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MULTIJET ATOMIZATION FOR SPRAY COOLING APPLICATIONS

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ABSTRACT

In this study an experimental setup was designed to create a high-performance spray cooling system based on a multijet atomization strategy. Our scope is to study multijet atomization as a way to achieve a spray at low-injection pressure which uniformly distributes droplets over the impinging surface. Three prototype atomizers heads with two, three and four holes have been used in the experiments. While disintegration phenomena with two jets are relatively well studied, little is known when more than two jets collide to form a spray. The experiments reported in this work evidence the differences between configurations and infer about the advantages for spray cooling. Since the injector is able to work either in a continuous or intermittent mode, our experiments show that poor atomization in the continuous mode can be significantly improved in the intermittent mode, which may suggest that intermittency may well be integrated as an inherent part of the multijet atomization process and constitute a new atomizer paradigm requiring further study.

INTRODUCTION

The potential of spray cooling systems for high heat flux removal in high power systems has been recognized and already applied to computer electronics, defense laser and microwaves systems. The main advantage of this thermal management strategy consists in using phase change as its main heat transfer mechanism and to ensure temperature uniformity across the heat-dissipating surface.

The two phase flow generated in the spray cooling event has a highly complex nature and depends on several parameters such as droplet size, velocity and density, so the atomization process is of great importance. There are several atomization strategies, such as using liquid discharge through a small orifice (pressure atomizers), high-speed rotating disks where liquid is introduced in its center (rotary atomizers), using air to assist the atomization of the liquid injected (air-assist atomizers), induce pressure forces through electrical charges to atomize the liquid, dissolving gas in the liquid to assist atomization (effervescent atomization), and many other strategies, but an easy and widely used way to produce a spray is to form a liquid sheet by impacting a jet on a solid surface [1], or on a facing similar jet [2]. The strategy used in this research work is this later involving multiple jet impacts.

The impinging-jet injectors are commonly used to introduce liquid propellants in a rocket chamber, causing the atomization into sufficiently small droplets, in order to promote an adequate mixture of fuel and oxidize, from which depends the efficiency of the combustion process [3].

The characteristics of an impinging-jet spray depend on the flow conditions of the pre-impinging jets (laminar or turbulent), the jet average velocity (V_j), the impinging angle (2θ), the jet diameter (D_j) and the properties of the liquid (viscosity and surface tension) [4]. The impact of two impinging jets produces a leaf-like shape liquid film perpendicular to the plane formed by the two jets. With an increase of the jet mean velocity, this liquid sheet becomes thinner and quickly disintegrates into unstable arc-shaped liquid ligaments which contract by surface tension forces and finally break into drops [5]. Li and Ashgriz [2] identified two breakup regimes: one derived from a capillary instability ($Re_{jet} < 2000$), dominating droplet formation from the rim of the sheet; and another regime associated with the Kelvin- Helmholtz instability ($Re_{jet} > 2000$) where the interaction between the sheet and the surrounding air causes its breakup into drops.

In the applied research work on the impinging of two jets, Heidmann et al. [6] identified four spray patterns using a 70% glycerol solution as the test fluid: (1) closed rim; (2) periodic drop; (3) open rim and (4) fully developed mode. Later, Dombrowski and Hooper [7] further studied these patterns and found that for higher velocities of the impinging jets, the impact force which leads to the formation of waves grows and their breakup is determinant for the spray atomization characteristics. While for laminar jets, there is a non-linear relation between drop size and jet velocity, with a local minimum at a certain characteristic mean velocity, for turbulent jets the evolution of drop size in monotonically, namely, a jet velocity increase leads to a finer atomization of gradually smaller drop sizes. This suggests the advantage of using turbulent jets relatively to laminar ones for spray cooling applications, if we require short break-up lengths between the point of jet impact and a fully developed spray.

It is noteworthy at this point that most research work published on multiple impinging-jet (multijet) atomization refers to the impact of “two” jets, however, this is only a specific case of the more broad multijet atomization, where this impact can be made with more than two jets. However, the information we find in the literature consist of a few references multijet atomization, but the absence of a systematic research work is clear, indicating the lack of knowledge of this atomization strategy. Therefore, the goal of our research work is to further investigate multijet atomization (with two, and more than two jets) and apply this atomization strategy to spray cooling. This is a major research project and in this study, we will focus our contribution on the improvement of the knowledge of multijet atomization process itself, and eventually infer about its implication for its impact on a solid surface, which means that heat transfer studies are the subject of future work.

The work reported here consists in comparing the disintegration processes associated with the impaction result of 2, 3 and 4 jets and assess the atomization quality, namely, through the size of droplets. Finally, the experimental setup is prepared to work in continuous and intermittent mode, and when these are compared, surprisingly, intermittency has been found to determine the atomization quality and may suggest a new atomization paradigm. Additionally, Intermittent Spray Cooling (ISC) has been previously studied as a new technology to control surface temperature due to its flexibility in switching between heat transfer mechanisms, i.e. from one based on phase-change to another based on thin film boiling [8]. Therefore, considering an integrative approach to the design process of thermal management systems, this new paradigm, based on multijet atomization science, may offer a significant contribution to the technological implementation of the ISC concept and potentiate the building of high-performance spray cooling systems with intelligent control algorithms.

EXPERIMENTAL APPARATUS

An experimental setup is developed to study the multijet atomization process composed by a pressurized tank with N_2, which supplies the fluid to the injector where a pressure gauge has been mounted to measure the injection pressure. The impinging jet system is composed by the injector, a fast response electronic valve (Parker Miniature Valves Series 99), also used in cryogen spray cooling systems, and three atomizer prototype heads have been design with 2, 3 and 4 holes, each having a the diameter of 400 µm and a constant impact angle of 90º in all configurations. The relation length-to-diameter (L/D) in each hole is about 7.5. The injector is triggered by a TTL pulse controlled by an arbitrary function generator NI5411 (National Instruments) allowing the control of the frequency and duration of injection. The schematic of the experimental apparatus shown in Figure 1 also contains the assembly used to visualize the spray.

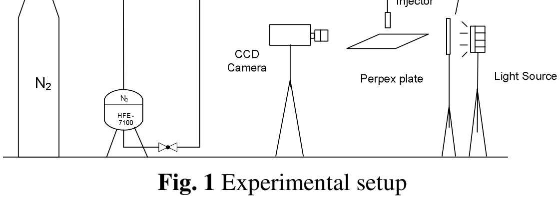

Fig. 1 Experimental setup

The fluid used in the experiments is a dielectric coolant manufactured by 3M™, the Novec™ HFE-7100, with density $\rho = 1488$ kg/m^3, surface tension $\sigma = 0.0136$ N/m and kinematic viscosity $\nu = 3.7 \times 10^{-7}$ m^2/s. A graduated glass tube of 10 ml is used to calibrate the injector, as a function of the injection pressure and the number of jets, by assuming an incompressible fluid flow.

The injector is attached to a micrometer in order to accurately adjust the distance from the atomizer to the impact surface. Visualization of the liquid sheet instability dynamics is recorded by a Phantom V4.2 CCD camera and all the pictures were taken at 2200 fps (frames per second). The same TTL pulse provided to control the aperture of the injector is used to trigger the camera. The light source is a projector OSRAM 1000W Professional, operating by a back lighting through a diffusing screen.

RESULTS AND DISCUSSION

The first set of results corresponds to the calibration curve for the three prototype atomizer heads, which is essential for the estimation of the average velocity of each jet. The second set of results compares the multijet atomization process in a continuous or intermittent mode.

Injector Calibration

Liquid flow rates have been measured for several values of injection pressure considering the impact of 2, 3 and 4 jets and calibration curves obtained as depicted in Fig. 2. This calibration has been used to estimate the mean jet velocity assuming that the flow rate is equally distributed in each jet. The estimated mean jet velocity is further used as the characteristic velocity of the jet Reynolds number.

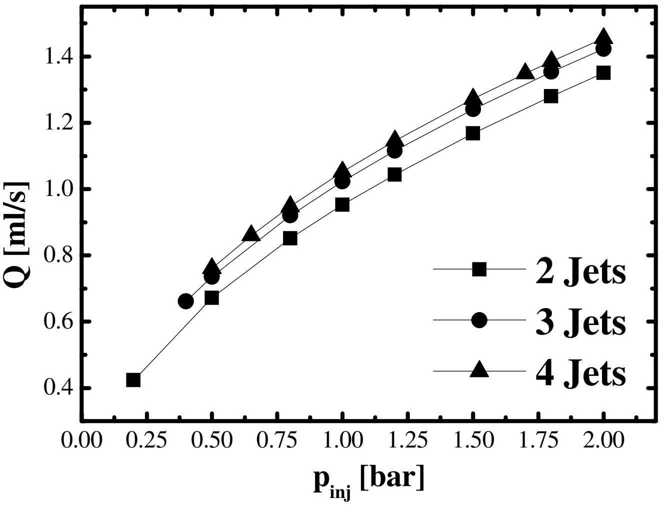

Fig. 2 Injector calibration curve

Multijet atomization disintegration process

Figure 3 and Figure 4 show the disintegration process in all multijet configurations for two different Reynolds numbers, which is calculated as $\mathrm{Re_j} = V_j \cdot D_j / \nu$.

The image on the left represents the original image of the spray, and the one on the right amplifies the region where the main disintegration process occurs.

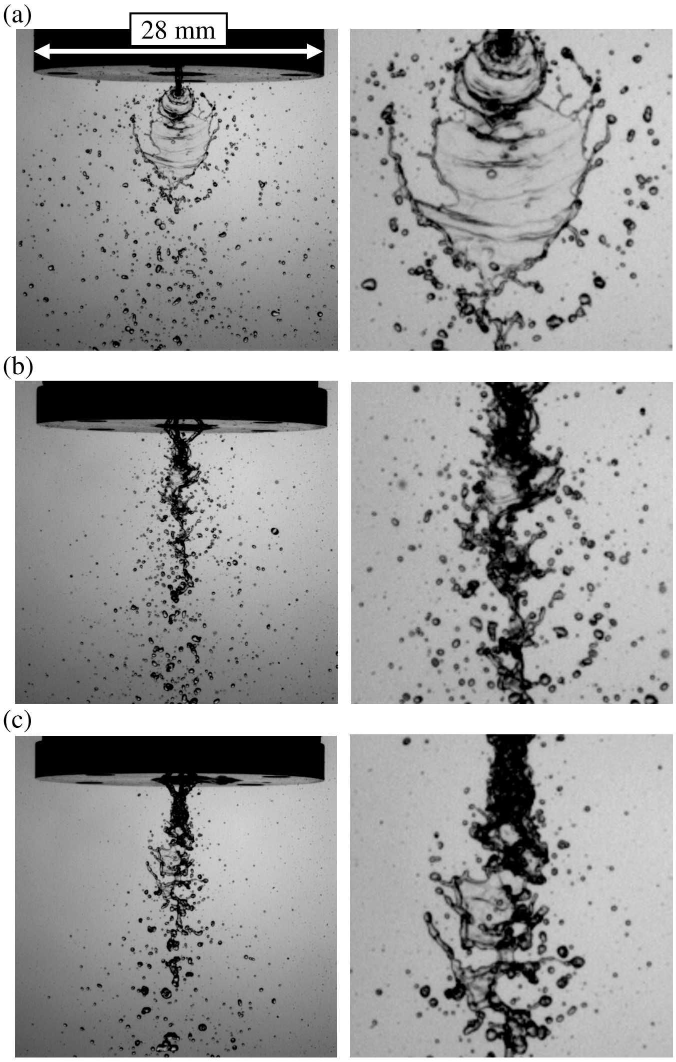

Fig. 3 (a)Two jets, $p_{inj} = 0.2$ bar, $V_j = 1.68$m/s, $\mathrm{Re_j} = 1820$,
(b)Three jets, $p_{inj} = 0.4$ bar, $V_j = 1.75$m/s, $\mathrm{Re_j} = 1896$,
(c) Four jets, $p_{inj} = 0.65$ bar, $V_j = 1.71$m/s, $\mathrm{Re_j} = 1850$.

For the two-jet configuration, Figure 3 (a) shows the formation of a rim caused by the surface tension force which contracts at the free edge of the liquid sheet. This rim will disintegrate causing the formation of thin ligaments due to capillary instabilities and eventually break into the spray droplets. These structures form a pattern described by Heidmann et al [6] as "open rim" as the result of aerodynamic forces splitting the sheet in the downstream location of the impinging point while the upstream part remains only ruffled.

When the $\mathrm{Re_j}$ increases by 55-60%, Figure 4 (a) depicts some changes in the disintegration phenomena, namely, the breakup length decreases and instabilities arise in the liquid sheet and not at the rim boundaries. This regime is usually identified with Kelvin-Helmholtz (KH) instabilities, where the interaction between the liquid sheet and the ambient air destabilizes the sheet and leads to its disintegration into droplets [7]. In Figure 4(a) the waves propagate in the liquid sheet, until they reach a critical amplitude, promoting sheet breakup in arc-shape ligaments from which the inertial stretching forces overcome surface tension ones in order to from the spray droplets. This confirms the results obtained by other authors [9, 10] and validates our experiments in order to compare the 2-jet configuration with the 3- and 4-jet.

With more than two jets, the planar liquid sheet changes into a liquid sheet with a tri-dimensional and more complex shape.

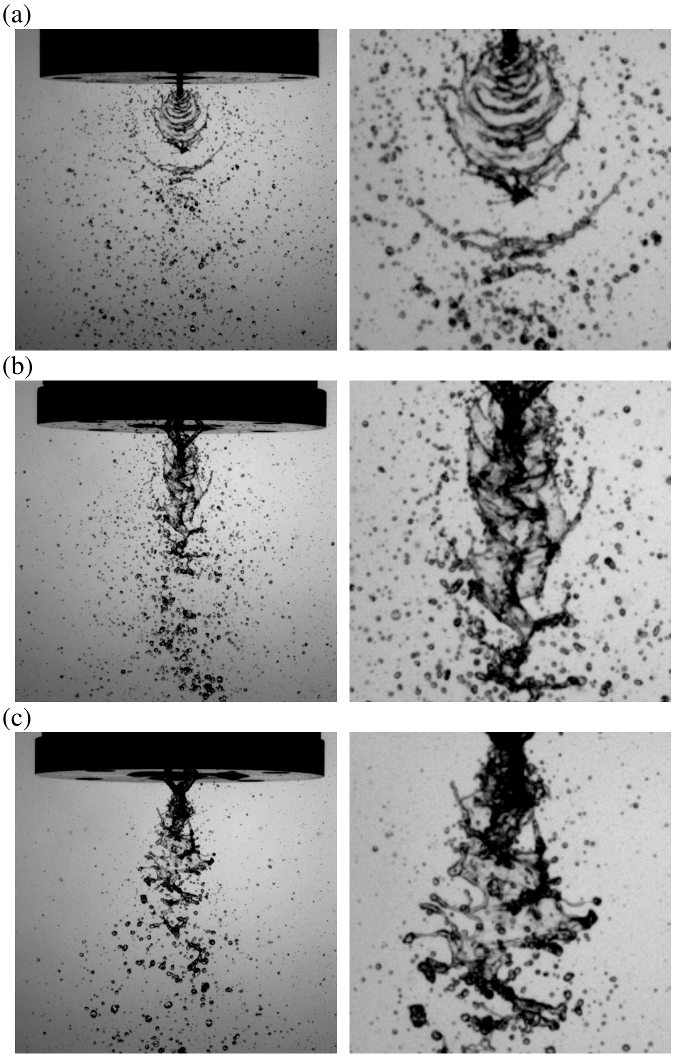

Fig. 4 (a)Two jets, $p_{inj} = 0.5$ bar, $V_j = 2.67$m/s $\mathrm{Re_j} = 2889$,
(b)Three jets, $p_{inj} = 1$ bar, $V_j = 2.71$m/s, $\mathrm{Re_j} = 2930$,
(c)Four Jets, $p_{inj} = 1.7$ bar, $V_j = 2.68$m/s, $\mathrm{Re_j} = 2900$.

For the test conditions considered, the cases with 3- and 4-jets depicted in Figures 3(b-c) and 4(b-c) show the disintegration of the tri-dimensional liquid sheet into ligaments from which the spray drops are formed. However, these droplets disperse less in the radial direction (as in the 2-jets case) and follow instead a downstream path. It should be noted that droplets appear to have larger mean sizes when the number of jet increases. Also, an increase of the mean jet velocity leads to the formation of thinner ligaments and, consequently, increasing the number of droplets and decrease their size.

Intermittent vs. continuous mode

The experimental setup can work either in a continuous or intermittent mode. Figure 5 depicts the results of this comparison and includes the TTL signal used to trigger the solenoid valve for each mode. The temporal evolution of the spray pattern and, consequently, of the atomization quality clearly changes in the continuous mode. However, surprisingly, this pattern change does not occur if the spray is intermittent. A possible explanation for this is that, in the continuous mode, the pressure fluctuations induced by the variations of momentum in the impinging jets, due to the opening and closing of injector, such as in the intermittent mode, tend to stabilize and jeopardize the atomization process. On the other hand, this means that, besides the energy of individual jets at impact,

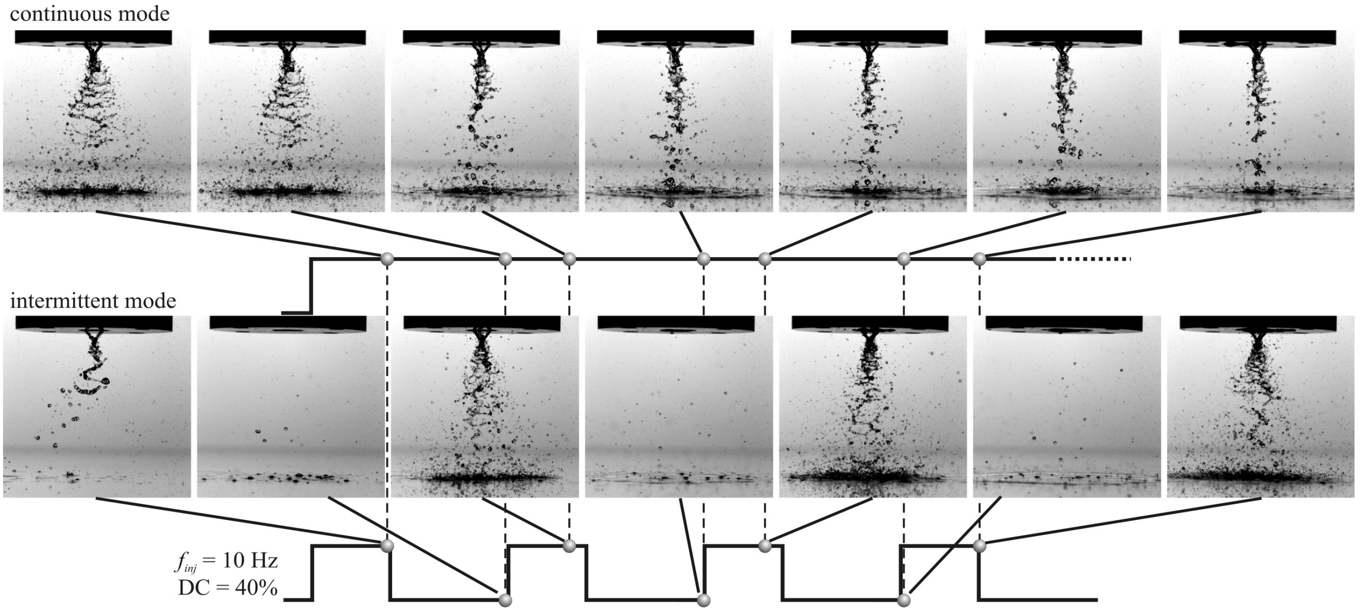

Fig. 5 Comparison of the multijet atomization quality between a continuous and an intermittent spray.

intermittency can also be considered as an inherent part of multijet atomizer. Analytical analysis of the atomization process must, therefore, take into account the time varying boundary conditions. Research is currently under progress to study the physical mechanisms responsible for the improvement of atomization in intermittent mode.

CONCLUSIONS

In this study an experimental setup was designed to integrate multijet atomization with the intermittent injection of liquid. The atomization generated at the impingement of two jets is often used in rocket propulsion in order to promote an adequate atomization and uniform distribution of the liquid propellant. The present study further investigates the applicability of this technique to the development of spray cooling systems.

The experiments reported here compare the atomization characteristics of multijet systems with 2, 3 and 4 jets. Visualization of the resulting spray shows that, when the number of jets increases with the momentum of each jet kept constant, the atomization tends to produce larger droplets and their dispersion follows a more downward path, thus avoiding a too large radial dispersion. Although this could benefit surface cooling upon spray impact, more studies are required to improve our understanding of the multiple drop impact density and improve our assessment of its uniformity.

Experiments performed at two different flow regimes, one dominated by the capillary instability ($Re_j < 2000$) and the other by the Kelvin-Helmholtz instability ($Re_j > 2000$), showed that, though the use of more than two jets does not alter the mechanisms of disintegration it enhances droplet formation as a result of an increase of the mean jet velocity.

Finally, the integration of pulsed injection with multijet atomization is suggested to improve the quality of atomization and set the pathway to the development of a new atomizer paradigm which makes use of temporal variations of the jet impact momentum to optimize the atomization process itself and the formation of a spray pattern with an uniform distribution of droplets over the impinging surface.

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