Analysis of the transient atomization characteristics of intermittent multijet sprays

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Abstract This paper analysis the transient characteristics of intermittent sprays produced by the single-point impact of multiple cylindrical jets. The aim is to better understand the effect of varying the number of impinging jets in the atomization process, considering intermittent sprays which allow a more accurate control of the flow rate. Some considerations are made relatively to the applicability of intermittent multijet sprays for spray cooling. The results presented evidences that hydrodynamic mechanisms underlying the physics of ligament fragmentation in 2-impinging jets sprays, in the turbulent sheet regime because of required short atomization distances, also apply to sprays produced with more than 2 jets. Edge and detached ligaments have been identified and were associated with distinct droplet clusters, which become more evident as the number of impinging jets increases. This has been supported by size-velocity correlations and droplets produced by detached ligaments found predominant, as well as their axial velocity which becomes more uniformly distributed with 4-impinging jets. Multijet spray dispersion patterns suggest the potential geometric nature associated with these sprays, depending on the number of impinging jets. And, finally, the Weber number range suggests that multijet sprays are more likely to deposit on interposed surfaces, thus, becoming a promising and competitive atomization solution for improving spray cooling.

1. Introduction

A considerable number of applications uses spray impingement to deposit liquid onto a solid surface, such as spray painting, spray cooling, shower sprays and others, however, such deposition depends on hydrodynamic mechanisms after drop impaction, namely, smaller and slower impinging droplets are more likely to deposit due to their lower impact energy. Otherwise, if the impact energy is relatively high, a secondary atomization could be induced by splashing type mechanisms and the liquid deposition is less efficient. The motivation for this work is to investigate an atomization strategy which produces small, slow and well dispersed droplets at short impact distances with the aim of depositing liquid for spray cooling purposes. The strategy considered is referred as multijet atomization, consisting in the production of a spray from the single-point impact of multiple cylindrical jets. Additionally, the efficiency of depositing liquid onto a solid surface depends on the accurate control of the flow rate and a way to do it intelligently, while keeping pump pressure constant is to have the atomizer spraying the liquid intermittently by proper matching the frequency with the duration of injection. Therefore, the work considers intermittent multijet sprays.

Most authors focus their research on sprays produced from the impingement of two jets. In fact, when two cylindrical jets collide on a single-point, a liquid sheet forms in a plane perpendicular to that of the jets. Instabilities in this liquid sheet further disrupt into ligaments and, subsequently, into droplets through capillary instabilities at the sheet’s boundary rim, or through the interaction of waves propagating from the point of jet impact with the surrounding air, such as Kelvin-Helmholtz instabilities (Li and Ashgriz, 2006). Since there is a limited availability of detailed analysis on multijet spray with more than 2 jets, it is the aim of the present work to quantify its characteristics as it develops in time and distance and identify the main differences relatively to the number of impinging jets. Namely, the analysis considers the effect of intermittency on ligament fragmentation processes, size-velocity correlations and, finally, the applicability of intermittent multijet sprays for
deposition.

2. Experimental setup

Three prototype atomizers have been built with the same impact angle (θ = 90°). The exit holes are equally spaced (ψ), as shown in Fig. 1, and the length to diameter ratio of this hole is kept constant (Lh/Dh = 7.5 with Dh = 400 μm). The atomizer is attached to a Parker Miniature (Series 99) electromechanical valve and the TTL pulse which opens it and closes is controlled by an NI5411 arbitrary function generator. The spray intermittency in these experiments considers a fixed duty cycle of 40 % and an injection frequency of 10 Hz.

Following our previous research on the application of multiple-jet sprays for thermal management in electronic devices, the liquid is methanol, due to its dielectric properties, which thermophysical properties are (Tamb = 23°C): density (ρ = 788 kg·m⁻³), surface tension (σ = 22.4 mN·m⁻¹), dynamic viscosity (μ = 5.81×10⁻⁴ kg·m⁻¹s⁻¹).

The spray characterization is made with a Phase-Doppler Interferometer from DANTEC Dynamics, allowing local time-resolved simultaneously measurements of droplet size and velocity. The system consists of a 55X transmitting optics, a 57x10 PDI receiving optics, oriented at 30° for maximizing the signal visibility, and a 58N10 Covariance processor, as illustrated in Fig. 2. The optical configuration of the system is summarized in Table 1. According to Panão and Moreira (2008), the inaccuracy in the discrete drop distributions used to calculate average quantities of drop size and velocity in the phase-average analysis follows an information theory approach where the standard deviation of the average residual value (σᵣ) between the discrete cumulative distribution given by the sample size in each time-bin and its ‘true’ cumulative distribution is correlated with the normalized information entropy of the discrete distribution (Hᵣ) as

$$\sigmaᵣ = 21.02 - 22.31Hᵣ^*$$

$$Hᵣ^* = H(p) · H_{max}^{-1} = \sum_{k=1}^{N_{bias}} p_k \ln(p_k) · (\ln(N_{bias}))^{-1}$$

(1)

$$N_{bias} = J · \ln(\text{sample size}) · \ln(1.618)^{-1}$$

where p_k is the probability associated with a certain size class and J is the number of interlaced Fibonacci series (more details are referred to Panão and Moreira, 2008). The average residual errors σᵣ were smaller than 8% for size and smaller than 12% for the drop velocity.
The information on the size and velocity of droplet is captured at several distances from the impact point for each experimental condition (as schematically shown in Fig. 3), using a measurement grid, which adequacy depends on the data rate of measured droplets, i.e. when its value decreased by less than 10% of the maximum data rate obtained for a given operating condition.

**Table 1. Optical configuration of the Phase-Doppler Interferometer**

<table>
<thead>
<tr>
<th>Transmitting optics</th>
<th>Receiving optics</th>
<th>Processor Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>Collecting angle</td>
<td>U and V signal bandwidth</td>
</tr>
<tr>
<td>Wavelengths</td>
<td>focal length</td>
<td>12 MHz</td>
</tr>
<tr>
<td>Beam spacing</td>
<td>500 mm</td>
<td>S/N validation</td>
</tr>
<tr>
<td>focal length</td>
<td></td>
<td>-3 dB</td>
</tr>
<tr>
<td>Frequency shift</td>
<td></td>
<td>Spherical validation</td>
</tr>
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<td></td>
<td></td>
<td>10%</td>
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**Fig. 3.** Indication of characterization plane and an example of measurement grid for a 2-impinging-jets spray at $Z = 20$ mm and the experimental conditions considered.
3. Results and discussion

In this work, the results and analysis focus on the differences and similarities between the sprays produced with a different number of impinging jets ($N_j$). Firstly, an important feature in multiple impinging jet sprays is the regime of the impinging jet (laminar or turbulent). Since a short distance atomization is desired, consequently, short breakup lengths, turbulent jets are preferable over laminar jets (Dombrowski and Hooper, 1964; Anderson et al. 1994). The detail of the turbulent jets used in the multijet sprays considered in this work is depicted in Fig. 4, along with an image of the spray produced by 2, 3 and 4 impinging jets. According to Li and Ashgriz (2006), with $N_j = 2$ a turbulent sheet is formed for $Re_j > 3000$, which is the case presented here and confirmed through the visualization of the corresponding spray where it is also possible to identify three typical characteristic hydrodynamic structures: edge and detached ligaments; and surface wave patterns (Anderson et al., 1994). Edge ligaments are strands of liquid attached to the intact sheet periphery, while detached ligaments are strands of fluid either completely or nearly completely apart from the downstream edge of the sheet propagation front (see Fig. 4). It could also be inferred from Fig. 4 that edge ligaments apparently produce smaller droplets while the disintegration of detached ligaments results in larger droplets. Such characteristics are still present in the $N_j = 3$ spray, however, in the $N_j = 4$ case edge ligaments scarcely appear in the image. Also, the dispersion angle of droplets appears quite large with $N_j = 2$ and droplets move in all possible directions, while gradually, as the number of jets increases, such dispersion angle decreases implying the production of a more compact spray.

In these experiments, the size and velocity of each jet is maintained, regardless their number, under the assumption that the hydrodynamic mechanisms triggering atomization would be the same, or at least similar, in all atomizers. The research question at this point is to investigate the influence of the number of jets in these mechanisms using the analysis on $N_j = 2$ as reference since it is the study-case most reported in the literature. Following this transient analysis of the fragmentation process and size-velocity correlations, some considerations are made on the practical significance of the results obtained for spray cooling applications.

3.1. Transient analysis of the fragmentation process

Since we are dealing with a fragmentation process, through a backward analysis formalism developed for $N_j = 2$, an attempt is made to assess if the results of applying it to the cases with 3 and 4 jets are consistent or not, and in the positive case how such analysis may improve the knowledge of the atomization strategy considered. Villermaux (2007) has made a comprehensive review on the fragmentation process in terms of ligament dynamics and suggested an approach to describe droplet formation from a statistical point of view where each isolated ligament is covered with blobs of
various diameters matching its local thickness (see the example in Fig. 5).

![Fig. 5 Example of detached ligament covered with blobs of various diameters (left); example of liquid sheet formation in the free space between 3 impinging jets (right).](image)

Considering that each time-bin in a phase-average analysis is much larger than the capillary time based on the initial average blob size ($t_c = \sqrt{\frac{\xi^3}{\sigma}}$), where $\xi$ is the initial average blob size, the way to compare the atomization with 2, 3 and 4 impinging jets is through the spatial distribution of the ratio between the average blob diameter $\langle d \rangle$ at time $t$ (equivalent to the arithmetic mean diameter) and the initial average blob diameter $\xi$, $\langle d \rangle / \xi$. These maps correspond to a certain time-bin after the start-of-injection (ASOI).

Firstly, Villermaux (2007) has derived analytically that the distribution of blobs inside a ligament can be described by a Gamma distribution function as

$$p_B(d) = \frac{n^n}{\Gamma(n)} \left( \frac{d}{\langle d \rangle} \right)^{n-1} \exp \left( -n \frac{d}{\langle d \rangle} \right)$$

(2)

where $\langle d \rangle$ is the current blob diameter which could be approximated by the mean diameter $d_{10}$ of our measurements and $n$ is the order of the Gamma distribution associated with the number of independent layers resulting from random motions in the ligament. The mean drop size can also be interpreted as the number of blobs at time $t$, $N(t)$, distributed by the ligament’s length $L(t) = \int n(d,t) \cdot d\tilde{d}d$ and given by

$$\langle d \rangle = \frac{L(t)}{N(t)} = \frac{\int n(d,t) \cdot d\tilde{d}d}{N(t)}$$

(3)

Considering the interaction parameter $\zeta$ determined by a relation between the initial distribution of blobs and the initial average blob size, it could be related to $n$ as $\zeta = 1 + 1/n$. While a uniform thread of constant thickness, made of many thin layers, has $\zeta = 1$, a corrugated ligament has $\zeta > 1$. According to Villermaux (2007), this implies that $n \rightarrow \infty$ correspond to smooth and uniform ligaments, giving rise to narrower size distributions around $\xi$ and one obtains

$$\frac{\langle d \rangle}{\xi} \sim \exp \left( \frac{1}{n} \right)$$

(4)
Otherwise, one has corrugated ligaments and

\[
\frac{\langle d \rangle}{\xi} \sim N(0)^{1/3} n^{-n/3}
\]  

(5)

where \(N(0)\) is the initial number of blobs in the ligament, correlated with \(N(t)\) as

\[
N(t) = N(0) \left[ 1 + N(0)^{1/3} \frac{t^*}{n(1 + n/3)} \right]^n
\]

\[
t^* = t / t_\xi
\]

(6)

and, according to Villermaux (2007), an average diameter relatively to \(\xi\) proportional to \(N(t)\) as

\[
\frac{\langle d \rangle}{\xi} \sim N(t)^{-1/3}
\]

(7)

However, Eqs. (5-7) imply that \(\langle d \rangle/\xi\) can only be solved recursively. Therefore, in order to apply Eqs. (4) or (7), it is essential to establish above which critical value can \(n\) be considered infinite. Assuming that \(t^*\) remains constant, for a certain critical value \(n_{\text{crit}}\), its value is searched in such a way as Eqs. (4) and (7) produce the same result at \(n_{\text{crit}}\). It has been verified that above \(n_{\text{crit}} = 10000\), \(t^*\) does not change significantly and is equal to 2.9988.

Assuming the blob size distribution is equivalent to the size distribution of droplets resulting from the fragmentation of the ligament, \(n\) is obtained from the analytical solution for the Sauter mean diameter in a Gamma distribution as

\[
\langle d \rangle = 10^{32} 10^{d_d} = \text{constant}
\]

The transient analysis of the intermittent spray considers the distribution of \(\langle d \rangle/\xi\) at 11.5 and 30.5 ms ASOI, each representing the injection periods at the initial stage of multijet atomization and another within the main period of injection, respectively. During these periods the spray is mainly formed through ligament disintegration. It is noteworthy that the mean drop size only enters calculations through \(n\), which in turn is a characteristic parameter associated with the entire distribution of droplets, implying that Figs. 6a-c is showing relatively independent results. Namely, \(\langle d \rangle/\xi\) maps stand for the spray while disintegrating whereas \(d_{10}\) represents the spray after disintegration.

The contour plots of \(\langle d \rangle/\xi\) and \(d_{10}\) in the initial stage of injection confirm that multijet sprays are no exception for the poor atomization typically verified for this period. Also, intuitively, after jet impact, liquid sheets are expected to freely develop in the space between the impinging jets, as shown in the images of Fig. 4, with \(N_j = 2\) developing a liquid sheet in the perpendicular direction of the plane defined by the jets (its rotation is explained in section 3.3) and depicted on the right side of Fig. 5 for \(N_j = 3\). From the images it seems reasonable to assume that the spray is mainly formed by detached ligaments instead of edge ligaments, and that the average thickness of detached ligaments, relatively to the initial average blob size \(\xi\), approaches the same order of magnitude, implying that \(\langle d \rangle/\xi\) would be closer to one, as evidenced in the results depicted in Figs. 6a, b within the main injection period for 2 and 3 impinging jets.

The results for \(d_{10}\) depicted in Figs. 6a-c also enable a better perception of the relation between average blob sizes in ligaments and their outcome when disintegrated, namely, that higher values of \(\langle d \rangle/\xi\) in outer regions of the spray imply a poorer atomization expressed by larger mean drop
sizes. The consistency of values between atomizers suggest that linear stability models underlying the physics of ligament formation and breakup into droplets developed for 2 impinging jets may be applied to predict spray formation with 3 and 4 impinging jets, although some differences have been observed in the relative importance between distinct ligament types as the number of impinging jets increases. The time representing a period after the injector closes is not depicted because the absence of jet impaction implies a null ligament formation from that time onward.

Fig. 6 (a) For $N_j = 2$, distribution of the ratio between the average blob size $\langle d \rangle$ and the average blob thickness $\xi$ for $t = 11.5$ ms (LFS) and 30.5 ms (SS) [top]; Distribution of $d_{10}$ for the same times $t$ [bottom].

3.2. Transient characteristics of an intermittent multijet spray

In intermittent sprays one may identify three typical periods within the entire injection cycle: the Leading Front of the Spray (LFS), the Steady Spray (SS, main period) and the Spray Tail (SS) (Abo-Serie et al., 2003; Panão et al., 2009). After having accurately delimited these periods (more details can be found in Panão et al., 2010), the joint probability distribution function of droplet’s axial velocity ($u_d$) and size ($d_d$), normalized by the jet velocity ($u_j$) and diameter ($d_j$), respectively, provide useful information for further comparison between atomizers (Fig. 7). In the LFS period, the size-velocity correlation has two clusters. The first a satellite cluster with a relatively low size polydispersion around small axial velocity values and a second main cluster where a larger size polydispersion is correlated with higher drop axial velocity values as well. The presence of the satellite cluster may be typically attributed to droplets which remain suspended in air between consecutive injection cycles (Hardalupas, 1992, Panão and Moreira, 2004) and the results in Fig. 7 evidence its gradually reduced importance with an increase of number of jets.
Fig. 6 (b) For $N_{j} = 3$, distribution of the ratio between the average blob size $\langle d \rangle$ the average blob thickness $\xi$ for $t = 11.5$ ms (LFS) and 30.5 ms (SS) [top]; Distribution of $d_{10}$ for the same times $t$ [bottom].

Fig. 6 For $N_{j} = 4$, distribution of the ratio between the average blob size $\langle d \rangle$ the average blob thickness $\xi$ for $t = 11.5$ ms (LFS) and 30.5 ms (SS) [top]; Distribution of $d_{10}$ for the same times $t$ [bottom].
Fig. 7 Joint probability distributions function of the size and velocity of spray droplets normalized by the jet size and velocity, respectively.

Relatively to the main cluster, earlier in this analysis the LFS (or initial stage of injection) has been characterized as a poor atomization period and Fig. 7 allows showing that LFS droplets are polydispersed around larger sizes when compared with droplets in the SS period. Also, the axial velocity distribution in the main cluster changes from $N_j = 2$ to 4. Namely, a 2 impinging jets spray produces a clear positive size-velocity correlation, $\partial u_d/\partial d_d > 0$, but increasing the number of jets, especially with $N_j = 4$, this correlation tends to zero, that is $\partial u_d/\partial d_d \rightarrow 0$, implying a trend toward the uniformization of the axial velocity around $u_d/u_j \approx 0.7$. It is interesting to note that such trend is also present in the SS period, and from 2 to 4 impinging jets the size-velocity correlation appears to gradually divide in two other distinct clusters, one around the more uniform axial velocity distribution and a second around less polydispersed sizes and lower axial velocity values. Such sorting might indicate the presence of distinct atomization mechanisms, or evidence the production of ligaments with different dynamic characteristics from which droplet clusters emerge even if the fragmentation process might is the same. Based on the previous analysis on ligament fragmentation,
the second hypothesis is more likely, which is also supported by the observation in Fig. 4 that edge ligaments are more likely to produce smaller droplets, while detached ligaments produce larger droplets, and that these later constitute the main spray (see \(d_{10}\) maps in Figs. 6a-c).

In all periods, droplet velocity is lower than jet velocity and drop size is no more than 18% of the jet diameter. Considering the case with \(N_j = 2\), the largest size appears to be as much as 16% of jet diameter. This is a significant outcome considering the work reported in the literature for multijet atomization with turbulent jets. Anderson et al. (1994) have proposed a correlation for the mean drop size as

\[
d_{10} = 2.217 \cdot d_j \cdot \left(\frac{\text{We}_j \cdot f(\theta)}{1 - \cos(\theta)}\right)^{-0.354},
\]

where \(f(\theta) = (1 - \cos(\theta))^2 / \sin^3(\theta)\) and \(\theta\) is the half-impingement angle. Considering a turbulent jet velocity of 8 m/s (see operating conditions in Fig. 3) the application of the previous correlation results in a \(d_{10}\) close to 131 \(\mu\)m, i.e. about 33% of jet diameter. For some reason yet in need of explanation, the atomization in the present experiments performs better than what is suggested in the literature for multijet sprays produced by turbulent liquid sheets, implying the need of further research, eventually, at a more fundamental level.

3.3. Intermittent multijet sprays dispersion pattern and applicability for spray cooling

Most sprays are axisymmetric, however, the spray dispersion pattern of multijet sprays is not and depends on the number of impinging jets, which means that spatial distribution and temporal variation of droplets characteristics (size, velocity, fluxes) should consider the entire measurement area. For example, based on the relation between inertial and surface tension forces underlying the atomization process, if we compare the Weber number (=\(\rho u^2 d_j / \sigma\)) which relates these forces, at the time representing the main period of injection (SS), \(t = 30.5\) ms ASOI, one may clearly see the characteristic elliptical shape of a \(N_j = 2\) spray (although rotated), and the geometric features of the spray patterns produced with \(N_j = 3\) and 4 (see Fig. 7).

![Fig. 8 Droplet Weber number distribution at 30.5 ms after the start-of-injection, within the main period of injection.](image-url)
These patterns suggest that multijet atomization may potentially produce geometric sprays with a shape depending on the number of impinging jets. Given the experimental character of the spray produced, the effect of jet misalignment observed in the rotation of the 2-impinging jets elliptical pattern (Gadgil, 2009) and what appears to be a distorted square with 4-impinging jets (Panão et al., 2009), should be further researched, even if, apparently, the general outcome of atomization is not affected since no significant heterogeneities are observed in the \( \text{We}_d \) dispersion pattern (Fig. 7).

Besides providing information on the spray spatial pattern, the Weber range is quite similar between sprays, although slightly higher with 3 and 4 jets because of a greater presence of larger drops. Also, as the spray droplets disperse in the spray propagation direction, the \( \text{We}_d \) tends to decrease eventually due to momentum exchanges between droplets and the surrounding air. Nevertheless, considering the case where the spray is used for surface cooling, the \( \text{We}_d \) values suggest that such sprays are more likely to deposit on the wall during its main period of injection according to the majority of criteria available in the literature. Following, for example, the criteria of Bai et al. (2002) for wetted surfaces (visualization of spray cooling confirms the presence of a liquid film, see Panão et al., 2010), the critical Weber for splash in all cases studied here is above 270.

4. Conclusions

The aim of the work presented here is to analyze the transient characteristics of a multijet atomization strategy operating intermittently and better understand the differences between what is reported in the literature for sprays produced by the impingement of two jets, and the sprays produced with 3 and 4 impinging jets. The multijet sprays considered are aimed at short distance atomization, therefore, the regime of turbulent sheet is chosen in the experiments performed. The information of the atomization characteristics has been acquired with a Phase-Doppler Interferometer which collects simultaneously the size and velocity of droplets. The analysis focus on the relation between the spray intermittency and the fragmentation process; the transient characteristics of multijet sprays exploring the differences induced by the number of impinging jets; and some brief considerations are made relatively to the spray dispersion pattern and the applicability of multijet sprays for spray cooling.

While most research works provide valuable insights into the physics of atomization with 2 impinging jets, little is known about the applicability of such knowledge to the atomization performed by more than 2 jets. Our results suggest that the physics of ligament fragmentation is applicable to multijet sprays produced by the impact of more than 2 jets. Visualization of the sprays produced by 2, 3 and 4 impinging jets allowed identifying two distinct kinds of ligaments: edge and detached. And the main differences observed from the backward formalism used to infer about the relation between ligament fragmentation and mean size of droplets lie in the relative importance of each ligament type in the spray generation. Namely, detached ligaments dominate the process and edge ligaments are gradually less important as the number of impinging jets increases.

The transient analysis of droplets characteristics from the point of view of the periods typically found in intermittent sprays (Leading Front of the Spray, Steady Spray and Spray Tail) has been made in terms of size-velocity correlations. The results suggest that an increase in the number of impinging jets leads droplets formed by detached ligaments to have a more uniform distribution of their axial velocity and, additionally, allow a better distinction from droplets produced by edge ligaments. Also, the present experiments appear to have better atomized the injected liquid, relatively to what correlations proposed in the literature suggest, implying that further research is need at a more fundamental level.

Finally, the dispersion pattern represented by the relation between inertial and surface tension forces, expressed through the Weber number, suggest that multijet sprays are potentially geometric
sprays, able to produce small and slow droplets which are likely to deposit on interposed surfaces and, eventually be more adequate for spray cooling than current sprays, thus, becoming a promising, as well as competitive atomization strategy.

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