Numerical investigation of turbulent-jet primary breakup using one-dimensional turbulence

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ABSTRACT

Primary breakup to form droplets at liquid surfaces is an important fundamental process to study as it determines the initial properties of the dispersed phase, which affect mixing rates, secondary breakup, droplet collisions, and flow separation within the dispersed flow region. Primary breakup can be regarded as one of the least developed model components for simulating and predicting liquid jet breakup. However, it is of paramount importance in many technical applications, e.g. fuel injection in engines and spray painting. This paper presents a numerical investigation of primary breakup of a turbulent liquid jet in still air at standard conditions using the one-dimensional turbulence (ODT) modeling framework. ODT is a stochastic model that simulates turbulent flow evolution along a notional 1D line of sight by applying instantaneous maps to represent the effect of individual turbulent eddies on property profiles. An important feature of ODT is the resolution of all relevant scales, both temporal and spatial. The restriction to one spatial dimension in ODT permits affordable high resolution of interfacial and single-phase property gradients, which is key to capturing the local behavior of the breakup process and allows simulations at high Reynolds and Weber numbers that are currently not accessible to direct numerical simulations (DNS).

This paper summarizes our extensions of the ODT model to simulate geometrically simple jet breakup problems, including representations of Rayleigh wave breakup, turbulent breakup, and shear-driven breakup. Each jet breakup simulation consists of a short temporal channel section to initialize a turbulent velocity profile at the nozzle exit followed by an adjacent jet section. The simulations are carried out for jet exit Reynolds number of 11,500, 23,000, 46,000 and 92,000 while the Weber number is varied within the range 10^2–10^7. We present results on breakup statistics including spatial locations of droplet release, droplet sizes and liquid core length. The results on primary breakup are compared to experimental results and models.

1. Introduction

The breakup of liquid jets is of paramount importance in many technical processes, e.g. injection of liquid fuel in engines, spray painting, and spray forming of metals. In the case of liquid fuel injection into engines, primary breakup determines initial droplet sizes and velocities and therefore impacts all subsequent processes such as secondary breakup, droplet collisions, droplet evaporation, and ultimately fuel–air mixing, which plays a central role in combustion efficiency and emissions.

The important influence of the atomization process on the overall system performance has led many researchers to focus on modeling and simulating liquid jet breakup and subsequent droplet formation with approaches ranging from fundamental investigations using DNS (Desjardins et al., 2008; Herrmann, 2011; Lebas et al., 2009; Shinjo and Umemura, 2010; 2011) and large-eddy simulation (LES) (Apte et al., 2003; Chesnel et al., 2011; Dam and Rutland, 2015; Jhavar and Rutland, 2006; Mahesh et al., 2006) to more applied engineering models based on the Reynolds averaged Navier Stokes (RANS) equations (O'Rourke and Amsden, 1987; Reitz, 1987; Tanner, 1997; Toninin et al., 2008).

In the latter engineering approach the gaseous phase is solved in an Eulerian frame whereas the dispersed phase is typically by modeled via Lagrangian parcels, each of which represents many

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droplets of a single size or a size distribution. The spray breakup process in these Eulerian–Lagrangian simulations can be modeled using standard deterministic breakup models based on Taylor analogy breakup (TAB) (O'Rourke and Amsden, 1987; Tanner, 1997) or wave models (Reitz, 1987). In both models, liquid blobs the size of the injector diameter are introduced into the simulation and undergo secondary breakup and atomization based on the balance between aerodynamic and surface tension forces acting on the liquid phase. Tuning is usually necessary every time the flow conditions are changed to achieve satisfactory results.

Apte et al. (2003) developed a stochastic secondary breakup model based on Kolmogorov's discrete model of breakup. The breakup process is simulated via a stochastic Fokker–Planck equation for the droplet radius. The model creates a broad spectrum of droplet sizes and the parameters of the model are computed dynamically based on the local Weber number, i.e. with less tuning than the standard blob model. However, the simulation starts by introducing computational blobs as in the models above. The model is applied in Apte et al. (2009) to simulate the atomization process in a gas-turbine swirl injector.

The above mentioned DNS and LES approaches are in principle capable of predicting primary breakup processes but due to computational costs they are usually limited to low Reynolds and Weber numbers. The number of grid points in a DNS needed to capture the physics increases with increasing Reynolds number, scaling as $Re^{9/4}$, which makes DNS (and LES in many cases as well) unfeasible for typical industrial applications with high Reynolds numbers and high Weber numbers.

There are only a few (simplified) models available for engineering applications which are actually simulating primary breakup. All have in common the use of an Eulerian description of the liquid phase close to the nozzle. The goal is to describe realistically the dense zone of the spray and its atomization. In the ELSA (Eulerian–Lagrangian spray atomization) model (Vallet et al., 2001), additional Eulerian transport equations for the liquid mass and the liquid surface density are solved. Production and destruction of liquid surface density due to shear, turbulence, collisions, and evaporation are accounted for via modeled source terms (Lebas et al., 2005; Ning et al., 2007). Besides the Eulerian zone describing the dense region of the spray, the model features a transition zone to switch from the Eulerian to the Lagrangian calculation and a Lagrangian zone with classical tracking of droplets. The ELSA model is usually implemented in conjunction with RANS turbulence models. Although the model and its further developments and variants have been an important step forward in modeling the dense region of the spray it still needs tuning and the form of the interface density equation that is used remains open to discussion.

The lack of predictive primary breakup models is partly due to our incomplete knowledge of the underlying physics close to the nozzle. Only recently have experimental techniques like ballistic imaging (Linne, 2013; Linne et al., 2009) enabled detailed investigation of phenomena in the optically dense region of the liquid core of a jet. In addition, DNS (Herrmann, 2010; Lebas et al., 2009; Shinjo and Umemura, 2010) is now able to provide in-depth knowledge of primary breakup for moderate Reynolds and Weber numbers, which will help to develop and validate new models. Certainly, the development of a predictive model for primary breakup is highly desirable not only from an application point of view but also to gain a better understanding of the relevant physical processes.

The main objective of the present paper is the development of a new computational model for primary jet breakup that is both computationally efficient and more predictive than other low-cost approaches. We propose a new model for simulating and predicting primary jet breakup that is based on a stochastic one-dimensional approach, namely one-dimensional turbulence

(ODT). We describe our extensions of the original ODT formulation (Ashurst and Kerstein, 2005; Kerstein, 1999) to gas–liquid multiphase flow to capture breakup mechanisms such as Rayleigh breakup, turbulence induced breakup, and shear-driven breakup. The low computational costs of ODT compared to fully resolved three-dimensional DNS overcomes the limitation of DNS to moderate Reynolds and Weber numbers and therefore allows exploration of the full parameter range of technically relevant breakup regimes while maintaining high spatial and temporal resolution of relevant phenomena.

We apply our method to the simulation of the stationary breakup process of a planar jet in air at standard conditions and present results for the location of the onset of breakup at the jet surface, the liquid column length, and parameter dependences of droplet sizes. The main results are presented in the form of a breakup regime map as presented by Wu and Faeth (1995) and Sallam et al. (2002) and are compared to their experimental results.

The paper is organized as follows: after a description of the ODT model in the next section, we present a validation study of ODT for turbulence decay in a liquid jet without breakup based on comparison of the results to measurements. The validation is followed by the investigation and discussion of liquid jet breakup for a range of Weber numbers.

2. ODT formulation

2.1. Background and objectives

The ODT model of Kerstein used in this study is briefly described in this section. For a fully detailed description we refer to Kerstein (1999), Kerstein et al. (2001), and the variable-density extension by Ashurst and Kerstein (2005). ODT is a stochastic model of turbulent flows that solves the unsteady one-dimensional transport equations for mass, momentum, and optionally other scalars such as species mass fractions.

The main advantage of using one-dimensional unsteady stochastic simulation is that it enables affordable simulation of high-Reynolds-number turbulence over the full range of dynamically relevant length scales. In particular, it affordably resolves property gradients needed to capture details of jet primary breakup. DNS provides such information for moderate Reynolds numbers but with much higher computational cost and a limited range of scales.

Meaningful applications of ODT are limited to relatively simple flow configurations, e.g. boundary layer flows (Kerstein, 1999), jets (Echekki et al., 2001) and mixing layers (Ashurst and Kerstein, 2005; Kerstein et al., 2001). For those flow problems ODT has been shown to produce the correct scaling laws and often to provide qualitatively and quantitatively good agreement with measurements and DNS results.

The present work focuses on modeling primary breakup along liquid turbulent jet surfaces and needs further extension of the ODT modeling approach. The successful application of ODT to multiphase flows may provide an additional tool for investigating such flows, especially if combined with DNS and experimental data.

2.2. Governing equations

The flows investigated in this study are governed by the incompressible lorred Navier–Stokes equations for immiscible two-phase flow. The momentum equation is given by

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot [\mu(\nabla u + \nabla^T u)] + \frac{1}{\rho} T_\sigma, \qquad (1)$$

where u is the velocity, ρ the density, p the pressure, μ the dynamic viscosity and T_σ the surface tension force which is nonzero