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Multi-scale analysis of atomizing liquid ligaments

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ABSTRACT

The atomization of individual liquid ligaments appearing during the disintegration of liquid sheets issuing from a triple-disk injector is investigated. High-speed visualizations report a temporal evolution of the ligaments from their production to their disintegration into drops. The parameter of the experiments is the surface tension of the liquid. A multi-scale analysis consisting in describing the temporal evolution of the ligament shape by measuring the scale-distribution is performed. This analysis introduces the notion of scale-diameter whose temporal variation leads to the following conclusion. The ligaments are subject to elongation, capillary deformation and break up and relaxation mechanisms. These mechanisms appear concomitantly on different scales. This concomitancy depends on the surface tension, i.e., on a Weber number based on the ligament initial elongation rate and initial size: the decrease of the surface tension favor the propensity of the atomization process to cascade in the scale space towards the small scale region. A mathematical scale-distribution of the final drops is satisfactorily derived from an atomization model of the literature. Furthermore, the parameters introduced by this model are well correlated to initial ligament Weber number and size.

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Introduction

Ligamentary structures are often encountered in liquid atomization processes. In 1962, Fraser et al. suggest that the atomization of liquid sheets subject to a Kelvin–Helmholtz instability goes through the production of transverse ligaments that disintegrate in droplets following a capillary instability mechanism. Since then, many experimental images of atomization processes have revealed the presence of ligaments before the final drop production stage. For instance, under sub-atmospheric pressure, liquid sheets perforate and rearrange as a ligament network before producing drops (Fraser et al., 1962). Liquid sheets surrounded by a high velocity gas-flow may disintegrate under a cellular regime characterized by the production of ligaments (Lozano et al., 1996). The perforation atomization regime observed on conical high-viscous liquid sheets produces ligaments (Sindayihebura and Dumouchel, 2001). Radial liquid sheets in the sinusoidal regime of instability reorganize as longitudinal ligaments at their edge before the drop production stage (Clanet and Villermaux, 2002). Air-assisted cylindrical liquid jets subject to a Rayleigh–Taylor instability generate longitudinal ligaments as the next to the last step of the atomization process (Marmottant and Villermaux, 2004a). Finally, liquid sheets produced by the impact of two jets reorganize as a succession of transverse ligaments that to their turn disintegrate as droplets (Brémond and Villermaux, 2006). In every situation the final spray characteristics depend on the atomization of the ligaments that therefore deserves targeted investigations. This work is dedicated to the breakup of such ligaments but not to their production.

The liquid ligaments considered in this study are those appearing during the atomization process of flows issuing from a triple-disk nozzle. The working principle of triple-disk nozzles was investigated in previous works (Dumouchel et al., 2005a, 2005b). Inspired from compound port fuel injector, a triple-disk nozzle is made of the superposition of three disks, the nozzle discharge orifice in the third disk being not aligned with the passages in the two other disks. Because of this geometrical characteristic, the liquid flow issuing from the nozzle is shaped as a 2D sheet. The atomization process of this sheet is initiated by the liquid turbulence and goes through the creation of gulfs, the reorganisation as a ligament network and the subsequent breakup of these ligaments into droplets. The last stage of this process is investigated here.

A cylindrical liquid ligament is naturally meant to breakup into droplets. It is subjected to an instability driven by capillary forces and whose growth leads to its breakup and the production of droplets. The first-order (or linear) theoretical description of this instability due to Rayleigh (1878) provides the instability wavelength λ ($= 4.51 D_L$ where D_L is the ligament initial diameter) and

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its characteristic capillary time t_σ (= $\sqrt{\rho_L D_L^3/\sigma}$ where ρ_L is the liquid density and σ the surface tension). The diameter D_G of the droplets produced by this mechanism can be estimated by considering that one drop is produced per wavelength. It comes $D_G = 189D$. Third order mathematical developments (Yuen, 1968; Rutland and Jameson, 1971) showed that the capillary instability is a non-linear effect with generation of higher harmonics, feedback into the fundamental and production of swelling between the crests of primary disturbance waves. Pimbley and Lee (1977) demonstrated that this non-linear effect is at the origin of satellite drops, i.e., smaller drops produced between two first-order droplets. The most relevant parameters that control the production of satellite drops are the amplitude of the perturbation and the wavelength-to-diameter ratio of this perturbation. The direct numerical simulation of ligament capillary instability performed by Ashgriz and Mashayek (1995) demonstrates that the satellite production depends on the jet Ohnesorge number Oh $(= \mu/\sqrt{\rho_L \sigma D_L}$ where μ is the liquid dynamic viscosity) and on the disturbance wavenumber k and initial amplitude. They succeed in identifying the satellite production region in the $(k, 1/Oh)$ domain and found that the satellite might disappear when the disturbance initial amplitude increases.

Frankel and Weihs theoretically investigated the effect of an elongation constraint on the instability of jets of non-viscous (1985) and viscous (1987) liquids. Their works demonstrate that the evolution of surface perturbations in the jet is an initial value problem instead of an eigenvalue one. Perturbation amplification depends on the relative effects of the surface tension and inertia terms associated with extensional flow. It depends also on the initial wavelength and on the specific time when the perturbation is introduced in the flow. In the case of viscous liquid, the ligament behavior depends on three characteristic times, i.e., the elongation characteristic time t_e (= $1/\alpha$ where α is the elongation rate), the capillary characteristic time t_σ and the vorticity diffusion characteristic time t_μ (= $\rho_L D^2/\mu$).

Stretched ligaments were experimentally investigated by Marmottant and Villermaux (2004b). When the ratio $t_\sigma/t_e \gg 1$, the elongation is rapid and the ligament elongates as a liquid column. This column eventually breaks into droplets. Contrary to the Rayleigh instability mechanism, the drops produced here have different sizes. This was explained by several mechanisms such as the capillary wave travel along the ligament, the transient growth of the capillary instability and the remnant motions in the liquid bulk. The second argument was theoretically evidenced by Frankel and Weihs (1985). Marmottant and Villermaux (2004b) paid a specific attention to the set of droplets after breakup. They found that the mean diameter D_{10} was of the order of twice the ligament diameter just before breakup occurs. Furthermore, the mathematical diameter distribution they established from a fragmentation model based on successive agglomerations of sub-blobs satisfactorily fitted the measured diameter distributions. This latter result was also found for droplets produced from Rayleigh–Taylor ligament atomization (Marmottant and Villermaux, 2004a).

The numerical investigation due to Tong and Wang (2007) highlights that elongated ligaments are not all meant to break into several drops. Under certain conditions, an elongated ligament can relax into a single drop. This behavior is due to a competition between opposite internal flows in the region of a neck deformation. This one-drop relaxation mechanism is enhanced when the ligament Ohnesorge number Oh is great or for pointed-ends ligaments. In a liquid atomization process, such a mechanism may be expected on liquid bridges between two main drops since they have a small diameter (i.e., great Oh) and may have pointed-ends if the motion of the two main drops imposes an elongation constraint.

The purpose of this work is to investigate the atomization mechanisms of ligaments emanating from the disintegration of 2D liquid sheets produced by a triple-disk nozzle. To achieve this, a high-speed camera is used to record ligament temporal evolutions. The subsequent analysis is based on the description of the shapes of the ligaments during time. Liquid ligaments emanating from atomization processes exhibit complex shapes and specific tools are required here. The question of shape characterization of disintegrating liquid systems has been addressed since the mid 90's (refer to the review paper of Dumouchel, 2008). Attempts of using the fractal dimension concept were conducted and revealed that atomizing liquid systems have fractal characteristics but that these characteristics do not provide a complete description of the system. Inspired from the fractal description, a multi-scale analysis has been established and applied to describe liquid sprays (Dumouchel et al., 2008) or a liquid atomization process (Dumouchel and Grout, 2009). This latter work shows also that a new modeling of liquid atomization processes can be based on the multi-scale description. The multi-scale analysis is used here. It is the first time it is applied on temporally resolved atomization process and the evaluation of its potential in such a situation constitutes another aim of the work.

The article contains three main sections. The experimental work is described in Section "Experimental work"; the multi-scale description tools are presented in Section "The multi-scale description tools", and the experimental results and analysis are shown and discussed in Section "Results and analysis".

Experimental work

The experimental setup is conceived to produce liquid sprays at low injection pressures under atmospheric conditions of temperature and pressure. The liquid is kept in a pressurized tank and filtered before reaching the injector. A single injector is used. It has a triple-disk nozzle as schematized in Fig. 1. This nozzle is constituted of the superposition of three circular disks. The liquid enters the nozzle through disk 1, flows through the cavity disk (disk 2) and discharges through the single orifice in disk 3. The drastic flow deflections imposed by the nozzle eccentricity (see Fig. 1) favors the development of a remarkable flow at the nozzle exit section:

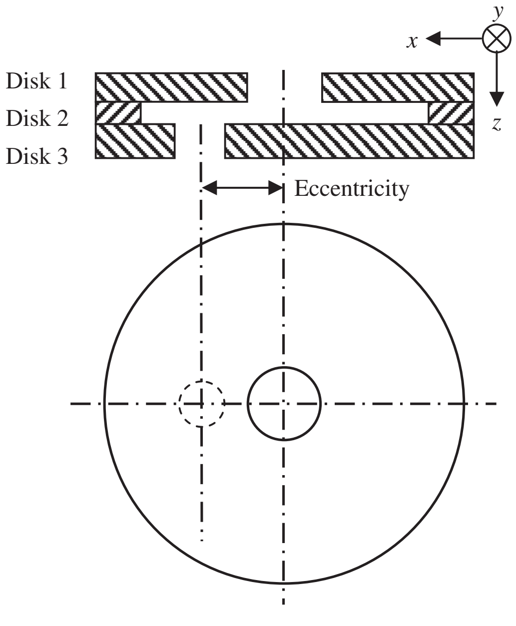

Fig. 1. The triple disk nozzle.

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