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Experimental study of the mixing of two impinging pressure-swirl sprays in crossflow

Haibin Zhang [a,b], Bofeng Bai [a,*], Li Liu [a], Huijuan Sun [a], Junjie Yan [a]

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

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ABSTRACT

This paper discusses the results from an experimental study on the mixing of two impinging pressure-swirl sprays in the crossflow with the PIV visualization system and the image-processing techniques. The experiments were carried out inside a rectangular duct (95 mm × 95 mm) at the ambient temperature and pressure. Five injection angles ($\alpha = 60–120°$, at 15° intervals from the negative direction of the crossflow) were experimented with the crossflow velocity range from Re = 25,700 to Re = 64,300. The droplet dispersion and its dependence on the spray injection angle and the crossflow velocity are examined. The large-scale vortex structures occurred are analyzed and their influence on the mean velocity, vorticity and turbulent characteristics of the droplet swarm are studied. The comparison is made with single-spray data of the previous studies. Double coherent structures are discovered and they greatly depend on the spray injection angle as that of single nozzle. When $\alpha < 90°$, the greater coherent structures occur and the droplet swarm turbulent intensity increase and hence, the droplet dispersion is promoted. When $\alpha = 90°$, the largest Counter-Rotating Vortex Pair (CVP) structure and the greatest entrained air flow are induced and compare with single nozzle the CVP structure becomes more enduring. Furthermore, the deposition of droplets at the bottom of the mixing duct is inhibited significantly when the second spray is introduced especially for $\alpha = 60°$ and $\alpha = 120°$.

1. Introduction

The injection of liquid spray into a crossflowing airstream is a commonly employed mixing technique in propulsion systems. Important applications include fuel injection for burners in rockets, secondary injection in rocket nozzles for thrust vector control in propulsive systems as well as sea water injection in mixing chamber for working substance addition in the hydroreactive metal fuel engine [1,2]. In these processes, a desirable mixing effect between the spray and the crossflow is critical for a good engine performance. Therefore, a better understanding of the resultant mixing flow structures related with such mixing enhancement is required. The mixing between the liquid spray and a crossflow is typically a three-dimensional transient two-phase flow. An in-depth knowledge of the complex mixing process is still challenging although many attempts have been made on this area over the past decades.

For several forms of jets in crossflow, such as the liquid jet [3–8], airblast liquid jet [9–12] as well as flat-fan spray jet [13–16], considerable efforts have been conducted to study the liquid breakup, the characterization of spray appearance, the dominate flow structures, the droplet dispersion and the two-phase interaction. The large-scale vertical structures excited in the flow field, including the Counter-Rotating Vortex Pair (CVP), the leading vortex, and the shear-layer vortex, have been detected, and the individual contributions of these vortices to mixing have also been clarified.

With regard to the pressure-swirl spray, however, few studies are available on its mixing characteristics in a confined crossflow. The pressure-swirl spray processes its distinct advantages that many other types of sprays do not have. It can be able to generate smaller spray droplets and larger hollow-cone spread area with a lower atomization pressure in a shorter distance. Many investigations have been reported on the break-up region and just beyond [17–22] in non-crossflow. Kachhwaha et al. [23,24] studied the movement and evaporation of the spray droplets in both parallel and counter-flow configurations. They proposed a two-dimensional model which agreed well with the experimental results. Deshpande et al. [25] numerical studied the hollow cone spray in a crossflowing air stream by using the conventional Lagrangian–Eulerian point parcel spray treatment. The spray in the near field and the effects of the crossflow velocity on the spray are discussed.

In real engine, the mixing commonly proceeds in confined space and finite distance, which inevitable leads to the impingement of the spray onto the wall. This results in further complication of the three-dimensional flow and makes close observations and

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

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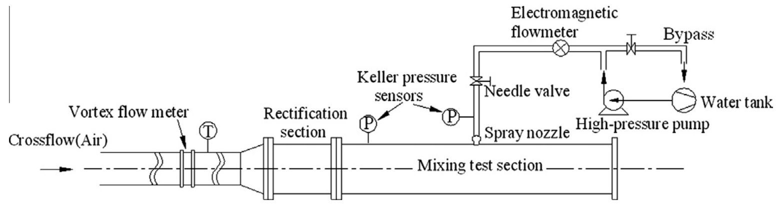

Fig. 1. Mixing system for a pressure-swirl spray in crossflow.

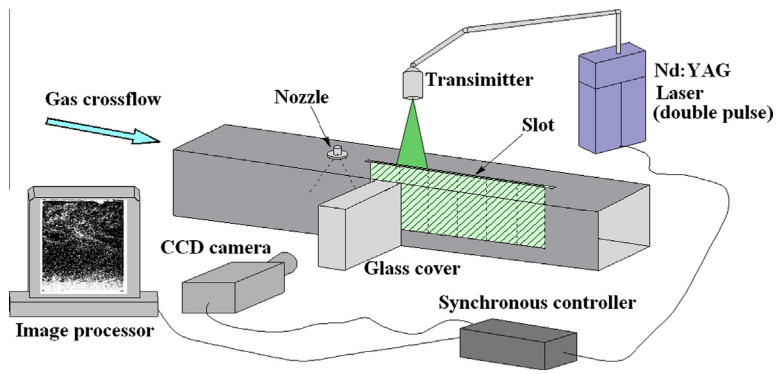

Fig. 2. Schematic diagram of the PIV testing setup.

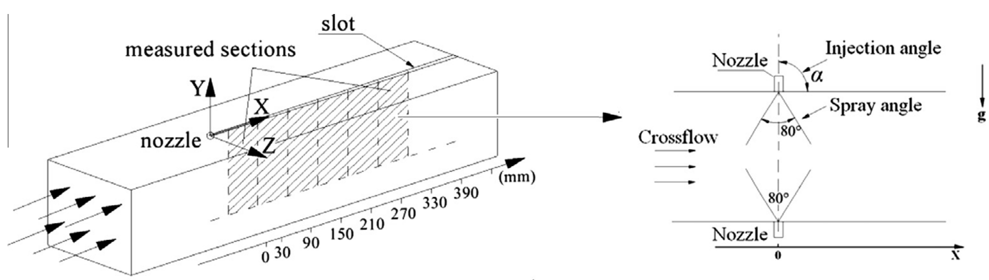

Fig. 3. Schematic of longitudinal measurement section and the nozzle arrangement.

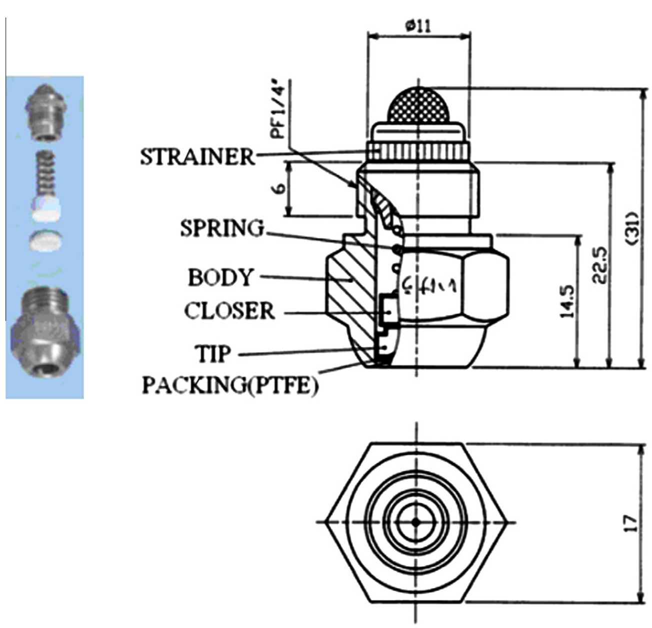

Fig. 4. Pressure-swirl spray nozzle (adopted from "The Mist Engineers", H. Ikeuchi & Co., Ltd.).

Table 1
Experimental conditions.

Number of nozzles	D_{32} (μm)	Re (gas)	Injection angle (α)
2	104	25,700	60°, 75°, 90°, 105°, 120°
		32,100	60°, 75°, 90°, 105°, 120°
		45,000	60°, 75°, 90°, 105°, 120°
		64,300	60°, 75°, 90°, 105°, 120°

analysis difficult. In our previous studies [26–29], the mixing of the pressure-swirl spray in a confined crossflow was measured using the PIV visualization system. Both the droplet distribution and structures of the flow field were obtained. The CVP structures and the coherent structure were confirmed and their influences on the droplet dispersion are discussed. Studies demonstrated that the stable large-scale vortices can lead to the preferential concentration of the droplets and consequently result in the non-uniform droplet dispersion.

Multiple sprays usually play an important role in practical mixing chamber. In this study, the mixing of two impinging pressure-swirl sprays in crossflow is investigated. The purpose aims to determine the dynamic dispersion of droplets and the effect of existed large-scale vortex structures on droplet dispersion. The two main large-scale vortices, the CVP and the coherent structure, which