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Toward the design of low flow-rate multijet impingement spray atomizers

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ABSTRACT

When setting the baseline for discussing options toward a more efficient use of water resources, one of the drivers for decoupling economic growth and environmental impact is the development of resource-efficient innovations and instruments. One of such fields of interest is the design of water efficient showerheads, which provide a good shower experience, while consuming low flow rates (<3 l/min), and potentiating energy savings for heating water. As a step forward in this challenge, the approach followed in this work is motivated by the need to develop tools for designing tailored sprays toward a high degree of efficiency in water usage. However, in order to design tailored sprays, it is important to establish a proper relation between the atomizer's geometric configuration, operating conditions and the desired characteristics for the spray droplets (size and velocity). Therefore, this work focus on this tailoring through a multijet impingement atomization strategy using 2 and 3 impinging jets. An investigation is reported on the parametric effects on the dynamic characteristics of droplets of jet-impingement angle (40–90°) and pre-impingement distances (2.5–7.5 mm), for a range of jet Weber numbers ($20 < We_j < 500$). The size of droplets is measured by image analysis, and their velocity by a Particle Tracking Velocimetry algorithm. The results evidence the similarities between droplet characteristics of sprays produced by 2- and 3-impinging jets, although the geometric effects induced by the jets' impingement angle are more relevant for the 3-impinging jets spray, while negligible for the 2-impinging jets spray. Moreover, empirical correlations for the arithmetic (d_{10}) and Sauter (d_{32}) mean diameters, normalized by the jet diameter (d_j), as well as drop velocity normalized by the jet velocity (u_d/u_j) are devised as tools for designing tailored multijet impingement sprays for low-flow rate water applications.

1. Introduction

Multijet impingement atomization can be argued as a strategy with the advantage of producing tailored sprays through an appropriate design of the atomizer. Also, compared with free jet atomization, it enables liquid mixing and requires lower injection pressure at nozzle exit to obtain a certain drop size, for example, relatively to the free jet strategy applied in Diesel sprays. The multijet spray is produced from the single point coincidence of two or more cylindrical jets, forming a liquid sheet. This later further destabilizes in its bounding rim into ligaments, or interacts with the surrounding air in such a way as to detach into ligaments. These further fragment into droplets, thus constituting the spray. Most of the research performed in this atomization strategy is focus on the impingement of two jets [1]. But, one may wonder whether there are any advantages, or not, if more than two jets are considered to produce the spray. In previous works, multijet sprays produced with 2, 3 and 4-impinging jets have been applied for thermal management [2–4], and drop dispersion patterns have presented some geometric features, depending on the number of impinging jets [5], which is a feature distinguishing these sprays from the usual ones based on circular, annular or elliptical patterns. Moreover, the characteristics of droplets (size and velocity) did not appear to change significantly between the impingement of two, and more than two jets, requiring more fundamental work to provide further insight into the hydrodynamics underlying the atomization process using more than two jets. This is one of the aims of the present work considering the impingement of 2 and 3 jets.

The work here follows a previous one [6] and is also aimed at finding the tools toward a proper design of tailored multijet sprays, which depends on the characterization of droplets dynamics (size

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and velocity) and what are the effects of geometry and operating conditions on these characteristics. The common approach to develop these tools is to devise appropriate correlations between design parameters and droplets' mean characteristics. This will be briefly reviewed in the following subsection. Afterwards, Section 2 describes the experimental setup, as well as the method used to characterize drop size and velocity. The following section contains the analysis of the results and discusses them from the point of view of liquid sheet morphology, and droplets characteristics, taking into account some of the theoretical work reviewed in Section 1.1. The empirical approach to characterize drop size is taken into account and analyzed to retrieve further insight into the underlying physics of multijet atomization. A similar analysis is done for droplet velocity, rarely considered in the literature. The paper ends with some concluding remarks containing the general effects of geometry and operating conditions on the outcome of multijet atomization made with 2 and 3 impinging jets.

1.1. Empirical correlations for droplet characteristics

In order to design tailored multijet sprays, it is important to establish a proper relation between the atomizer's geometric configuration, operating conditions and the desired characteristics for spray droplets (size and velocity), in order to develop appropriate tools. Usually, these take the form of empirical correlations for mean drop size, and there are several approaches to its modeling in multijet impingement sprays. One of the first empirical correlations for the Sauter mean diameter (d_{32}) reported by Dombrowski and Hooper [7] is expressed as

$$\frac{d_{32}}{d_j} = \frac{4}{u_j^{0.79} \sin\theta^{1.16}} \tag{1}$$

where d_j and u_j are the jet diameter and average velocity and θ is the half-impingement angle. This correlation has been derived considering a normalized pre-impingement distance of $l_{pi}/d_j = 4$, $\mathrm{We}_j \in [370; 2635]$ and $2\theta \in [50^\circ; 140^\circ]$. The powers associated with u_j and θ are different to account for the influence the later has on the former, as well as on the liquid sheet thickness. In Tanasawa et al. [8], instead of considering variations of the jet impingement angle, different jet diameters (d_j) are taken into account (0.4–1 mm), thus obtaining the correlation for a jets impingement angle comparable to [7]

$$\frac{d_{32}}{d_j} = \frac{1.73}{\rho_a^{0.1}} \mathrm{We}_j^{-1/4} \tag{2}$$

with σ, and ρ as the liquid surface tension and density, respectively, and ρ_a as the density of the surrounding environment. Recently, a dimensionless empirical approach has been proposed by Durst et al. [9] where the Sauter mean diameter is normalized by the jet's diameter and empirically correlated with a function of the half-impingement angle $f(\theta)$ and a function of both Ohnesorge $\left(\mathrm{Oh}_j = \mu/\sqrt{\rho\sigma d_j}\right)$ and Reynolds numbers $(\mathrm{Re}_j = \rho u_j d_j/\mu)$, $g(\mathrm{Oh}_j, \mathrm{Re}_j)$, generally expressed as

$$\frac{d_{32}}{d_j} = a \cdot g(\mathrm{Oh}_j, \mathrm{Re}_j) \cdot f(\theta) \tag{3}$$

On the one hand, the aforementioned correlations are relevant in the sense that d_{32} is a mean diameter expressing the relation between the volume and surface of a droplet, which is particularly important when heat transfer processes are considered. On the other hand, for the arithmetic mean diameter (d_{10}), based on a sheet instability analysis delineated by Dombrowski and Hooper [10], Ryan et al. [11] have presented a correlation for turbulent liquid jets expressed as

$$d_{10} = \left(\frac{2.62}{\sqrt[3]{12}}\right)\left(\frac{\rho_a}{\rho}\right)^{-1/6} \left(\mathrm{We}_j \cdot f(\theta)\right)^{-1/3} \tag{4}$$

where We_j is the Weber number $\left(= \rho u_j^2 d_j / \sigma\right)$, and $f(\theta)$ is a function given by $f(\theta) = (1-\cos(\theta))^2 / \sin(\theta)^3$. Despite Ryan et al. [11] have limited the empirical approach by opting for a dimensional format, the result is interesting in the sense that it points to the weak inverse dependence on the scaling parameter $\mathrm{We}_j f(\theta)$.

Other empirical correlations can be found in Ashgriz [1], generally involving parameters related with the jet diameter and velocity, and the half-jet-impingement angle θ. However, the jet velocities in these correlations are usually high, implying that these correlations are limited to operating conditions where atomization mechanisms often depart from the turbulent liquid sheet category.

1.2. Brief theoretical considerations

A more theoretical model for predicting the size distribution of droplets has been devised from the early analysis on the aerodynamic disintegration of viscous liquid sheets by Dombrowski and Johns [12], considering the growth rate of instabilities in long waves. Through a mass balance between a drop and the fraction of ligament from which it is generated, droplet size can be expressed as a function of liquid properties and the diameter of that ligament fraction (d_L) as

$$\frac{d_d}{d_L} = \left(\frac{3\pi}{\sqrt{2}}\right)^{1/3}\left[1 + \frac{3\mu}{\sqrt{\rho\sigma d_L}}\right]^{1/6} \tag{5}$$

Based on a non-linear model for impinging jet atomization, Ibrahim and Outland [13] suggested that ligaments disintegrate from the liquid sheet twice per wavelength and that the sheet thickness at breakup is $2h$, thus $\frac{\pi}{4}d_L^2 = \frac{1}{2}\lambda(2h) \iff d_L = \sqrt{\frac{8h}{k}}$. If this result is included in the theoretical model developed by Dombrowski and Johns [12], the ligament characteristic diameter d_L is expressed as

$$d_L = 0.9614\left[\frac{K^2\sigma^2}{\rho_a \rho u_j^4}\right]^{1/6}\left[1 + 2.60\mu\sqrt{\frac{K\rho^4 u_j^7}{72\rho^2\sigma^5}}\right]^{1/5} \tag{6}$$

where K is the thickness parameter given by the product of the liquid sheet thickness h and the radial distance to the liquid sheet bounding rim r, which according to Hasson and Peck [14], considering an elliptic impingement region, results in

$$K = \frac{R^2 \sin\theta^3}{(1-\cos\phi\cos\theta)^2} \tag{7}$$

or, if the impingement region is considered circular, according to Ibrahim and Przekwas [15], the thickness parameter becomes

$$K = \frac{R^2 \beta \exp\left(\beta(1-\phi/\pi)\right)}{\exp(\beta) - 1} \tag{8}$$

where β is a coefficient determined by conservation of mass and momentum, and it is numerically determined according to [15] by

$$\cos\theta = \left(\frac{\exp(\beta)+1}{\exp(\beta)-1}\right)\frac{1}{1+(\pi/\beta)^2} \tag{9}$$

In the visualization performed in this experimental work, a closer observation of the jet impingement region supports the approach of a circular impact. Moreover, it is noteworthy that applying Eqs. (8) and (6) in (5), the variable parameters are the azimuthal angle ϕ, the jet velocity u_j and the half-impingement angle between the jets θ. A closer analysis of Eq. (5) shows that the azimuthal angle evidences how droplets produced at $\phi = 0$ are esti-