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Towards an interpretation of the scale diffusivity in liquid atomization process: An experimental approach

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HIGHLIGHTS

- Detailed scale diffusion mechanism of atomizing liquid jets is achieved.
- Atomization divides the scale space into elongation and contraction sensitive scales.
- Two phases of the atomization processes are identified.
- During the process, the contracting scales diffuse in the elongating ones.
- The scale diffusivity characterizes this diffusion mechanism.

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ABSTRACT

Recent investigations have presented an application of the scale entropy diffusion theory to model liquid atomization process. This theory describes multi-scale behavior by a diffusion equation of the scale entropy function. In atomization, this function is related to the scale-distribution which provides a measurement of the specific-length of the eroded liquid system according to the scale of erosion. The present paper performs a detailed description of the scale diffusion mechanism for the atomization process of a liquid jet emanating from a gasoline injector with the objective of determining the scale diffusivity parameter introduced by the diffusion theory. The 2-D description of the gasoline jet as a function of the injection pressure reveals that the scale space is divided into two regions according to the sign of the scale specific-length variation rate: The small-scale region refers to the scales that undergo an elongation mechanism whereas the large-scale region concerns the scales that undergo a contraction mechanism. Furthermore, two phases of the atomization process are identified depending on whether the elongation mechanism is governed by the jet dynamics or surface tension effects. A non-dimensional number segregating these two phases is established. During the atomization process, the contraction mechanism diffuses in the small scale region. This manifests by a temporal decrease of the scale with a zero specific-length variation. It is found that the scale diffusivity parameter can be determined from the evolution of this characteristic scale in the second phase of the atomization process.

1. Introduction

The atomization of a liquid jet ejected into a gaseous environment is a process during which the jet deforms and fragments until a flow of stable droplets of different size and velocity, called a spray, is formed. The prediction of the spray

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drop-size distribution has always been considered as an important issue and still requires specific investigations aiming to develop liquid atomization models. Visualizations found in the literature demonstrate the multi-scale nature of atomization processes. The fractal concept due to Mandelbrot [1] was convoked to describe the tortuosity of the atomizing system contour [2,3]. It reported that atomizing liquid systems require a scale and time-dependent fractal dimension to be fully described. This deviation from pure fractality has been pointed out for different systems and a specific geometrical framework to describe these systems and their temporal evolution has been introduced by Queiros-Conde [4] in the context of turbulent interfaces. Derived from the entropic-skins geometry formalism [5], this model defines the scale entropy function to describe the system and uses a diffusion equation to model its temporal evolution. Similar to a 1-D heat diffusion equation with a local heat production term, this scale entropy diffusion equation introduces the concepts of scale diffusivity and of scale entropy flux sink or scale-evolutivity. The scale diffusivity defines the capacity for the system to propagate perturbations through scale-space [6] and the scale-evolutivity describes variation of the evolutive potential (i.e., the scale entropy flux) of the system. The scale entropy diffusion model has been applied to turbulent interfaces and turbulent flames [4,7]. Among other results, an expression for the scale diffusivity has been established for turbulent interfaces.

In the context of two-phase flows, the scale entropy diffusion model has been applied on a liquid spray [8] and on the atomization of a liquid sheet [9–11]. The analysis of a liquid spray revealed a constant scale entropy flux gradient through scale space which corresponds to a parabolic behavior for scale analysis [8]. In the description of the liquid sheet atomization, it has been evidenced that the scale entropy function can be obtained from the cumulative scale-distribution $E_2(d)$ introduced in a previous investigation [12]. Performed on 2D images, this distribution is obtained from the application of the Euclidean Distance Mapping (EDM) method which is a "sausage technique" to determine the fractal dimension of a contour [13]. $E_2(d)$ is a measurement of the proportion of surface loss caused by erosion operations at successive increasing scales. Its first-derivative according to the scale is a 2D and generalized version of the concept of specific-area introduced by Evers [14]. The specific-area designates the interface surface per unit liquid volume and the surface energy of a two-phase system is proportional to this quantity. It is therefore relevant in atomization. In the present case, the 2D description reports specific-length quantity and the generalization means that this specific-length is considered as a function of the scale, becoming the scale specific-length. The application of the scale entropy theory to describe liquid sheet atomization revealed that the process of flow deformation, fragmentation and droplet production is associated to a continuous evolution of the scale entropy function [9]. The scale diffusivity was determined and correlated to the experimental operating conditions [10] and a scale parabolic behavior was identified in the small scale region [11].

Although these previous investigations demonstrate the interesting potential of the use of the scale entropy diffusion theory in the context of liquid atomization, they show a limitation: the procedure to determine χ does not suit other systems than turbulent liquid sheets. Overcoming this problem requires a good understanding of the scale diffusion mechanism in the context of liquid atomization processes. For this task, the recent introduction of the concept of the scale-diameter could be considered [15]. This length is equal to the inverse of the first derivative of $E_2(d)$. The temporal evolution of the scale-diameters leads to a scale segregation according to their own perception of the whole system evolution. Furthermore, for the case of atomizing stretched ligaments, the quality of this perception allows identifying the physical mechanisms involved in the breakup process [15].

The present investigation aims to produce a multi-scale analysis of the atomization process of a jet produced by a Gasoline Direct Injector (GDI) with the objectives of reaching a detailed description of the scale diffusion mechanism and of determining the scale diffusivity parameter. Despite the injector is conceived to work in transient conditions and has three identical discharge orifices, the study concentrates on one of the three jets and during the fully open stage of the injector only. Furthermore, the injection pressures are mainly low to ensure exploitable visualizations of the atomization process. Section 2 presents the scale entropy diffusion model and the scale diffusivity parameter. The experimental work is presented in Section 3. The experimental results and their analysis are the subject of Section 4.

2. The scale entropy diffusion model and the scale diffusivity

The scale entropy diffusion model as it is used in the present context has already been presented in previous articles [9,10] and is summarized here only. This model concerns the temporal evolution of multi-scale systems showing scale- and time-dependent fractal dimensions. At each instant, the system is described by the scale entropy function $\Sigma(x, t)$. This function is a global quantity that monotonously decreases and reaches zero for the outer cutoff scale of the system. The scale entropy can be seen as a quantification of the representativeness of a scale d on the system's morphology: the smaller the scale entropy is, the more organized is the shape of the system at this scale. The diffusion model suggests modeling the temporal evolution of the system by the following diffusion equation [4]:

$$\frac{\partial^2 \Sigma(x,t)}{\partial x^2} - \omega(x,t) = \frac{1}{\chi}\frac{\partial \Sigma(x,t)}{\partial t}. \tag{1}$$

The variable x is defined by $x = \ln(d/d_{ocs})$ where d is the scale and d_{ocs} is a characteristic outer cutoff scale of the problem. In turbulence, this scale would be the integral scale. In Eq. (1) the parameter χ is the scale diffusivity and the function $\omega(x, t)$ is the scale entropy flux sink defined by a unit of scale logarithm. It is in fact a scale entropy flux density. Queiros-Conde [4] emphasizes the analogy between Eq. (1) and the one-dimensional heat conduction equation: the scale logarithm x would