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Droplet dispersion characteristics of the hollow cone 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

The flows in a jet entering a crossflow are unsteady and the droplet movement is of vital importance for the two-phase mixing effect. In this paper, the hollow cone spray into the crossflow is investigated experimentally by using the PIV visualization system and the image-processing techniques. The experiments are carried out inside a rectangular duct (95 mm × 95 mm in cross-section) at the ambient temperature and pressure. Different nozzle injection angles and crossflow velocities are experimented on. The instantaneous droplet distributions and the velocity vector fields are obtained. Our results show that the flow field falls into three main domains and their effects on the movement and distribution of the droplet are varied. The coherent structure which breaks the stability of the upper counter-rotating vortex pair (CVP) structure is induced on the interface between the upper CVP and the mainstream zone. When the spray is against the crossflow the larger coherent structures are induced and impose greater influences on the mixing process. The turbulence intensity on the shear layer increases and the dispersion of the droplet is promoted. The experimental findings will benefit the understanding of the mixing mechanism of the hollow cone spray in the crossflow and the achievement of an optimum mixing.

1. Introduction

The liquid spray injected into a crossflowing airstream has found wide applications. Examples include film cooling for turbines, fuel injection for burners, secondary injection in rocket nozzles for thrust vector control in propulsive systems as well as in the research of V/STOL aircrafts, and high quality steam generation in steam generators for in situ thermal recovery of heavy oil (which has great application prospect in the future oil industry). In most of these cases, the jets enter at right angles to the mainstream. The non-uniform droplet distribution in the flow can significantly inhibit the efficiency of the evaporators in heat exchanges. Engineering applications require a more profound understanding of the resultant flow field with such mixing augmentation. For all the previous intensive researches, a complete knowledge still eludes researchers.

Analytical and experimental studies were carried out on the jets in crossflow, including the liquid jet [1–6], the airblast liquid jet [7–11] and the flat-fan spray jet [12–14]. The liquid breakup, flow field characteristics, droplet movement, two-phase interaction were investigated in details. The vortices such as the counter-rotating vortex pair (CVP), the leading vortex, the shear layer vortex and the multiple vortexes and their contribution to the mixing were obtained. In the mixing process, the dispersion of the droplet is a major factor for the evaluation of the mixing. The dispersion of the droplet is determined by the spray nozzle and the crossflow in the initial mixing stage and is affected by different scales of vortices occurring in the flow field in the later mixing stage. Studies confirm that the stable large-scale vortices can lead to the preferential concentration of the droplet and consequently result in the non-uniform droplet distribution. So how to control the droplet dispersion in order to achieve a desirable mixing is an important issue in the spray/crossflow study.

In the study on the hollow cone spray nozzle, the liquid first emerges in the form of a sheet which quickly disintegrates into droplets due to the aerodynamic instability in the 'break-up region' and which interacts strongly with the atmosphere. Just downstream in the 'spray region', the liquid is in the exclusive form of droplets. Considerable research efforts have been directed towards the investigation on the break-up region and just beyond [15–19]. But the studies on the dispersion of the droplets in a crossflow are relatively few. Ghosh and Hunt [20] developed an analytical model within all the practical ranges of the ratio of the jet speed to the crossflow speed to address the fundamental problem in the fluid mechanics about how fluid jets were deflected and deformed. Kachhwaha et al. [21,22] studied the movement and evaporation of the spray droplets in both the parallel and counter-flow configurations. They proposed a two-dimensional model which agreed well with the experimental results.

In the mixing chamber of a real engine, the mixing is commonly conducted in confined space and finite distance, which inevitably

* Corresponding author. Tel.: +86 29 8266 5316; fax: +86 29 8266 9033.
E-mail address: bfbai@mail.xjtu.edu.cn (B. Bai).

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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 analysis difficult. The primary concern in the practical mixing is to achieve a desirable mixing within the distance as short as possible. Therefore, in the experiments we focus on the mixing process in the early stage over a relatively short distance. We find that the mixing is mainly determined by the large-scale vortices. Furthermore, due to the confined mixing flow field and the measurement technical limitations, it is quite hard to decide the micro-dynamic behavior of the individual droplet. In engineering applications, such major influencing parameters as nozzle atomization conditions, crossflow velocity and spray injection angle are our main consideration. Hence, the mixing flow field structure, the spray droplet group dispersion and the droplet preferential concentration caused by the large-scale vortices are given priority to in our studies.

In our previous flow visualization investigations [23,24], the transverse droplet distributions and the velocity vector distributions were obtained in different cross-sections along the crossflow direction. The mixing effect is analyzed from the view of the time-averaged droplet distribution, and the preliminary evaluation of the mixing quality is given. But this method can merely correctly reflect the uniformity of the distribution of droplets mathematically, but not spatially. In order to resolve this problem, the mixing should be investigated from the point of view of the profound mixing mechanism. In our recent research, the dynamic of the

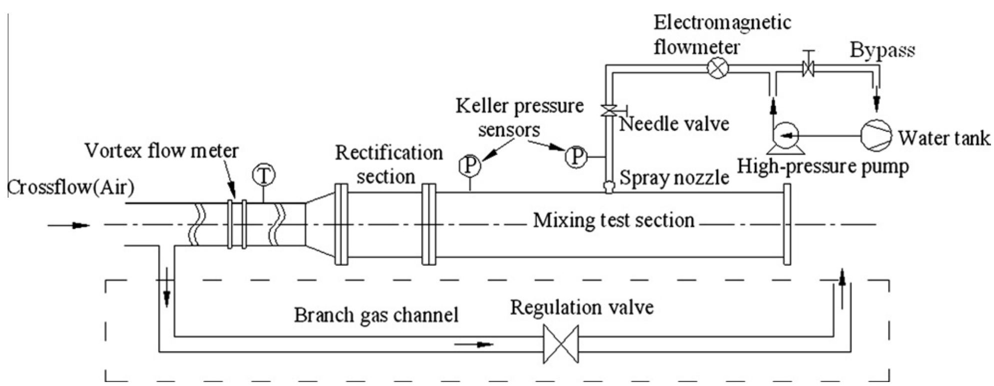

Fig. 1. Mixing system for a hollow cone sprays in crossflow.

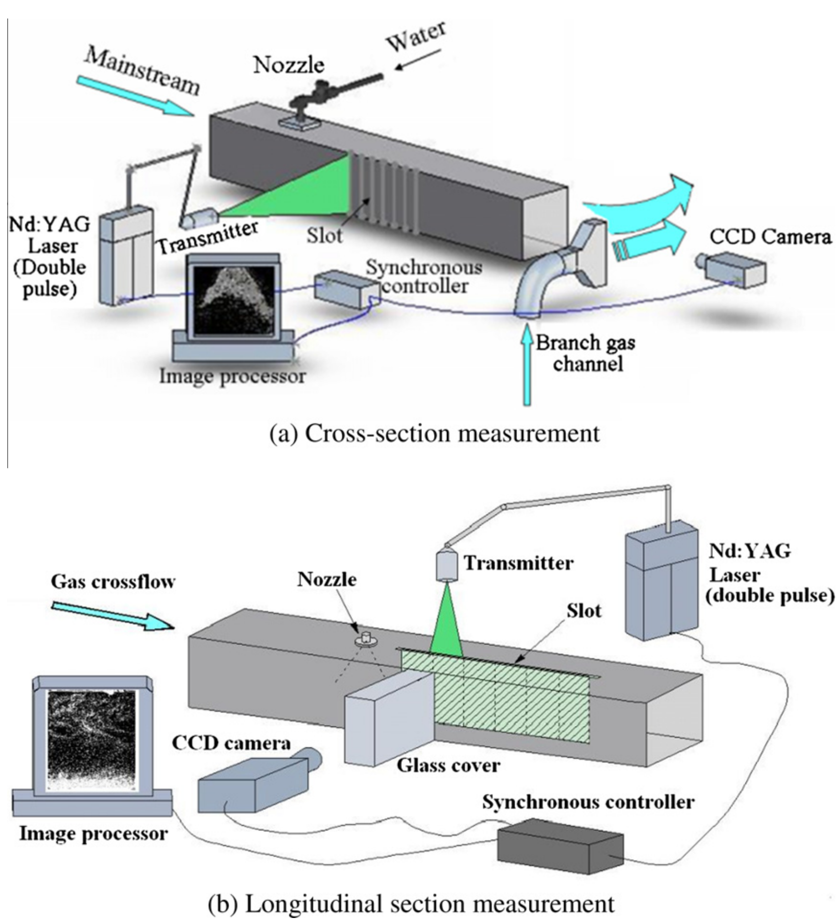

Fig. 2. Schematic diagram of the PIV measurement system.