International Journal of Multiphase Flow 60 (2014) 103–118

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

LES of turbulent liquid jet primary breakup in turbulent coaxial air flow ☆

F. Xiao [1], M. Dianat, J.J. McGuirk *

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough LE11 3TU, UK

ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 27 November 2013
Accepted 28 November 2013
Available online 8 December 2013

Keywords:
Large eddy simulation
Primary breakup
Liquid jet in coaxial air flow
Core breakup length
Synthetic LES inlet conditions

ABSTRACT

A robust two-phase flow Large Eddy Simulation (LES) algorithm has been developed and applied to predict the primary breakup of an axisymmetric water jet injected into a surrounding coaxial air flow. The high liquid/gas density and viscosity ratios are known to represent a significant challenge in numerical modelling of the primary breakup process. In the current LES methodology, an extrapolated liquid velocity field was used to minimise discretisation errors, whilst maintaining sharp treatment of fluid properties across the interface. The proposed numerical approach showed excellent robustness and high accuracy in predicting coaxial liquid jet primary breakup. Since strong turbulence structures will develop inside the injector at high Reynolds numbers and affect the subsequent primary breakup, the Rescaling and Recycling Method (R^2M) was implemented to facilitate generation of appropriate unsteady LES inlet conditions for both phases. The influence of inflowing liquid and gas turbulent structures on the initial interface instability was investigated. It is shown that liquid turbulent eddies play the dominant role in the initial development of liquid jet surface disturbance and distortion for the flow conditions considered. When turbulent inflows were specified by the R^2M technique, the predicted core breakup lengths at different air/water velocities agreed closely with experimental data.

1. Introduction

Atomisation of liquid jets in coaxial air flow (air-blast or air-assisted atomisation) has been widely used in combustion systems of gas turbines and rocket engines. Rapid liquid fuel atomisation exerts an important influence on fuel/air mixing, and thus affects combustion performance significantly. Study of this atomisation process is fundamentally important, but also very challenging.

In order to describe the atomisation of a single round liquid jet injected into a coaxial annular gas flow, the following characteristic non-dimensional parameters have traditionally been used: the gaseous Weber number We_G, liquid and gas Reynolds numbers Re_L and Re_G, momentum flux ratio M, and momentum ratio MR, defined as:

$$We_G = \frac{\rho_G (U_G - U_L)^2 D_L}{\sigma} \quad (1)$$

$$Re_L = \frac{\rho_L U_L D_L}{\mu_L} \quad Re_G = \frac{\rho_G U_G D_G}{\mu_G} \quad (2)$$

$$M = \frac{\rho_G U_G^2}{\rho_L U_L^2} \quad MR = \frac{\rho_G U_G^2 A_G}{\rho_L U_L^2 A_L} \quad (3)$$

Here, D_L is the liquid jet round nozzle diameter; D_G is the hydraulic diameter of the annular gas nozzle; A_L and A_G are cross-sectional areas of round liquid and annular gas nozzles; ρ_L and ρ_G are the densities of liquid and gas; μ_L and μ_G are liquid and gas dynamic viscosities; U_L is the liquid injection speed; U_G is the velocity of the coaxial gas flow; finally σ is the liquid surface tension coefficient.

Experimental studies of air-assisted atomisation using a coaxial jet configuration have been carried out by many researchers; a recent review by Dumouchel (2008) has provided a useful summary. Faragó and Chigier (1992) classified the air-assisted atomisation into five regimes (axisymmetric Rayleigh breakup, non-axisymmetric Rayleigh breakup, membrane breakup, fibre breakup, and superpulsating breakup) via a map of gaseous Weber number vs. liquid Reynolds number. Lasheras and coworkers (Lasheras et al., 1998; Lasheras and Hopfinger, 2000) carried out their experiments using a different atomiser in term of geometrical dimensions (liquid jet diameter, gas/liquid diameter ratio), and suggested that the momentum flux ratio M is an important and additional parameter to Re_L and We_G for a universal classification of air-assisted atomisation.

The primary breakup of a liquid jet in a coaxial flow can be divided into two stages: initial jet surface perturbation is triggered near the nozzle exit; this perturbation is then amplified under the influence of aerodynamic forces, resulting in jet breakup. When the

* Corresponding author. Tel.: +44 1509227211.
E-mail address: j.j.mcguirk@lboro.ac.uk (J.J. McGuirk).
[1] Current address: College of Aerospace Science & Eng., Nat. Univ. of Defense Tech., Changsha, China.

0301-9322/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.11.013

liquid flow is turbulent inside the nozzle (as is inevitable if the central and/or annular jet Reynolds numbers are large enough), Eroglu and Chigier (1991) and Mayer and Branam (2004) argued that the initial perturbation arose from eddies originating in the liquid jet. For the case that jets are injected from a nozzle under laminar conditions, Marmottant and Villermaux (2004) suggested that the initial destabilisation is caused by a Kelvin–Helmholtz instability; the most unstable wavelength is then proportional to the thickness of the gaseous boundary layer formed in the annular nozzle. In the second stage, the initial surface perturbations grow due to aerodynamic interactions, liquid structures protruding from the liquid surface are accelerated by form drag due to the gas flow, making them subject to the Rayleigh–Taylor instability, and finally ligaments and droplets disintegrate from the liquid jet surface.

The liquid core length (or liquid jet breakup length) L_C is the axial downstream location where the continuity of the liquid jet discharged from the nozzle exit is interrupted over the entire jet cross-section, and is considered a fundamental and important parameter for evaluation of atomisation performance. Measurement of L_C has been carried out by many authors (see Eroglu et al., 1991; Engelbert et al., 1995; Lasheras et al., 1998; Porcheron et al., 2002; Leroux et al., 2007), and several correlations have been proposed as indicated in Table 1. Although each correlation shows appropriate agreement with the experimental data from which it was deduced, no single correlation is able to predict correct liquid core length for other experiments. Since the characteristics of the flow developed inside the nozzles can considerably influence the primary breakup, the liquid core length will inevitably be strongly dependent on the details of the injector geometry. This is a primary cause of the scatter or discrepancy in currently available empirical correlations. Another cause of inaccuracy is measurement error in the shadowgraph technique, which has commonly been used in experimental studies. Droplets stripped off the periphery of the central liquid jet during the early stages of breakup can obscure observation of the liquid core due to the line-of-sight nature of the technique. A novel optical technique, based on internal illumination of the continuous liquid jet core by Laser Induced Fluorescence (LIF) has been proposed by Charalampous et al. (2009a,b) for conducting measurements of liquid core length. Their data demonstrated that LIF can provide more accurate detection of the liquid jet geometry than the shadowgraph technique.

Numerical modelling of liquid jet atomisation has made significant progress since the 1970s, with the promise of eventually achieving as much success as for single phase flow (Fuster et al., 2009; Gorokhovski and Herrmann, 2008). In the last decade or so, most proposals have adopted the more expensive but more advanced Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) approach to turbulence modelling in order to capture unsteady effects on the interface dynamics. Unsteady numerical simulations can show many more details than are possible to capture in experiments, providing further insight into atomisation mechanisms. However, such numerical modelling of primary breakup of a liquid jet under the influence of strong aerodynamic and turbulence effects is still very challenging, especially for high liquid/gas density ratio O(1000). Numerical error arising from the high density ratio can be large (sufficient even to cause the simulation to fail), and many published numerical simulations to date have been limited to a liquid/gas density ratio no more than 100 (see Herrmann, 2010, Level Set (LS) interface tracking method; Herrmann et al., 2011, LS; Desjardins et al., 2008, LS; Pai et al., 2008, LS; Kim et al. (2007), LS; Fuster et al., 2009, Volume of Fluid (VOF); Tomar et al., 2010, VOF; Ménard et al., 2007, Coupled LS and VOF (CLSVOF); Lebas et al., 2009, CLSVOF; Shinjo and Umemura, 2010, CLSVOF). Since the majority of liquid jet atomisation experiments are carried out at atmospheric pressure with high density liquids, quantitative comparison between numerical modelling and experiment is quite rare. A robust method capable of dealing with the high density ratio of for example air–water systems is therefore of great interest (Fuster et al., 2009). In order to deal with this problem, Rudman (1998) proposed to advect the momentum using a density estimated from the interface geometry in cells intersected by the surface, aiming to improve the consistency between interface and momentum transport. This technique as well as a two-velocity Ghost Fluid Method were investigated by Desjardins and Moureau (2010), although they have not yet been demonstrated to work well in simulating liquid jet atomisation. Sussman et al. (2007) proposed an approach using a liquid velocity field extrapolated across the interface into the gas phase region. This approach was applied by Li et al. (2010) to simulate a liquid jet in air cross-flow at a high (650) density ratio. Adaptive Mesh Refinement and the removal of under-resolved small liquid structures were both necessary since the experimental data selected for comparison were far downstream. In spite of the advanced modelling, agreement with measurements was relatively poor (Li et al., 2010). A robust two-phase LES algorithm also making use of a modified extrapolated liquid velocity field has recently been proposed by Xiao (2012), and validated against experiments by simulating droplet and liquid jet primary breakup; it was demonstrated that the proposed method showed high robustness and good accuracy compared with experiments for air–water systems.

The objectives of the current paper are therefore: (i) to simulate a round water jet injected into a coaxial air flow at atmospheric pressure (a high density ratio of 830) and compare the predicted results directly with the experimental data and (ii) to investigate the mechanisms behind the initial jet surface disturbance and the liquid jet primary breakup. Note: the aspects of liquid jet primary breakup which are given particular focus in the present paper are the initial destabilisation of the liquid/air interface and the location of first complete rupture of the jet core. Whilst the subsequent ligament and droplet formation is captured in the simulations shown, the measured data used do not allow quantitative assessment of these aspects, and, in the far downstream region of the solution domain, the mesh density currently used is inadequate for this purpose, so this has been left for a separate study. The experimental tests of Charalampous et al. (2009a,b) are simulated, as the LIF technique used there can provide more accurate measurements of liquid jet core length. Due to the high Reynolds number of both liquid and gas streams, turbulent boundary layers undoubtedly develop on the internal nozzle walls of the injector system, and may influence significantly the primary breakup process. As in any LES prediction, the generation of unsteady 3D correlated inlet conditions is a challenging task. The Rescaling and Recycling Method (R^2M) developed by Xiao (2012) and Xiao et al. (2010) has shown good performance in single phase flows, and will therefore be implemented here. Since the inflow conditions can be specified as whatever one wishes in numerical modelling, the effect of turbulence on primary breakup is investigated by switching between laminar and turbulent inflow conditions. Since the breakup length is a parameter of great importance in performance assessment of air-assisted atomisation, the dependence

Table 1
Correlations for liquid core length.

Eroglu et al. (1991)	$\frac{L_c}{D_L} = 0.66We_G^{-0.4}Re_L^{0.6}$
Engelbert et al. (1995)	$\frac{L_c}{D_G - D_L} = 5.3MR^{-0.3}$
Lasheras et al. (1998)	$\frac{L_c}{D_L} = \frac{6}{\sqrt{M}}$
Porcheron et al. (2002)	$\frac{L_c}{D_L} = 2.85\left(\frac{\rho_G}{\rho_L}\right)^{-0.38}Oh^{0.34}M^{-0.13}$
Leroux et al. (2007)	$\frac{L_c}{D_L} = \frac{10}{M^{0.3}}$