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Liquid jet in a subsonic gaseous crossflow: Recent progress and remaining challenges

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ABSTRACT

This article reviews published literature on the characteristics of a liquid jet injected transversally into a subsonic gaseous crossflow. The review covers the following aspects: (i) liquid jet primary breakup regimes, (ii) liquid jet trajectory and penetration, (iii) liquid jet breakup length, and (iv) droplets features and formation mechanisms. The focus is on analyzing the role of different prominent parameters which include gaseous and liquid properties, and liquid injector geometry. The review revealed that gas Weber number plays a crucial role in defining non-turbulent primary breakup regimes, while liquid jet Weber number is of great importance for the transition to turbulent primary breakup. Jet-to-crossflow momentum flux ratio is the most important parameter for predicting the trajectory, penetration, and breakup length of a liquid jet in a crossflow. The characteristics of droplets disintegrated during the primary breakup are mostly influenced by the nozzle exit conditions, whereas the characteristics of droplets produced via the secondary breakup are strongly dependent on the velocity of cross airflow. Although the review revealed that substantial progress has been made in understanding this complex two-phase flow phenomenon, there still remain several shortcomings which require further research.

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1. Introduction

The flowfield associated with a jet injected transversely into a crossflow (referred to as JICF), also known as a transverse jet, can be generally classified into two main categories: a gaseous (or liquid) jet in a gaseous (or liquid) crossflow (i.e., single-phase flow), and a liquid (or gaseous) jet in a gaseous (or liquid) crossflow (i.e., multiphase flow). A transverse jet has numerous applications in industrial, environmental and natural systems. Examples of these applications include air-breathing engines (e.g., dilution air jets, turbine blade film cooling systems, V/STOL aircraft, fuel/air mixers and ramjet/scramjet fuel injectors), rocket engines (e.g., thrust vector control), environmental control systems (e.g., effluent from chimney, smokestack, and flare stacks plumes as well as liquid effluent dispersal in streams), and natural flows (e.g., volcanic plumes in crosswind, bivalve clams and blue crabs, and central venous catheters).

Earliest research of a jet in a crossflow has been motivated by applications related to environmental problems such as plume dispersal from exhaust or pipe stacks or liquid effluent dispersal in streams [1–3]. Thrust vector control in rocket engines by injecting an array of transverse jets to deflect the flow in the nozzle, is another example of the applications of both a liquid and a gaseous transverse jet [1,2]. This jet configuration is also adopted during takeoff, hover, and transition to wing-borne flight in vertical/short takeoff and landing (V/STOL) aircraft for controlling the lift and thrust vectors [1,3]. The superior mixing properties of a transverse jet compared to a jet in quiescent surroundings make this flowfield layout appealing especially for engineering applications when rapid injectant mixing is desired [1,2]. Also, dilution of gaseous jets is introduced downstream of the primary and/or secondary combustion chamber zones in order to decrease the temperature of combustion products before entering the turbine section of a gas turbine engine [1,2,4,5]. Transverse injection of a liquid fuel jet into a gaseous crossflow is an approach which is often employed in both aviation and stationary power generation systems where rapid fuel penetration, vaporization, mixing of vapor/air and ignition, and consequently sustained combustion process are desired. This method of liquid fuel/air mixture preparation enhances flame stabilization, fuel conversion efficiency, and accordingly emissions reduction [6–9]. The overall performance of a propulsion engine, in terms of thrust and specific impulse, can be enhanced through controlled or actively forced dilution jet injection [1,2,10]. Contrary to film-cooling in gas turbine engines where air jets should penetrate less and adhere to the surface as much as possible, dilution jets require a higher penetration and spread into a crossflow [2]. Transversely injected air jets are also used in the primary zone of gas turbine combustors as a means of controlling the air–fuel mixture ratio and hence the emissions of nitrogen oxides (NO_x). Tunable air–fuel mixing allows simultaneous control of NO_x and carbon monoxide (CO) emissions [1,2,11]. In the combustion chamber of a direct injection diesel engine, where the air has a strong swirl movement in the cylinder, the interaction between a diesel spray and a crossflow is of importance [6–8].

While the focus of the present review lies on the injection of a liquid jet into a subsonic gaseous crossflow, the main characteristics of a transverse gaseous jet are relevant to the understanding of this topic. In essence, several published studies explored the analogy between a transverse gaseous jet and a transverse liquid jet to overcome the lack of comprehension of the latter [9], even though there exist some distinct differences between their features and controlling parameters which will be discussed later on. For instance, earlier studies (e.g., [12,13]) hypothesized that the occurrence of a progressive flattening of a liquid column, due to the acceleration of the gas flow around the jet, could induce a bow (or kidney) shape deformation of the jet cross-section. Given the similarities between these two flowfields, the general features of a transverse gaseous jet will be presented first in the following Subsection 1.1 followed by the general features of a transverse liquid jet and its corresponding controversial issues introduced in Subsection 1.2.

1.1. *Features of a gaseous jet in a subsonic gaseous crossflow*

A gaseous jet in a gaseous crossflow has been widely investigated, and several review papers on this topic are available in the literature [1–3,14,15]. This flowfield typically consists of a jet with a mean velocity v_j injected transversely into a gaseous crossflow with a velocity u_g, and it is usually divided into two main regions: a jet region (near-field region), where the deflection of the jet is still small, and a wake-like region (far-field region), in which the jet is almost aligned with the crossflow. Between these two regions, there exists a region of high jet trajectory curvature. The interaction of a jet and a crossflow creates a complex set of vortex structures as is depicted in Fig. 1. The most obvious structure is the counter-rotating vortex pair (CVP). Other coherent structures include horseshoe-shaped vortices, wake vortices, and jet shear layer vortices. The horseshoe and shear layer vortices are best described in the near-field region, whereas the CVP and wake-like characteristics are most evident in the far-field region [15–18].

Among the non-dimensional parameters used to correlate the observed features of this flowfield with fluid properties, test conditions and geometrical parameters are the jet-to-crossflow momentum flux ratio, $q \equiv \rho_j v_j^2 / \rho_g u_g^2 \equiv SR^2$, jet Reynolds number, $Re_j \equiv \rho_j v_j d_j / \mu_j$, and crossflow or gas Reynolds number, $Re_g \equiv \rho_g u_g d_j / \mu_g$; where $S \equiv (\rho_j / \rho_g)$ is the jet-to-crossflow density ratio, and $R \equiv (v_j / u_g)$ is the jet-to-crossflow velocity ratio. In the limit of iso-density, $q \equiv R^2$ for a jet in a crossflow.

Another important feature of a transverse gaseous jet is the jet trajectory, which is of fundamental interest and has been widely studied [19–23]. For instance, Karagozian [20] considered a vortex pair issuing from a jet orifice into a crossflow, and by solving the

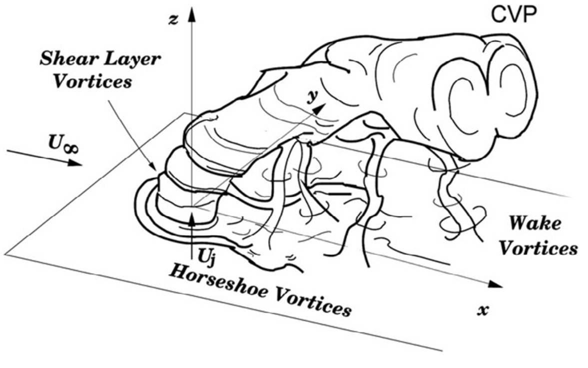

Fig. 1. Schematic of a transverse gaseous jet, and relevant flow structures (Reprinted from Fric and Roshko [16] with permission from Cambridge University Press).