

Mechanistic Model for the Breakup Length in Jet Atomization

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ABSTRACT

In jet atomization, breakup length is the length of the continuous jet segment, before its breakup to discontinuous droplets. Hydrodynamic instability theory, implemented in CFD codes, is often complemented by semi-empirical correlations for breakup length, which may limit parametric investigations. A basic mechanistic approach to the breakup length prediction, based on a simple momentum balance between the injected jet and the aerodynamic drag force due to the surrounding gas, which complements the classic hydrodynamic instability breakup mechanism, is suggested. This model offers a simple complementing mechanistic model. It is shown that obtained results compare well with published experiments, and with the established empirical correlation of Wu and Faeth (1995). A simplified version of the model, taking into account an inviscid hydrodynamic model is shown to maintain plausibility of breakup length predictions in fuel-injection relevant conditions.

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INTRODUCTION

The ever growing interest in low pollutant emissions and improved fuel economy of combustion systems has necessitated the quest for improved liquid fuel combustion efficiency, which is strongly dependent on fuel atomization. The atomization process has been studied by experimental, computational and theoretical means. Jiang et al. [1] have carried out a substantial review of studies on liquid fuel atomization, mainly from computational fluid dynamics (CFD) point of view. Many recent studies have addressed linear and nonlinear analyses of instabilities and distortion of liquid streams injected into a gaseous media, with various fundamental breakup mechanisms and predictive capabilities being addressed (see examples in Sirignano and Mehring [2]; Qian et al. [3]). Atomization processes play a significant role in the combustion of liquid fuels injected into gas turbines, internal combustion (IC) engines and incinerator combustors, in order to achieve proper mixing of fuel and air and for rapid evaporation and combustion (Stiesch [4]). The coupling between fuel atomization and fuel-air mixing processes and the engine combustion emissions has been identified by many previous studies (as see in Baumgarten [5]). The in-depth understanding of the science of atomization is paramount for improved design and analysis of internal combustion engines. However, such understanding is still developing, given the inherent complexity surrounding the multiphase flows of the atomization processes.

The breakup of liquid is divided into two main processes: the primary atomization and the secondary atomization processes, which is illustrated in Figure 1. The primary atomization processes take place

in the near nozzle region, and combine effects of hydrodynamic and aerodynamic interactions with ambient gaseous phase and the internal phenomena of the nozzle flow, such as cavitation and turbulence. The secondary atomization processes, which take place down the flow stream, do not depend on the nozzle internal flow, but on the aerodynamic and hydrodynamic interactions processes of detached liquid droplets (Hadsen et al. [6]). The breakup of the bulk liquid, which may be a jet, sheet or film, is a result of several complex physical interactions: aerodynamic, surface tension, viscous and inertial. These determine the atomization characteristics, namely, breakup time and length, droplet size, spray angle and velocity distribution. An understanding of the interactions is crucial to the characterization of the breakup mechanism. Much experimental work on primary atomization of liquid streams of Newtonian fluids free of external forcing has been reviewed in (Dumouchel [7]).

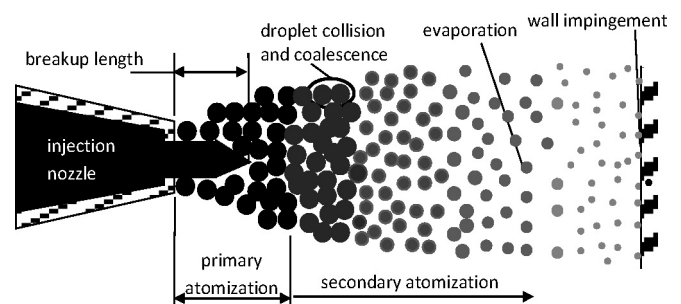


Figure 1. Illustration of Liquid Breakup Processes

Amongst the characteristics of breaking jets of most interest are the breakup length and the drop size. The graphical representation of the breakup length and the injection velocity, mostly referred to as the stability curve, is illustrated in Figure 2.

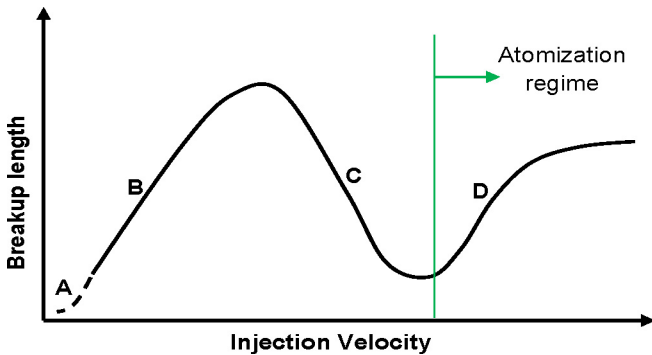


Figure 2. Stability Curve showing Primary Breakup Mechanisms (Dumouchel [8])

The Letters, A, B, C, and D in Figure 2, indicate the Rayleigh, first-wind induced or wind assisted, second-wind induced and atomization regime of primary breakup, respectively (Dumouchel [7]). The atomization regime of the primary breakup (D), as shown in Figure 2, is the most prevalent in diesel direct injection systems and in most other combustion systems as it produces the smallest droplets.

Young and Laplace may be considered as the pioneer researchers that set the stage opened for the systematic mathematical study of liquid breakup [9]. However, Savart in 1833 was the first to propose that liquid jet breakup are controlled by some physical laws. Savart attributed the physical laws to intermolecular attraction without the recognition of other important effects. Plateau in 1849, however, recognized the important role the surface tension plays in liquid breakup, as pioneered by Young and Laplace. The second half of the nineteenth century, which coincided with the industrial revolution, pushed forward the role of surface tension in liquid breakup - theoretical and experimental wise. Notable contributors to the theory of liquid breakup are: Eötvös in 1886, Quincke in 1877, Lenard in 1887 and Bohr 1901. Theoretically, Rayleigh's linear instability analyses were the cornerstones for the analyses of liquid breakup mechanism (interested reader should see Eggers [9] for the detailed history of liquid breakup). Reitz and Bracco [10] theoretically investigated the mechanism of liquid jet breakup under the influence of aerodynamic interaction between the liquid jet and the ambient gas (the theory is anchored on Castleman's postulation[10]). However, the theoretical analysis is stressed for spray angle without direct consideration of the breakup length, which is a measure of jet instability.

Experimental measurements have contributed significantly to the understanding and development of atomization technology over the last eighty years (Dumouchel [7]). Nonetheless, some important insights into atomization processes are achievable through the use of simplified basic mathematical models (Shepard Jr. and Palan [11]; Qian et al.[3]).

BREAKUP LENGTH OF THE ATOMIZATION REGIME

There are divided opinions regarding the predominant breakup mechanisms for the atomization regime, which include: hydrodynamic forces, aerodynamics interaction, turbulence, cavitation and bursting effect in vibration induced breakup. Given the uncertain detailed mechanisms of the atomization regime, some workers in this field assert that the jet breakup length increases with increasing velocity (Shibata et al., [12], while others Gulder et al. [13]) have suggest that the breakup is right at the nozzle exit, therefore, breakup length is negligible. However, there is strong experimental evidence, which suggests that the atomization regime breakup length at low velocity is comparable to the jet diameter (Yule and Salters [14]; Dumouchel [8]). Hiroyasu and Arai [15] investigated the structures of fuel sprays in diesel engine in the near-injector region of the flow and suggested that liquid core length, which is the breakup length, exists. While opinion regarding the presence of an intact liquid core still ranges, recent works by Kastengren et al. [16] and Pickett et al. [17] on the x-ray measurements of diesel sprays, which is based on time-resolved x-ray radiography of sprays, have also shown that an intact liquid core is present. Experimental measurements have contributed significantly to the understanding and development of empirical and semi-empirical models for the breakup length (Siebers [18]; Sallam et al. [19]; Sallam et al. [20]).

Based on extensive experimental data, liquid breakup length correlations for turbulent jets are mainly grouped into three categories (Lee et al. [21]; Egger and Villermaux [22]) as follows: (a) the onset of turbulent primary breakup along the liquid surface (b) the end of turbulent primary breakup along the liquid surface and (c) breakup of the entire liquid column as a result of the turbulent primary breakup mechanism, the atomization regime. The widely accepted and used empirical correlation, which assume that inertial and surface tension forces dominate in the near-field breakup regime, for breakup length in breakup of the entire liquid column due to the turbulent primary breakup mechanism is the one introduced by Wu and Faeth [23], which was also verified in Sallam et al. [20]):

$$L_{bu}^* = \frac{L_{bu}}{d_j} = 9.37 We_0^{0.34} \quad (1)$$

where L_{bu}^* is the dimensionless breakup length, L_{bu} is the breakup length, d_j is the nozzle exit diameter and $We_0 \equiv \rho_j r_j U_0^2 / \sigma$ is the Weber number of the jet; also, ρ_j is the density of the liquid jet, U_0 is the jet velocity at the nozzle exit and σ is the surface tension of the liquid jet.

The Wu and Faeth [23] empirical breakup length correlation offers good predictive performance despite the fact it doesn't account for aerodynamic interactions of the jet with the surrounding gas, nor for any viscous effects. The following suggested model offers a mechanistic model based breakup length theoretical correlation, that accounts for the jet's aerodynamic drag (by surrounding gas), complementing the classical viscous hydrodynamic instability breakup model.