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Quantitative description of droplet dispersion of hollow cone spray in gaseous crossflow

Haibin Zhang[a,b], Bofeng Bai[a,*], Yechun Wang[a]

[a] *State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China*
[b] *School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, PR China*

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ABSTRACT

In this study, we experimentally investigate the large-scale vortex pair formed by droplets in the spanwise direction of the flow field of a hollow cone spray injected transversely into a gaseous crossflow. Experiments are conducted in a square channel for a wide range of spray and crossflow conditions. The spatial and velocity distributions of the spray droplets for different cross-sections of the flow field in terms of different flow conditions are measured through flow visualization. Three parameters, namely, vortex vorticity, depth of vortex core, and distance between both vortex cores, are used to characterize the counter-rotating vortex pair (CVP) formed by droplets. The crossflow Reynolds number, (initial atomized) droplet Reynolds number, and number of droplets injected per unit time are all found to significantly influence the features of droplets CVP. We newly define the spray-to-crossflow momentum flux ratio ($J*$) based on the injected momentum flux of initial atomized droplets. Accordingly, we develop a set of correlations for predicting the features of droplets CVP based on experimental measurements and the Buckingham π theorem. The results show that these correlations well predict all measured conditions. The results of this study should provide insights into the dynamics of spray droplets in a crossflow and an understanding of the large-scale mixing between a hollow cone spray and a crossflow.

1. Introduction

Liquid jet (spray) injection into a gaseous crossflow is used in various applications such as film cooling of turbine blades, fuel injection in ramjet/scramjet combustors, fuel/air mixing in pre-vaporizers and combustors (e.g., lean, premixed, pre-vaporized (LPP) combustion [1]), and liquid water injection in the mixing system of a hydroreactive metal fuel engine [2] (water is vaporized by the absorbing heat of the high-temperature fuel gas and then used as additional working fluid for increasing the specific impulse). In such applications, especially in the last two listed above, rapid and thorough spatiotemporal mixing between the liquid and the gas is generally needed to ensure efficient cooling or combustion. Among various types of jets/sprays, a hollow cone spray (generally produced by a pressure swirl injector) can achieve finer atomization and larger spread of droplets within a short distance owing to its intrinsic breakup mechanism; therefore, it is expected to mix more efficiently with the crossflow, making it promising for the above applications [1–3]. Therefore, it is essential to clarify the flow field associated with a hollow cone spray injected transversely into a crossflow to optimize relevant engineering processes and develop improved designs.

In a hollow cone spray nozzle, the liquid is sprayed out in the form of a hollow cone-shaped sheet owing to pressure swirling; the liquid then atomized quickly owing to various aerodynamic instabilities. This atomization mechanism is quite different from that of a plain liquid jet [4–9] in which liquid column breakup occurs and from that of an air-blast/air-assisted spray [10–14] and aerated liquid jet [15–17] in which secondary atomizing air is required. Therefore, a hollow cone spray in a crossflow evolves in a distinctive and different way from that of other jets/sprays in a crossflow. In the last few decades, studies have focused on the breakup and atomization of a hollow cone spray being discharged into a stagnant gas [18–21]. However, few study have focused on a hollow cone spray in a crossflow. In recent years, Surya Prakash et al. [1], Lynch et al. [2], and Lee et al. [22] experimentally investigated a hollow cone spray in a crossflow and clarified the near-field breakup characteristics of the spray, such as breakup regimes, breakup length, and droplet diameter distributions. However, few studies have clarified the far-field droplet dispersion, which is also of great importance in premixed and precooling applications. Salewski and Fuchs [23] reported a numerical study on the trajectory of a hollow

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[*] Corresponding author.
E-mail address: bfbai@mail.xjtu.edu.cn (B. Bai).

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Nomenclature

D	hydraulic diameter of the channel [m]
d_{32}	sauter mean diameter [μm]
h	depth of cores of droplets CVP [m]
l	distance between both cores of droplets CVP [m]
M_g	momentum flux of the crossflow [–]
M_I	injected momentum flux of the spray [–]
N_d	droplet number flow rate of the spray
$\Delta \mathrm{P}$	injection pressure [MPa]
q	liquid volume flow rate [L·h^{-1}]
Re	Reynolds number [–]
u	velocity [m/s]
$J*$	spray-to-crossflow momentum flux ratio [–]

Greek symbols

Ω	vorticity [s^{-1}]
ρ	density [kg·m^{-3}]
μ	viscosity [kg·m^{-1}·s^{-1}]
θ	spray angle [°]

Subscripts

d	droplet
g	gaseous crossflow

cone spray in a crossflow based on simplified atomization models. However, they only qualitatively discussed the effects of different parameters on the droplet trajectory and the large-scale vortices induced by the spray. Deshpande et al. [24] and Gao et al. [25] numerically studied the dynamics of pulse hollow cone sprays interacting with a uniform crossflow. They reported only limited findings applicable to gasoline direct injection engines. Recently, our research group experimentally investigated the droplet dispersion characteristics of a hollow cone spray in a crossflow. We found that the interactions between the spray and the crossflow induce a larger-scale counter-rotating vortex pair (CVP) and a coherent structure in the spanwise and streamwise directions, respectively; these, in turn, greatly influence the droplet dispersion in the far-field [26–31]. The formations of these vortices and their influence mechanism on droplet dispersion were also analyzed. However, these studies provided only qualitative results, and quantitative results for droplet dispersion characteristics of this complicated multi-parameter two-phase flow process remain lacking.

This experimental study aims to systematically investigate the effects of flow conditions on droplet dispersion and to accordingly construct predictive models for the main features of the far-field spray. We focus on the main droplet dispersion characteristics of a hollow cone spray in a crossflow, namely, the CVP formed by spray droplets. The vortex vorticity (Ω), vortex core depth (h), and distance between both vortex cores (l) are used to characterize the intensity and structure of the droplet vortex pair, and the effects of Reynolds number and droplet number flow rate of the spray (i.e., number of droplets injected per unit time) on them are first identified. Then, a new calculation is proposed for the spray-to-crossflow momentum flux ratio based on the injected momentum flux of the initial droplets. Finally, a set of correlations for predicting the main features of the droplets vortex pair (i.e., Ω, l, and h) is developed by using the Buckingham π theorem and regression analysis method.

2. Experimental setup and methods

2.1. Experimental facility

Fig. 1 shows a schematic diagram of the experimental system for a hollow cone spray in a crossflow. The experimental rig consists of a cross-flowing air supply system, a liquid supply system, and a rectangular mixing test section with inner dimensions of 0.18 × 0.18 m and length of 0.8 m (see Fig. 2). Air is supplied by a centrifugal blower with maximum capacity of 1800 m^3/h. A frequency converter (ABB-ACS510, 0–5 kW) is used to control the air blower to produce a variable flow rate. The airflow enters a wind tunnel and then flows through a well-designed rectifier section (see Fig. 3) into the test section. The rectifier section contains a wire mesh and honeycomb that are used to remove nonuniform, filter large-scale turbulence, and straighten the flow. The airflow velocity profile at the entrance of the testing section is characterized using a Pitot tube. A total of 64 points that are evenly distributed at the entrance cross-section of the testing section are tested. The velocity profile is found to be fairly uniform with velocity values varying within 4.2% of the mean. The injector is positioned at the centerline of the top plate at 0.28 m distance from the inlet of the testing section. The injection water is pressurized using a high-pressure nitrogen gas source. A pressure regulator is used to control the nitrogen gas pressure. The pressure upstream of the injector is monitored via a pressure transmitter. A stainless steel needle valve (working pressure up to 10 MPa) is installed ahead of the nozzle to precisely regulate the pressure and ensure the stability of the liquid mass flow rate. The coordinate axes (shown in Fig. 2) used to orient the measurements are centered at the nozzle orifice. The crossflow and spray injection are along the x- and y-directions, respectively.

A commercially available hollow cone spray nozzle (KB-series, H. Ikeuchi & Company, Ltd.) with spray angle of 80° is chosen in this

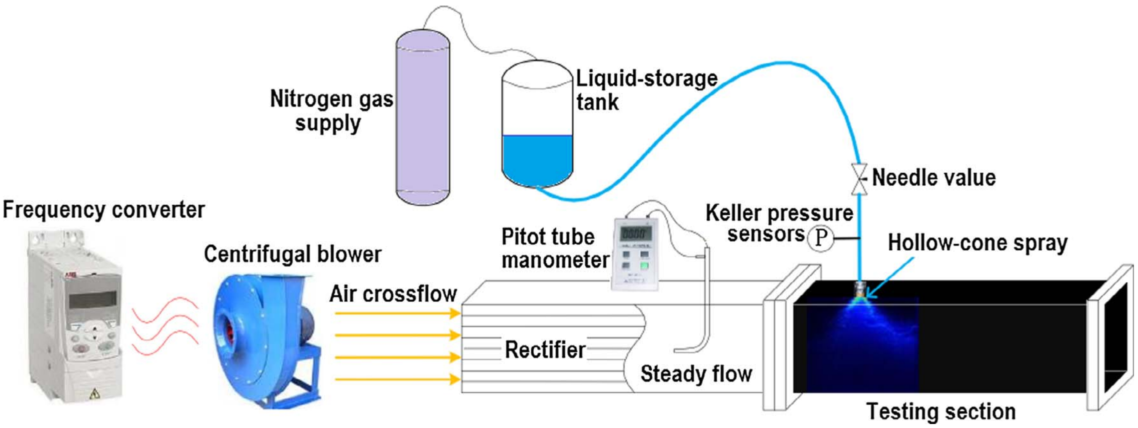

Fig. 1. Schematic of experimental facility.