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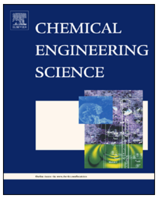

Influence of viscosity on the impingement of laminar liquid jets

Jiakai Lu, Carlos M. Corvalan*

Transport Phenomena Laboratory, Department of Food Science, Purdue University, West Lafayette, IN 47907, USA

HIGHLIGHTS

- We study the collision of viscous liquid jets solving the full Navier–Stokes system.
- The impact pressure is directly proportional to the viscosity of the jets.
- Sheet thickness decreases logarithmically with the distance from the impact point.
- Increasing viscosity increases the thickness and uniformity of the fluid sheet.

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ABSTRACT

The impingement of low-viscosity liquid jets has been studied extensively for over a century due to their fundamental scientific interest and their practical importance in spray and atomization technologies. However, the role of the fluid viscosity in the impingement dynamics is largely unknown despite the fact that viscous liquids are common in spray and atomization processes ranging from spray drying in the food industry to the atomization of gelled propellants in rocket engines. Here, we report direct numerical simulations that enable a detailed analysis of the influence of viscosity on the impingement dynamics. The simulations solve the complete Navier–Stokes system governing the free-surface dynamics, and so fully account for the interplay of inertia, viscous and capillary forces. Results show that the liquid viscosity profoundly affects the impingement dynamics. The collision of viscous liquid jets generates a fluid sheet that thins at a rate r^{-1} with the distance r from the impact point at intermediate viscosities, in contrast to the inertial case in which the sheet thins at a faster rate r^{-2}. As the viscosity increases, the fluid sheets become thicker and more uniform, and contrary to the inertial case, the velocity of the sheets is lower than the velocity of the jets. Results further reveal that due to viscous stresses the impact pressure generated by the collision of viscous liquid jets scales as Re^{-1}, where Re is the jet Reynolds number.

1. Introduction

The collision of two inviscid liquid jets facing one another has been extensively studied since the pioneering works of Savart (1833) and later Ranz (1959) and Taylor (1960) due to its fundamental fluid mechanics interest, and its practical importance in spray and atomization processes. As a result of these studies, we now know that liquid sheets resulting from the collision of low-viscosity liquid jets expand radially at constant speed unopposed by viscosity (Ranz, 1959; Taylor, 1960). As the inertial sheets expand, the liquid at the edge of the sheets accumulates in a toroidal rim which eventually disintegrates into drops at a distance from the impact point which is known as the Taylor radius (Taylor, 1960; Huang, 1970; Clanet and Villermaux, 2002; Bush and Hasha, 2004). Understanding this free-surface flow is relevant to diverse spray technologies including spray drying, spray painting and crop spraying, and is central to the production of food emulsions, the atomization of fuel in combustion engines, and the atomization of propellants in rocket engines for space and defense technologies (Lefebvre, 1989; Sutton, 1992; Ryan et al., 1993; Mahajan and Kirwan, 1996; Clanet and Villermaux, 2002; Bremond and Villermaux, 2006; Ashgriz, 2011).

Although the bulk of the research has focused on the dynamics of inertial jets, understanding the influence of viscosity on the dynamics of jet impingement is critical, as viscous fluids are ubiquitous in spray and atomization processes. Examples of these fluids include inks, paints, food emulsions and polymeric solutions, and, more recently, gelled propellants for rocket and missile engines (Kampen et al., 2007; Howell et al., 2010; Baek et al., 2011; Yang et al., 2012; Villermaux et al., 2013; Yang et al., 2014). These are typically highly viscous fluids, which may also exhibit non-Newtonian shear thinning and elastic behavior.

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* Corresponding author.
E-mail address: corvalac@purdue.edu (C.M. Corvalan).

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Recent studies using viscous glycerol solutions (Choo and Kang, 2001; Yang et al., 2014) and viscous alcohol-sugar solutions (Lai et al., 2010) have shown that the collision of viscous jets generates expanding sheets which are thicker than those generated from the collision of inviscid jets, with the consequent impact in sheet stability and drop size. However, how precisely viscous stresses influence the impingement dynamics, and how these dynamics determine the velocity and thickness of the expanding sheets remain poorly understood.

Here we use direct numerical simulation to gain insight into the influence of viscosity on the dynamics of jet impingement. In Section 2, we state the Navier–Stokes system governing the axisymmetric impingement of two facing laminar jets, and the finite-element procedure used to simultaneously solve the system for velocity, pressure and location of the interface by Newton iteration. In Section 3, we discuss the results from the simulations. By varying the liquid viscosity over about six decades, we identify the influence of viscous stresses in the dynamics of jet impingement at intermediate liquid viscosities, and contrast these findings against the inviscid and Stokes limits.

2. Problem description

The dynamics of jet impingement is analyzed here by following the evolution of the axisymmetric collision of two identical facing jets of an incompressible liquid of density ρ, viscosity μ, and surface tension σ (Fig. 1). The problem is described below in dimensionless form using the jet radius a as the characteristic length scale, $a\mu/\sigma$ as the viscous timescale, and σ/a as the stress and pressure scale.

The evolution of the liquid velocity $\mathbf{v}$ and pressure p is calculated by solving the full, axisymmetric Navier–Stokes system

$$\nabla \cdot \mathbf{v} = 0, \tag{1}$$

$$\mathrm{Re}^2 \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \nabla \cdot \mathbf{T}, \tag{2}$$

where $\mathbf{T} = \mathrm{We}/2(-p\mathbf{I} + \nabla\mathbf{v} + \nabla\mathbf{v}^T)$ is the dimensionless Cauchy stress tensor. The Reynolds number $\mathrm{Re} \equiv \rho \hat{U} a/\mu$, where $\hat{U}$ is the jet velocity, measures the importance of inertia relative to viscous forces.

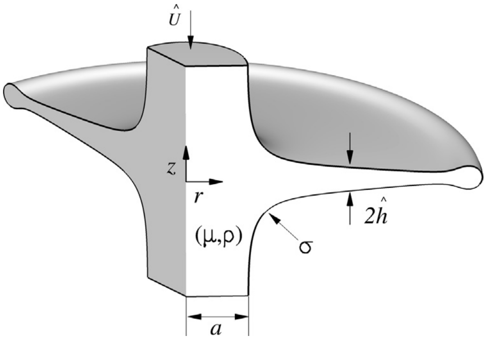

Fig. 1. Impingement of two laminar liquid jets. Axisymmetric impingement of two facing liquid jets of radius a and velocity $\hat{U}$. The density of the liquid is ρ, the viscosity μ, and the surface tension σ. The thickness of the radially expanding liquid sheet is $2\hat{h}$. The sheet profile corresponds to the case discussed in Fig. 2b.

The effect of capillarity enters in the Navier–Stokes system through the balance of forces at the free interface (Slattery, 1990):

$$\mathbf{T} \cdot \mathbf{n} = \mathrm{We} H \mathbf{n}, \tag{3}$$

where $\mathrm{We} \equiv 2a\rho\hat{U}^2/\sigma$ is the Weber number which measures the importance of inertial forces relative to surface tension forces, and $\mathbf{n}$ is the unit vector normal to the interface. The mean curvature of the interface H is calculated as $H = -1/2\nabla_s \cdot \mathbf{n}$, where $\nabla_s = (\mathbf{I} - \mathbf{nn}) \cdot \nabla$ is the surface gradient operator (Deen, 1998, p. 580; Slattery, 1990, p. 653). Simulations are carried out in the smooth region $\mathrm{We} < 1000$ in which the adjoining gas phase can be considered dynamically inert (Huang, 1970; Clanet and Villermaux, 2002).

The requirement that there is no mass transfer across the interface is guaranteed by imposing the kinematic condition

$$\mathbf{n} \cdot (\mathbf{v} - \mathbf{v}_s) = 0 \tag{4}$$

where $\mathbf{v}_s$ is the velocity of the points on the interface. At the plane and axis of symmetry the shear stress vanishes and the velocity normal to the boundaries are set to zero because of the non-flux condition.

The system of highly nonlinear Eqs. (1), (2) and (4) that governs the free-surface dynamics is solved simultaneously for velocity, pressure and location of the free interface using direct numerical simulation (Scardovelli and Zaleski, 1999). The simulations use the finite element method for spatial discretizations along with the arbitrary Lagrangian–Eulerian method of spines for accurate parametrization of the gas–liquid interface (Kistler and Scriven, 1983; Xue et al., 2008; Muddu et al., 2012; Lu and Corvalan, 2012). An adaptive trapezoidal method with the Adam–Bashforth predictor is used for time integration to minimize truncation errors (Gresho et al., 1980), and the first-order continuation method by Corvalan and Saita (1991) is used to adaptively select the time steps to improve computational efficiency. Finally, the system of nonlinear algebraic equations resulting from the spatial and temporal discretization is solved by Newton's method with full analytical Jacobian. To account for the sensitivities associated with the deformation of the free interface, the analytical Jacobian is calculated using the procedure developed by Kistler and Scriven (1983).

3. Results and discussion

By solving the full Navier–Stokes system of equations, the free surface model developed in Section 2 enabled a detailed analysis of the influence of viscosity on the dynamics of jet impingement. The analysis revealed important differences between the viscous and inertial impingement dynamics in both the early and late stages of sheet formation.

The influence of the liquid viscosity in the early stages of sheet formation is illustrated in Fig. 2, which compares incipient sheet profiles for three different Reynolds numbers. In the high Re case

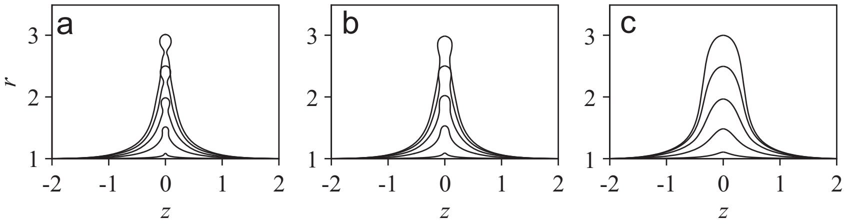

Fig. 2. Influence of viscosity on the shapes of radially expanding sheets. Profiles of axisymmetric liquid sheets during the early stages of expansion for (a) Re = 1000, (b) Re = 100, and (c) Re = 10. As the viscosity of the liquid increases, the thickness of the sheet increases, and viscous forces delay the formation of the toroidal bounding rim. Here We = 200, and the profiles correspond to sheet edges located at 1.1, 1.5, 2, 2.5 and 3 jet radii away from the impact point.