Multijet spray characteristics for spray cooling

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Abstract

This paper reports an experimental study on the development of a spray pattern, based on the impact of multiple jets on a single point (multijet spray), for the recently proposed concept of intermittent spray cooling (Panão and Moreira, *Int. J Heat Fluid Flow*, 30:117-130, 2008). Most experimental research in this atomization strategy is focused on the impact of 2 jets, and there is a lack of experimental evidence about the possible advantages of using more than 2 jets. Therefore, we consider the simultaneous impact of 2, 3 and 4 jets (N_{jet}), having developed prototype atomizers assembled with an electromechanical valve for spraying intermittently. The main objective of this work is to develop low-pressure intermittent sprays useful for spray cooling applications at short impingement distances (10-30mm). The visualization of the flow shows that impinging more than 2 jets leads to tridimensional structures underlying the atomization process. It is observed that a slight increase in mean drop size as the number of jets increases, implying a gain in directionality in spray propagation and, consequently, decrease of the spray dispersion angle. Namely, with 4 impinging jets, the mean size and particle density, within the plane of characterization, are more evenly distributed, resulting in a more uniform spray throughout the impact area. Also, given the spray intermittency, for 90% of the cycle, the correlation between the droplets axial velocity and their size is inversely proportional, which is positive if we require liquid deposition on the surface for cooling purposes. In fact, if we use the criteria established in the literature to estimate the impingement regimes expected to occur (stick, rebound, spread and splash), when the spray droplets strike an interposed surface at the characterization plane, the impact energy range is mostly within the rebound and spreading regimes, favoring the latter, and generally leading to the deposition of the liquid. Also, the effect of increasing the number of impinging jets in this atomization strategy, maintaining the impact momentum in each jet, is to shift the impact energies of droplets striking a surface to higher values, favoring the occurrence of spreading and, consequently, improving the liquid deposition in spray cooling. The experimental results obtained from the spray characterization indicate that multijet sprays have the potential for enhancing heat transfer when applied to spray cooling systems.

Introduction

The basic atomization processes of spray formation include the disintegration of liquid jets or sheets into droplets which are used in numerous and important applications, such as combustion, ink-jet printing, vegetable washing, domestic and hydrotherapeutic showers, thermal management systems, to name but a few [1-3]. There are several atomization strategies such as: 'pressure atomization'; 'air-assist atomization'; 'effervescent atomization'; 'electrostatic atomization'; and many others. However, most atomization strategies require complex nozzle geometries (pressure-swirl, air-assist, electrostatic), or a complex assembly of pressure-pump, air supplier, valves, gas dissolution systems in order to obtain quality in the atomization process. This is where the simplicity in geometry, manufacture and maintenance easiness, rapid atomization and, eventually, liquid mixing, found in atomization achieved by multiple and convergent impinging jets (henceforth, multijet atomization) become a substantial advantage and a worth exploring research area.

In multijet atomization, most research works have been focused on the impingement of two jets with a certain velocity, V_j, and diameter, D_j (e.g. rocket engines for propellant mixing). The impact of two jets generates a liquid sheet in the plane perpendicular to that of the impinging jets, followed by its breakup into droplets at its boundaries [4]. The breakup mechanisms first depend on the hydrodynamic condition of the impinging jet: laminar or turbulent. Once the liquid sheet is formed, the disintegration mechanisms have been divided in two regimes. In the lower Reynolds range ($Re_j = V_j \cdot D_j/\nu < 2000$), the regime is dominated by the capillary instability at the rim of a stable liquid sheet formed after jet impaction. From this rim, small disturbances begin growing and eventually lead to the disruption of the rim in ligaments, from which droplets are formed. With higher Reynolds values ($Re_j > 2000$) , the second

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regime is dominated by the Kelvin-Helmholtz instability, where the interaction between the liquid sheet and the ambient air destabilizes the sheet and leads to its disintegration into droplets after the wave amplitude has reached a critical value [5].

The literature is still limited to the impingement of two jets and fundamental research work with the impact of more than two jets is scarcely found. Only in Vassalo et al. [6] and Won et al. [7] one finds two pairs of doublet-impinging-jets with two impingement stages, thus forming a triplet-impinging-jets strategy, which is different from the simultaneous impact of more than two jets. In a previous work, the simultaneous impingement of 2, 3 and 4 jets has been approached from the point of view of micro-sprays in microelectronic cooling, and through visualization, similar and dissimilar disintegration mechanisms were observed, relatively to those usually found with two impinging jets [8].

Multijet sprays allow significant changes in droplet dispersion control and deposition on interposed surfaces. However, this work clearly points to the need of more fundamental experiments to improve and enhance our knowledge of the flow, and how can the atomization process be optimized toward its technological implementation. The empirical work here presented explores three topics: 1) visualization of the hydrodynamic structures of a multijet spray with different number of impinging jets; 2) effect of increasing number of impinging jets on spray dispersion with; 3) assessment of multijet sprays for thermal management systems based on the impingement regimes associated with single drop impact.

Experimental Setup and Diagnostic Techniques

The experimental setup developed to study the multijet atomization process is composed by a pressurized tank with N_2, supplying fluid to the injector where a pressure gauge has been mounted to measure the injection pressure. The impinging jet system is composed by a fast response electronic valve (Parker Miniature Valves Series 99), also used in cryogen spray cooling systems, and three atomizer prototype heads 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 (see Fig. 1 on the right). 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 on the left of Fig. 1 also contains the assembly used to visualize the spray.

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 4052 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.

Local time-resolved measurements of droplet size and velocity are simultaneously made at 10-30 mm below the point of impact, with a two-component Phase Doppler Interferometer (PDI) DANTEC system consisting of a 55X transmitting optics, a 57x10 PDI receiving optics, oriented at 30º for maximizing the signal visibility, and a 58N10 Covariance processor. According to Panão and Moreira [9], the inaccuracy in the discrete drop distributions used to calculate average quantities of drop size and velocity in the phase-average analysis are smaller than 8% for size and smaller than 12% for the axial velocity, although during the main period of injection, where the heat fluxes are higher, the mean values are around 1.5% and 4%, respectively.

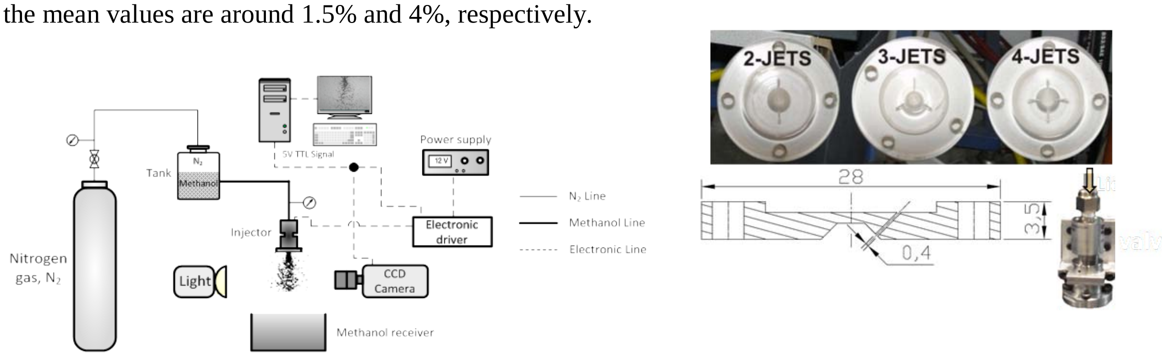

Figure 1. Scheme of experimental setup and atomizer

The fluid used in the experiments is a dielectric fluid, methanol, with density ρ = 790 kg/m^3, surface tension σ = 0.0225 N/m and kinematic viscosity ν = 7.4645×10^{-7} m^2/s at atmospheric pressure with a ambient temperature of 22ºC. The mass flow rate for each atomizer has been obtained using a calibrated balance with a minimum resolution of 0.1 g. The volumetric volume was then found according to the methanol density. From the calibration curves of volumetric flow rate as a function of injection pressure the results obtained for the discharge coefficient $c_d = \dot{Q} \big/ \left(N_j \pi r_j^2 \sqrt{2 p_{inj} / \rho} \right)$ are: c_d =0.544±0.0107; c_d = 0.4347±0.0045 and c_d = 0.3667±0.0062, for 2, 3 and 4 jets respectively, where ($\dot{Q}$), is the estimated flow rate and (p_{inj}), the pressure differential at nozzle exit. This calibration allows the estimation of the velocity at the jet exit nozzle. In the experiments reported here the injection frequency (f_{inj}) has been set to 10 Hz and the duty cycle (DC = $f_{inj} \cdot \Delta t_{inj}$) to 40 %, where Δt_{inj} is the pulse duration. The parametric variations considered are the number of simultaneous impinging jets (2, 3 and 4 jets). The results presented here correspond to the characterization plane from the point of jet impact of 20 mm. The injection pressure is adjusted to obtain similar Weber numbers with different number of jets. Therefore, for 2, 3 and 4 impinging jets, the pressures used were 1, 1.6 and 2.2 bar, respectively, resulting in Weber jet numbers of $We_j = \rho V_j D_j / \sigma$ = 1123, 1094 and 1065.

Results and Discussion

The results here presented are twofold. First, experimental evidence is presented on the hydrodynamic structures associated with the atomization process and droplets characteristic size and velocity. Secondly, the information on droplets characteristics is used to assess the impact outcome, according to current transition criteria [10], *i.e.* if droplets adhere to the wall for cooling purposes, or if secondary atomization removes liquid from the impinging surface.

The first observation is the flow regime of the impinging jets used in the experiments, which turbulent nature of the jet exiting each channel is evident from the images in Fig. 2. The hydrodynamic structures with two impinging turbulent jets shown in the figure can be found in earlier research works [4, 12], confirming the liquid sheet disintegration into ligaments from Kelvin-Helmholtz instabilities [5] and the periodicity indicated by the waves in the sheet and the spacing between detached ligaments [12]. When additional jets are introduced, the spray formation process significantly changes. With 3 and 4 impinging jets it is still possible to identify the formation of liquid sheets and ligaments, as well as the periodicity characteristic of the process of atomization. However, its hydrodynamic structure is tridimensional. The images also evidence that droplet dispersion is quite scattered with 2 jets and gains directionality, with a smaller spray cone angle, when the number of jets increases, although droplets appear to be larger. These visualization results suggest the need of more fundamental research to attempt a theoretical description of the liquid sheet morphology and the phenomenology associated with the instabilities in the wave-like patterns which disrupt into ligaments before breakup and formation of the spray droplets.

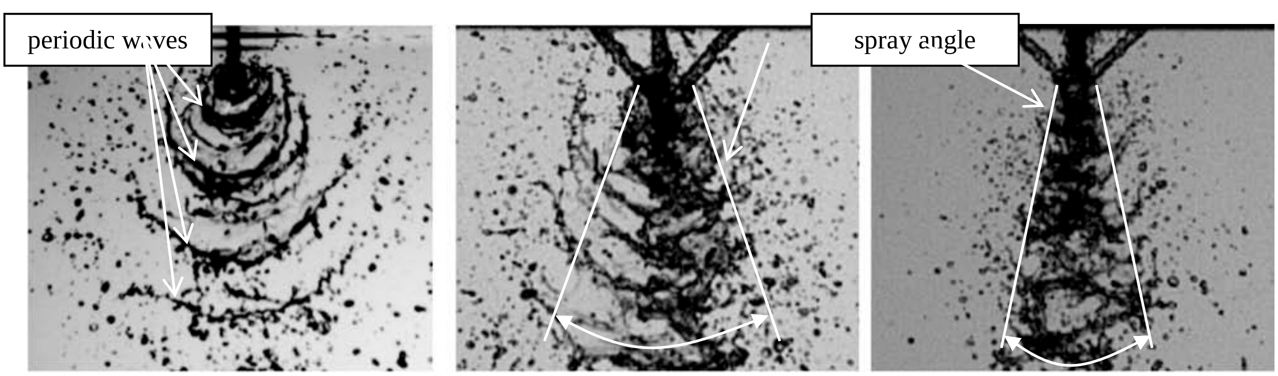

Figure 2. Macroscale hydrodynamic structures with 2, 3 and 4 multiple simultaneous impinging jets at 3.2ms after the instant of simultaneous jet impact.

Since the spray is intermittent, there are three systematic periods typically associated with its dynamic behavior which are also found in multijet sprays. These periods are the leading front of the spray, the steady spray and the spray tail [11]. The first two images in Fig. 3 show the moment of impact in the leading front of the spray, the third image represents the steady spray (and main period of injection) and the fourth represents the end of injection. If these periods are analyzed from the measurements of droplets' size (D_d) and velocity (U_d) point of view, made by the Phase-Doppler instrument, it is interesting to note what happens to the axial velocity – size correlation for the different periods of the spray dynamic behavior. Usually in sprays, the higher velocities are associated with larger sizes, thus, the impact energy is proportional to this correlation and the likeliness of producing secondary sprays is significant. However, this only occurred for the leading front of the spray period, while for 90% of the cycle time (steady spray and spray tail periods) this is inverted, namely, larger droplets are actually slower and smaller droplets are faster (see Fig. 4), which is beneficial from the spray cooling point of view and evidences the advantage of using intermittent multijet sprays for thermal management.

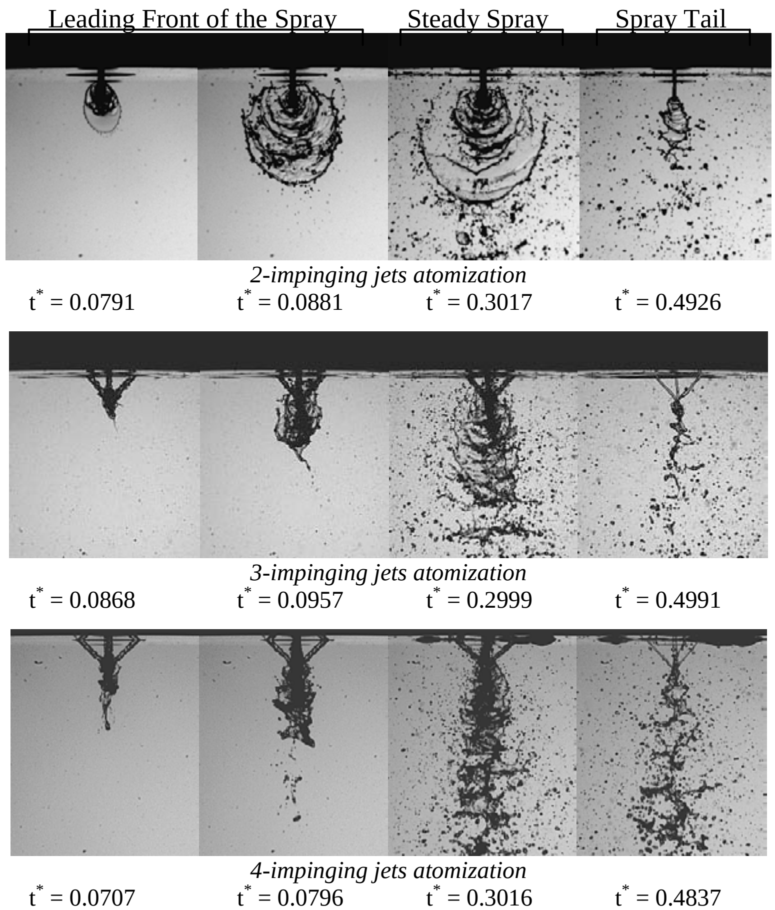

Figure 3. Macroscale hydrodynamic structures with 2, 3 and 4 multiple simultaneous impinging jets ($t^* = t/t_{cycle}$).

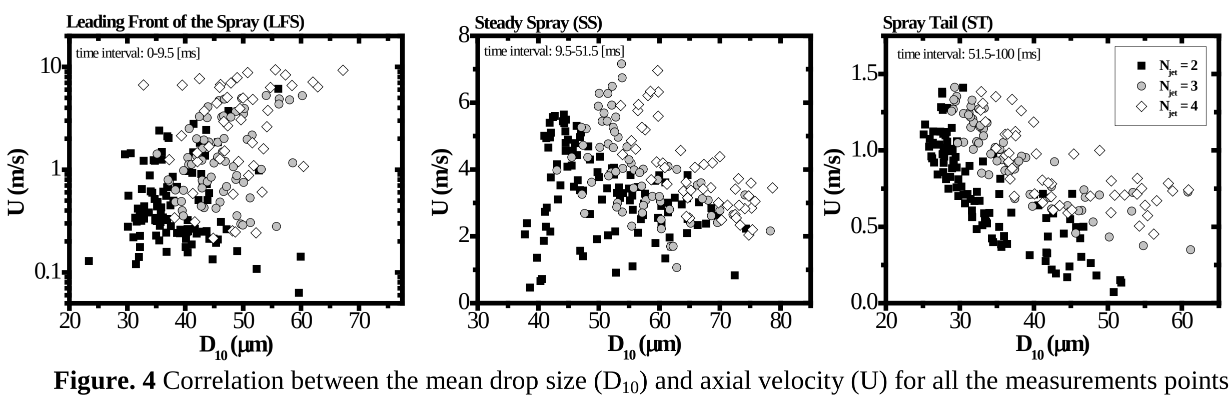

Figure. 4 Correlation between the mean drop size (D_{10}) and axial velocity (U) for all the measurements points at 20 mm below the point of jet impact, considering the three characteristic periods of an injection cycle.

It is also possible to evaluate how average sizes are distributed on a certain plane of characterization, as well as the particle data rate distribution (see Fig. 5). The spray pattern for a 2-impinging jet spray is usually elliptical in its shape, however, the particle data rate in Fig. 5 shows the pattern of a rotated ellipse. This is the result of jet skewness at the point of impact as studied by Gadgil and Raghunandan [13]. These authors have theoretically analyzed the skewness effect on the rotation angle and the application of their analysis to our experiments resulted in a deviation of about 280μm between jets at the point of impact. Since our analysis is overall and not local, such condition does not affect the interpretation made when discussing the results obtained.

The circles in Fig. 5 are proportional to drop size and evidence its slight increase with the number of impinging jets (also visualized in Fig. 2). However, the data rate appears to be much more uniformly distributed with 4-impinging jets, indicanting that an effect of increasing the number of impinging jet is not only directionality, as observed in Fig. 2, but also uniformity. Therefore, besides larger drop sizes, and less droplets, more impinging jets means that droplets are more evenly distributed throughout the spray dispersion path.

Additionally, with the size and velocity of droplets it is possible to apply transition criteria which are used to estimate the outcome in the case of spray impaction. According to the transition criteria in Bai et al. [10], the four main impact mechanisms considered are: stick, rebound, spread and splash. In the case of splash, a wetted surface is assumed, since the application here considered for multijet spray technology is spray cooling. The sorting between regimes is based on droplet Weber number ($We_d = \rho U_d^2 D_d/\sigma$) and its critical values are: $We_c = 2$ (stick→rebound); $We_c = 20$ (rebound→spread) and; $We_c = 1320\ La_d^{-0.183}$ (spread→splash), where La_d is the Laplace number ($La_d = Re_d^2/We_d$, with Re_d and We_d as the drop Reynolds and Weber numbers, respectively). For each point in the measurement grid (inferred from Fig. 4), droplets are sorted by their expected outcome and the results are processed in their average percentage of occurrence in the entire measurement grid.

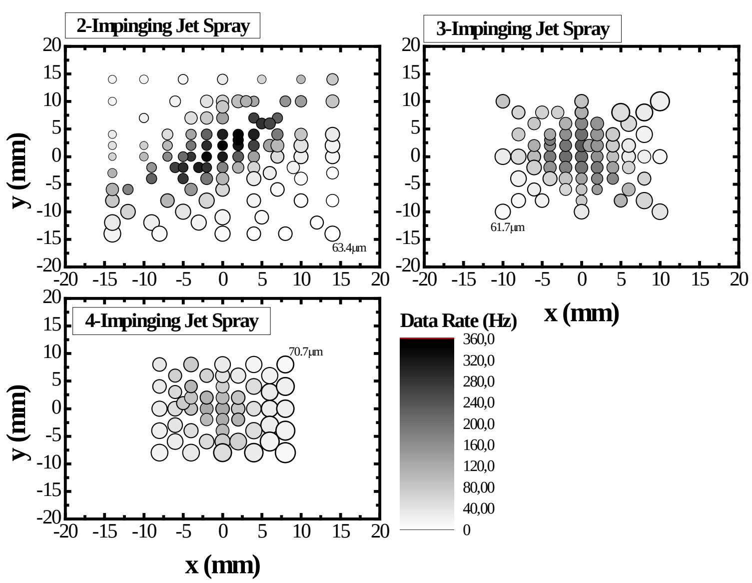

Figure 5. Mean size and particle density maps for the multijet spray. The circle size is proportional to mean drop size and the grayscale to the particle density in each measurement point of the characterization plane.

The two plots on top of Fig. 6 correspond to the regimes which lead to the deposition of the impinging drops onto the surface for cooling purposes (stick and spread), and the plots on the bottom correspond to those regimes which lead to secondary atomization, thus, removing liquid and affecting the performance of the cooling process. Relatively to the deposition regimes, it is noteworthy that droplets have a very low probability of sticking to the surface, except in the periods before-the-start- and after-the-end-of-injection, where very few droplets impinge on the surface. Therefore, it is the spreading regime which leads to the formation of liquid films, during the main part of the injection cycle (steady spray period). Splash is only likely to occur in the beginning of spray impaction and a non-negligible part of impinging droplets is expected to rebound, also during the main period of injection. The results evidence that an increase of the number of impinging jets is likely to increase the overall impact energy of drops, seen by the decrease in the percentage of drops expected to rebound and accompanied by an increase of those expected to spread. Based on the transition criteria, this indicates that a multijet spray produced by 4 impinging jets, not only is more directional and uniform in terms of drop dispersion, but is also expected to enable a greater deposition of liquid and, consequently, a greater control of the cooling process, ensuring its suitability for thermal management. However, it could be generally argued that multijet spray technology shows promising potential for being a leading atomization strategy in applications where deposition of the injected liquid is required and its consequent control.

Concluding remarks

Multijet spray technology is based on atomization processes triggered by the simultaneous and convergent impact of multiple jets. Considering that most experimental evidence is reported for the impact of 2 jets, experiments using prototype atomizers have been made with the purpose of visualizing the differences in the main hydrodynamic breakup mechanisms when more than 2 jets collide. The information on the size and velocity of droplets is characterized with a Phase-Doppler interferometer and used to assess the expected spray impact outcome, based on transition criteria available in the literature for sorting between impact regimes. The analysis of the results obtained evidence: 1) the emergence of tridimensional structures when more than 2 jets collide, with a periodic pattern associated with the formation of ligaments, eventually disrupting into droplets, however, more fundamental studies are required to explore their morphology and physical description; 2) increasing the number of simultaneous and convergent impinging jets: i) produce sprays which are more directional and uniformly distributed along the spray dispersion path and; ii) promotes droplet spreading. The overall assessment of using multijet sprays technology in applications requiring a better control of liquid deposition is promising and further research should be encouraged.

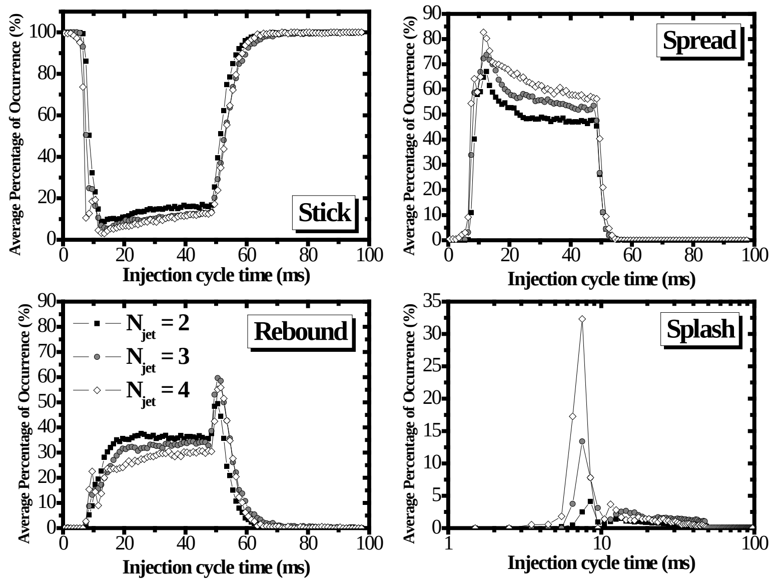

Figure 6. Evolution of the average percentage of occurrence of impact mechanisms along the injection cycle.

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