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Formation of fluid structures due to jet-jet and jet-sheet interactions

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HIGHLIGHTS

- Establishment of different sheet structures formed by the collision of low viscous water jets.
- Correlations are proposed to delineate the radial expanse of the liquid sheet in the azimuthal direction.
- Tracking of different phases of fingering instability as a precursor to drop formation and atomization.
- Collision of inertia based asymmetric jets forms sheet deflected from the median plane.
- Analytical modeling of sheet deflection predicts experimental observation with 95% accuracy.

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ABSTRACT

The main focus of the present work is to investigate the collision of two oblique cylindrical water jets through a series of experiments. Different regimes for the collision of water jets are illustrated and transitions to the fingering instability and subsequently to the violent flapping regime are discussed. The collision between high inertia and low viscous liquid jets is often used for generating liquid sheets which atomize to form droplets. They are mainly used in the combustion chambers of rocket engines involving liquid fuels having viscosity of the order similar to water. Further, inertia-based asymmetry is studied and an analytical method is proposed (L^1 error norm = 0.05) to understand the deflection observed in the plane of sheet formation. The resultant sheets formed are also compared with those generated by the collision of symmetric jets. The range of dimensionless numbers targeted in this study are within $10 \leqslant We \leqslant 1200$, $1.5 \leqslant Fr \leqslant 18.5$ and $1900 \leqslant Re \leqslant 20,000$. We have also illustrated the life cycle of a single sheet in the low inertial regime to form chain-like structures. At last, a different method of generation of multiple interconnected sheets is demonstrated through the distortion of a sheet by the impact of a liquid jet.

1. Introduction

The collision of liquid jets is one of the canonical configurations for generation of liquid sheets which gives way to atomized droplets in the high inertial regime. If the strengths of the jets are identical, the liquid sheet is formed in the median plane, ie., in a plane perpendicular to the axes of the jets and passing through the point of collision (Bush and Hasha, 2004). This configuration is usually employed in the afterburners of the aircraft or in the thrust engines used in rockets (Chen et al., 2013) and has advantages over the conventional coaxial liquid-gas jet atomization technique because of the improved inertial driven destabilization and mixing between jets (Erni and Elabbadi, 2013). Moreover, the droplets formed in this process come from the thin sheet, making the size distribution skewed towards the lower size and more evenly spread (Inoue et al., 2008, 2009) as compared to the droplets formed from the single jet atomization as in the latter case, droplets are ejected from a thick liquid core instead of a thin sheet. This aids in the post-atomization combustion process (Lhuissier and Villermaux, 2011). In a recent attempt, Visser et al. (2018) developed a chip-free platform to manipulate micro-scale liquid stream (jets) in the air. Such systems can be used to fabricate mono-disperse emulsions, particles, and fibers.

A wide range of experimental works can be found exploring the dynamics of collision of liquid jets (Ibrahim and Przekwas, 1991; Choo and Kang, 2002; Inamura and Shirota, 2014). In low inertial regime, the process features a stable sheet, bounded by a thick rim, in the median plane perpendicular to the axes of the jets (Bush and Hasha, 2004). As the inertia is increased, finger-like projections can be observed at some of the nodal points across the rim ejecting droplets. On further increase of inertial strength, violent

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atomization takes over as illustrated by Dombrowski and Fraser (1954). Taylor (1960) realized the importance of fluid inertia and interfacial surface tension on the process and emphasized on predicting the shapes of the leaf-like sheet bounded by a thicker rim. The rim is stable as long as the curvature force developed by surface tension provides the necessary centripetal acceleration (Bremond and Villermaux, 2006). On further increasing the inertia of jets, Kelvin-Helmholtz instability takes over and results in the formation of destabilizing waves (Villermaux and Clanet, 2002), which first leads to opening of the rim and fragmentation of the sheet. The rim becomes unstable as well with fingering instabilities leading to the formation of a large number of minute droplets in the violent flapping atomization regime. These features are important in the design of atomization chambers to make use of this configuration. Furthermore, Miller et al. (2005) explored the experimental results of the formed fluid sheet of viscoelastic liquid. They described flow kinematics and stability of thin fluid sheets formed by impingement of viscous fluid.

1.1. Motivation and objectives of the present study

Atomization patterns of less viscous fluids are more prominent and different destabilizing patterns like holes and waves can be easily identified (Zheng et al., 2015). Moreover, most of the liquid fuels have viscosities in the lower range and often many times smaller than the liquid used in the previous works (Bush and Hasha, 2004; Bremond and Villermaux, 2006; Choo and Kang, 2007; Yang et al., 2014). In order to bridge this gap, in the present study, we have selected water (low viscous fluid) as the working fluid to explore different modes of jet-jet and jet-sheet interaction. Further, in all the works described above, the constituting jets have equal inertial strengths and as a result, the sheet is formed in the median plane. In this regard, it can be mentioned that inception of fingering instability with unequal jet lengths has been reported by Jung et al. (2010), but in their study, like others, equal inertial strengths of the jets are tried. However, it is impossible to obtain equal strengths jets for practical applications. In the present study, we investigate the consequences of this asymmetry in the process as well. Finally, we have discussed fluidic configurations generated because of collision between a liquid jet and a sheet. In the next section, we discuss the experimental setup used to investigate this process.

2. Experimental setup

Fig. 1 gives details of the experimental setup used for the present study. Deionized water ($\rho_{measured} \approx 1000$ kg m^{-3}, $\mu_{measured} \approx 0.001$ Pa s and $\sigma_{measured}$ (with air) ≈ 0.072 N m^{-1}) is used in circulation to form liquid jet. Flow-rate is controlled using a system of valves and rotameter. The by-pass line takes the excess water back to the reservoir. The angle of impingement between the similar/dissimilar jets (2α) is changed using adjustable nozzles, each at an angle α from the vertical. The angle of adjustable nozzles is measured using digital inclinometer and verified during processing of photographic data. The collision of jets is ensured to be at a point on the line midway between the jets. The diameter of the nozzle used is kept fixed at 0.005 m and angle of impingement 2α at 90°, unless otherwise specified. A brief look at the functional form of different process parameters reveals that the dependent variables, like the extent of sheet expansion (given by r_0) and the deflection of the sheet (ϕ) are functions of the dimensionless numbers. The Froude number of the ith jet ($Fr_i = \frac{u_{j,i}}{\sqrt{gd_j}}$, where $u_{j,i}$, d_j and g correspond to velocity of ith jet, diameter of the jet at nozzle outlet and acceleration due to gravity) gives a relative strength of inertia and gravity. The Reynolds number ($Re_i = \frac{\rho u_{j,i} d_j}{\mu}$, where μ is the viscosity of the fluid) gives an idea about the dominance of inertia over viscous forces. Since the regimes of jet-jet collision studied in the present effort are heavily inertia dominated, the formed liquid sheet is usually open or in transition to open regime from the sheet structure with fingers. This implies the importance of Weber number ($We_i = \frac{\rho u_{j,i}^2 d_j}{\sigma}$) for flow characterization as the inertia of jet is varied over surface tension. A high-speed camera (Phantom Miro 110) is used to record the temporal variation in the sheet characteristics, rim dynamics, and atomization at 1800 frames per second. There are several other important features as well, like the formation of holes and Plateau-Rayleigh instabilities (Rayleigh, 1879). Since these features are repetitive in nature, a 50-megapixel high definition camera is used to capture them. The images are processed using in-house image processing codes to obtain the shape and size of liquid sheet core (maximum 2% spatial and 0.06% temporal error). The obtained images are converted to gray-scale followed by passing them through a noise removal filter. The smooth image is then converted into binary (black and white) one, on which the polar coordinates are superimposed to obtain

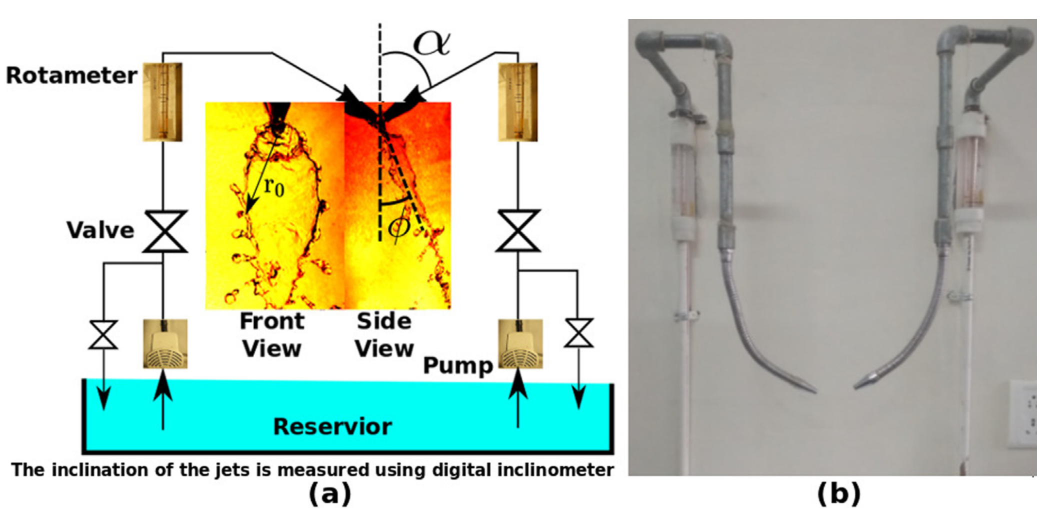

Fig. 1. Experimental facility used to study the collision of liquid jets: (a) the schematic of the apparatus (inset figures show the collision of liquid jets in air). (b) A snapshot of the actual experimental setup.