within a liquid and their shells have been subsequently destroyed by applying a mechanical impulse (pressure of a compressed air) once the bubbles came over the liquid surface. The main characteristics of the generated tap water mists have been experimentally measured by means of the laser diffraction technique under various conditions for each prototype. One of the prototype devices allowed obtaining mists containing 90–99% of droplets smaller than 1 µm, with the minimum arithmetic and Sauter mean droplet diameters of 1.48 µm and 2.66 µm, and the 2.64 ml/min of droplet flow rate for 3.5 bar manometer pressure of atomizing air. The gas to liquid mass ratios (GLR) in the new device are depending on the atomizing tube length and the number of perforated orifices in the tube: more the tube length, hence more the number of perforated orifices, and therefore more liquid droplets will form for the same gas flow rate. The measured GLR values related to 1 m length of the utilized atomizing tube were in the range of 0.65–1.06, and for the specifically utilized atomizing tube of 72 mm length were among 9.07–14.67. The results of this study demonstrate that the developed method of generation of very fine droplet mists has many advantages over the existing techniques and can be perspective for many practical applications.

1. Introduction

Micron and sub-micron droplets and functional particles suitable for delivery, controlled release, protection, and masking active ingredients are actively used in pharmaceutical, food, cosmetics, medicine, chemical and agricultural applications. Liquid atomization and spraying of droplets are widely utilized in particle technology: the droplets can either be subjected to drying (spray drying, spray freeze drying, supercritical fluid drying), or used for agglomeration/coating of core particles (spray-fluidized bed drying/coating), or involved into a chemical reaction at high temperature (aerosol flow reactor) (Chan and Kwok, 2011). Droplets of low-electrical conducting solutions are obtained for subsequent processing by electro-spray drying/coating/deposition technologies. Apart from the particles production, sprays of droplets, owing to their high surface to volume ratios, are widely utilized for fabrication of functional films, generation of medical aerosol dispersions for nasal, throat, alveoli and ocular drug delivery, injection of fuels in combustors and internal combustion engines, electrospray printing, cooling/heating of surfaces and fluid media, coating of surfaces, fragrance and moisture spreading, dust and contaminants removing from air and many other applications.

Recent progress in engineering and science demonstrates stable trends of micronization and nanonization of production methods and growing demand for micro- and nano-products. This tendency is also observed in the field of atomization techniques where the efforts are concentrated on obtaining submicron and nano-droplets (Abate et al., 2011; Booth et al., 2012; Kemp et al., 2013a; Kemp et al., 2013b; Li et al., 2010; Thiele et al., 2011).

In nature, droplets of aerosols may typically form by bursting of single or multiple bubbles at liquid surface (Duchemin et al., 2002; Guezennec et al., 2004; Gunther et al., 2003; Lhuissier and Villermaux, 2012), spouting that accompanies respiration of marine cetacean mammals (e.g., dolphins, whales, killer whales) (Cresswell et al., 2007; Scammon, 1968) and sneezing and cough of humans and animals (Ferrara, 2010).

E-mail addresses: maksime@ac.sce.ac.il, maskymm@princeton.edu, maksim.mezhericher@gmail.com (M. Mezhericher).

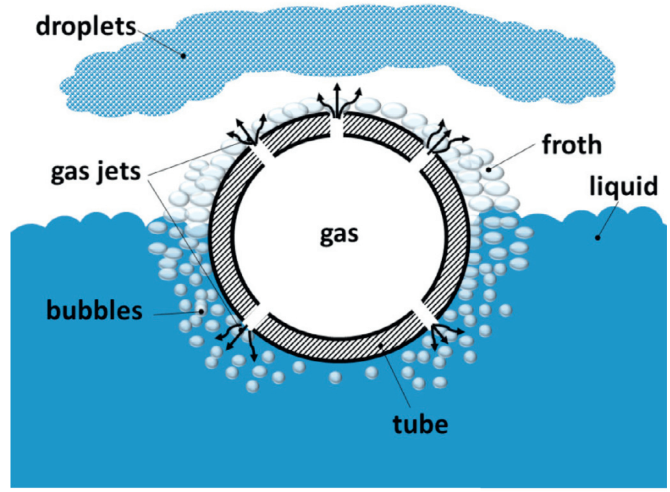
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.07.015
0301-9322/

The known artificial methods and devices for liquid atomization into droplets, sprays of droplets and fine mists can be generally subdivided into (Ashgriz, 2011; Booth et al., 2012; Drazil et al., 1978; Lefebvre, 1989): spray nozzles (including twin-fluid nozzles: air-blast, air-assist, effervescent; hydraulic nozzles: plain orifice, flat fan, solid stream; rotary nozzles: vaneless disk, vaned disk, rotary cup, twin-fluid rotary; swirl nozzles, ultrasonic wave nozzles and electrostatic nozzles), rotating discs; droplet generators (bubble jet, piezoelectric, acoustic, pneumatic, microfluidic, electro-hydrodynamic, aerodynamic); nebulizers for inhalation; analytical nebulizers; other atomizers - pintle injector, cross-flow liquid jet atomizer, impinging jet atomizer, splash plate atomizer, flash evaporation atomizer and rotating film atomizer. Additional methods of direct production of droplets include generation of droplets from thin liquid films by subjecting such films to either cross-coming gas jet (Kontush et al., 2003; Snyder and Reitz, 1999; Snyder and Reitz, 1998) or gas bubbles (Bekshaev et al., 2003; Feng et al., 2014) or shock-waves (Bremond and Villermaux, 2005).

The major drawbacks of the aforementioned methods for production of submicron and nano-droplets is either demands of high atomization energy (Kemp et al., 2013a; Kemp et al., 2013b), or high temperature and boiling of liquid (Booth et al., 2012), or presence of electro-magnetic fields and ultrasonic waves (Suslick, 1988; Suslick, 1989), or big droplet sizes, or low droplet flow rates, or wide distribution of droplet sizes, or poor scalability, or low flexibility and controllability. In addition, specific costs of submicron and nano- atomization (expenses on atomization per effective atomization flow rate) are typically high and such atomizing devices may require elaborate manufacturing processes.

Fabrication of ordered particle microstructures, micro-encapsulation and coating of micro-particles is nowadays performed by many methods and is being extensively studied both theoretically and experimentally (Lin, 2012; Mittal, 2013). Many of the techniques for high throughput production, especially dealing with organic and pharmaceutical materials, utilize sprays of droplets and particles, and thus the revealed drawbacks of liquid atomization are presented in these technologies as well.

Therefore, development of simple in manufacturing, low cost, low energy consuming, ecological, high-throughput way of generation of submicron and nano-droplets is required for further progress of technology and science. For particle technology, the new liquid-atomization method should be compatible with production of particle microstructures, encapsulation and coating of micro-particles.



(a)

(b)

Fig. 1. New concept of liquid atomization: production and disintegration of thin liquid films using gas jets. a – sketch of the new atomization method (Mezherichery et al., 2015), showing vertical cross-section of perforated tube partially submerged in liquid; b – photograph of a low-cost prototype device in operation (a video record of the prototype in operation is available at https://sites.google.com/site/maxmezhome/research).

2. Objectives

The main objective of this study was to investigate the feasibility of generation of mists of fine droplets by new atomization method. The method involves production and disintegration of thin liquid films in the form of froth by gas jets. Within the framework of this research, experimental visualization of the new process was performed, and generated size distributions and flowrates of droplets and atomizing air were examined.

3. Experimental

A prototype new liquid-atomization device implementing our original invented method of fine droplets generation from thin liquid films disintegrated by gas jets has been constructed. The main part of the device was an elastic rubber tube of 11 mm in diameter. The 2 mm walls of the tube were perforated with 0.6 mm orifices along the tube circumference at several axial positions. The tube was horizontally oriented and partially submerged into a vessel filled with tap water: the lower portion of the tube was immersed in the liquid, and the upper portion of the tube was exposed to the environment, see Fig. 1a. The tube was connected to a source of compressed air, and the supplied air was continuously discharging through the perforated orifices. The compressed air, released through the submerged lower part of the tube, formed ensembles of small bubbles, which came up to the liquid surface and created a froth - ensembles of thin spherical liquid films (estimated thicknesses is less than 500 nm (Geguzin, 1985)) in the vicinity of the tube upper part. Subsequently, the air discharged through the upper orifices broke and disintegrated these liquid films into ensembles of fine droplets (mist/spray). In one of the constructed prototypes, the atomizing perforated rubber tube was placed into a plastic vessel which had dimensions 25 cm (height) x 8 cm (length) x 4 cm (width) and a circular outlet of 1–1/4″ at its upper horizontal wall. An elbowed PVC pipe of 17 cm length and a transparent plastic confusor of 10 cm length having 3 cm outlet diameter were connected to the vessel outlet enabling horizontal outflow of droplets and gas from the container. The atomizing tube was horizontally fixed at 9 cm from the bottom of