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Analysis of ligamentary atomization of highly perturbed liquid sheets

Trung-Thanh Vu, Christophe Dumouchel*

CORIA – UMR 6614, Normandie Université, CNRS, Université et INSA de Rouen, Avenue de l'Université, BP 12, Saint-Etienne du Rouvray 76801, France

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ABSTRACT

Ligamentary structures are often encountered in liquid atomization processes. They appear for instance during the atomization of liquid sheets issuing from triple-disk nozzles. Because of the development of turbulence along the internal wall of the discharge orifice, these sheets are highly perturbed and exhibit the formation of ligaments along their sides. The present investigation addresses the question of the origin of size dispersion of the droplets emanating from the atomization of these ligaments. The adopted strategy consists in describing the atomization process reported by experimental images by using a multi-scale tool and in conducting an analysis that concentrates on the dynamic of the small structures carried by the ligaments that might be the main small droplets providers. The advantages of the tool are its ease of application as well as its capacity to bring an information that incorporate the shape of the analyzed interface. The statistical scale analysis demonstrates that the small structures carried by the ligaments are subject to an elongation mechanism whose strength varies from one liquid to another. This mechanism is not dominant in the production of the small drops from the breakup of the ligaments. The dispersion of the drop size distribution, represented by the order of a Gamma distribution, is found to strongly correlate with the initial deformation of the ligaments. An interesting result here is the ease of characterizing the average ligament deformation with the concept of scale distribution. The fact that a single parameter is sufficient to represent the drop size dispersion and that this dispersion correlates with the ligaments deformation suggests the dominance of a single mechanism in the ligament breakup, i.e., the capillary mechanism. As demonstrated in a previous investigation, capillary mechanism is associated with elongation mechanism at small scales. All these results are strengthened by the fact that the explored experimental conditions are uncorrelated.

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1. Introduction

The breakup of liquid ligaments into a set of droplets has often been identified as the last stage in uncontrolled liquid atomization processes. The production of ligaments may result from the development of a Rayleigh–Taylor instability as reported on a flapping radial liquid sheet (Villermaux and Clanet, 2002) or on an air-assisted cylindrical jet (Marmottant and Villermaux, 2004a). The development of perturbations observed on the borders of a liquid sheet produced by the impact of cylindrical jets always creates ligaments (Brémond and Villermaux, 2006). A highly perturbed liquid sheet shaped by a double contra-rotating swirling flow rearranges as a ligament network before producing the final drops (Dumouchel and Grout, 2009). The mechanism of breakup of liquid ligament is therefore an important point to be addressed.

Villermaux et al. (2004) and Marmottant and Villermaux (2004a) suggested a coalescence type mechanism to represent the fragmentation of a liquid ligament from the instant at which it detaches the bulk flow. This suggestion is motivated by the fact that some of the drops have substantially larger sizes than the ligament itself. The coalescence mechanism establishes that the diameters of the drops are distributed according to a Gamma distribution of order ν:

$$f_0(D) = \frac{\nu^\nu}{\Gamma(\nu)} \frac{D^{\nu-1}}{{D_{10}}^\nu} \exp\left(-\nu \frac{D}{D_{10}}\right) \tag{1}$$

where $\Gamma(\nu)$ is the Gamma function. The Gamma distribution has two parameters, i.e., D_{10} and ν. The size parameter, D_{10}, is the arithmetic mean diameter of the distribution (refer to Mugele and Evans (1951) for the mean diameter series definition): it positions the distribution in the diameter space. The order ν is the dispersion parameter: it controls the shape of the distribution. In particular, when D tends towards zero, the distribution becomes $f_0(D) \propto D^{\nu-1}$: a small order designates a high dispersion in the small diameter range. On the other hand, a high order characterizes a set of drops with similar sizes.

The ν-order Gamma distribution was found competent to represent the sizes of the drops produced by the fragmentation of lig-

* Corresponding author.
E-mail address: christophe.dumouchel@coria.fr (C. Dumouchel).

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Nomenclature

d	Scale
D	Diameter
e_2	Scale distribution
E_2	Cumulative scale distribution
f_0	Number-based diameter distribution
$P(d)$	Perimeter of the system eroded at scale d
Re	Reynolds number
S_T	System total surface area
$S(d)$	Surface area of system eroded at scale d
T	variation rate
V_q	Average flow velocity
We	Weber number
δ	Blob diameter
Γ	Gamma function
μ	Liquid viscosity
ν	Order of the Gamma distribution
ρ	Density
σ	Surface tension

aments in several experimental situations (Marmottant and Villermaux, 2004a,b; Brémond and Villermaux, 2006; Tratnig and Brenn, 2010; Dumouchel et al., 2015; Kershavarz et al., 2016). The atomization of ligaments issuing from the Rayleigh-Taylor instability that develops on a cylindrical jet interface surrounded by a high-speed air stream reported order ν ranging from 2 to 4 according to the air velocity (Marmottant and Villermaux, 2004a). Considering the fragmentation of stretched liquid ligaments, Marmottant and Villermaux (2004b) found that the order ν of the drop diameter distribution is actually related to the deformation of the ligament at initial time, i.e., when it detaches from the bulk. This deformation is associated with a series of spherical blobs of diameter δ that allows fitting the initial ligament. It is established that:

$$\nu = \frac{\delta_{10}^2}{\delta_{20}^2 - \delta_{10}^2} \quad (2)$$

where δ_{10} and δ_{20} are the arithmetic and surface mean diameters of the spherical blobs (refer to Mugele and Evans (1951) for the mean diameter series definition).

The investigation of stretched ligaments (Marmottant and Villermaux, 2004b) underlines the random nature of the outcoming droplet size which manifests by different ligament deformations at initial time for identical operating conditions. It also demonstrates that the stretching motion of the ligament during its formation damps the capillary contraction. Stretching therefore influences the detachment event and the subsequent initial deformation.

The influence of the shape of a ligament on its behavior has also been addressed by Tong and Wang (2007). This numerical investigation of moderately elongated ligaments demonstrated that their relaxation dynamic was governed by the initial shape of the ligament and by its Ohnesorge number. In particular the end shape of the ligament is essential in the breakup process.

In a previous work (Dumouchel et al., 2015), ligaments emanating from highly-perturbed liquid sheets was investigated. A multi-scale tool described the ligaments from their detachment from the bulk flow to their subsequent breakup. One of the advantages of this tool is its ability to describe any system with a continuous function – the scale distribution – even if it is constituted of a few droplets. Furthermore, the requirement for these droplets to be spherical is not necessary anymore and the multi-scale tool includes this information in the description it provides. Thanks to this tool, the investigation of individual ligaments was performed. The analysis introduced the notion of equivalent system, i.e., a set of spheres whose scale distribution is the same as the actual system. The equivalent system corresponding to the drops was found to have a diameter distribution well represented by a Gamma distribution. The order ν ranged from 3 to 125 and appeared connected to a Weber number defined as the square of the product of the initial ligament capillary time with its stretching rate. This Weber number was associated with the presence of thin liquid threads between bulges during the ligament deformation. These threads were able to produce small droplets according to a mechanism described by Tong and Wang (2007). However, the connection between this number and the initial deformation of the ligament was not established.

Finally the Gamma distribution was found able to represent the size distribution of droplets issuing from the atomization of an air-assisted jet of polymeric solutions (Kershavarz et al., 2016). That investigation also pointed out the existence of a minimum value for the order ν ($\nu_{\min} = 4$) for ligament mediated sprays. Surprisingly, some results in the literature (Marmottant and Villermaux, 2004a, Dumouchel et al., 2015) reported smaller values for the order ν.

The present experimental work considers the ligaments that emanate from highly-perturbed liquid sheets shaped by a double contra-rotating swirling flow. The objective is to identify the origin of the dispersion of the drops they produce. The investigation concentrates on the impact of the initial deformation of the ligaments and of the dynamics of the thin threads they develop while approaching breakup. Contrary to the previous investigation mentioned above (Dumouchel et al., 2015), the ligaments are not individually considered, but a mean behavior is searched. Therefore the randomness of the ligament production and atomization are out of the context of this work. In order to identify representative and general behaviors, it is decided to consider uncorrelated working conditions which are achieved by using several liquids with different physical properties. The analysis of the atomization process and of the spray is based on the multi-scale description of the liquid system. To demonstrate the positive contribution of the multi-scale tool is also an objective of this work.

2. Experimental setup, diagnostic and image processing

The experimental setup allows feeding an atomizer with a liquid kept in a pressurized tank. This tank is equipped with a piston separating the two phases and avoiding air dissolution in the liquid when the gas is under pressure. The pressurization of the reservoir is controlled by the compressed network of the laboratory. The liquid is filtered and the injection pressure taken as reference is measured just before the atomizer. This latter is mounted on a 3D displacement system and the spray it produces is gently evacuated by an aspirating system.

The atomizer is equipped with a triple-disk nozzle made of the superposition of three circular disks each of them being perforated by a circular orifice (see Fig. 1). The circular hole in disk 3 is the atomizer discharge orifice. As illustrated in Fig. 1, the disks differ by their thickness as well as by the diameter of their orifice. Furthermore, the shift of the discharge orifice-axis, i.e., the eccentricity e, is an important geometrical characteristic of the nozzle. As demonstrated in a previous experimental investigation (Dumouchel et al., 2005), the triple-disk nozzle favors the development of a turbulent flow with a double contra-rotating swirl in the discharge orifice which results in the production of a 2D highly-perturbed liquid sheet. This sheet reorganizes as a ligament network which atomizes into droplets of different size. The surface energy per unit volume of the spray correlates with the sum of the non-axial kinetic energy and of the turbulent kinetic energy of the flow issuing from the nozzle (Dumouchel et al., 2005).

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