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Numerical and experimental study on the spray characteristics of full-cone pressure swirl atomizers

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Numerical and experimental studies have been performed to investigate the macroscopic spray structure and spray characteristics of sprays generated by a full-cone pressure swirl atomizer. The simulation employs Eulerian-Lagrangian scheme to account for the multiphase flow and the linearized instability sheet atomization model to predict film formation, sheet breakup and atomization. Reynolds-Averaged Navier–Stokes (RANS) equations are solved for turbulent gas flow. The model predictions show great consistency with the experimental measurements of the spatial variation of the droplet size and velocity obtained from Phase Doppler Particle Analyser (PDPA). The robustness of this model makes it useful to predict the structures and characteristics of co-flow sprays produced by pressure-swirl atomizers. This particular spray is quite important in spray cooling application but is not extensively studied. The study reveals that the entrainment effect and intense central-region atomization cause small droplets to concentrate on the spray axis and large droplets to dominate in the peripheral region of the spray. This finding is consistent with the observation that turbulence kinetic energy of air is maximum near the nozzle exit, where atomization is intense and momentum exchange is strong, and gradually decreases in both radial and axial directions. Moreover, the drops inside the full cone are relatively small, and evaporate more easily than their large counterparts in the peripheral region, hence removing substantial sensible heat from surrounding air and creating low-temperature region in the central of the spray.

1. Introduction

Liquid spray is widely used in many industrial processes, such as inlet air cooling for gas turbines and cooling towers [1–3], building comfort [4], electronic chip cooling [5], firefighting [6], fuel injection for burners [7], food processing [8], internal combustion [9], etc. To improve the performance of the injector nozzles, a profound understanding of the liquid spray is necessary. Atomization, the process of disintegrating bulk fluid into a multitude of individual droplets, is found to be the key process influencing the behaviour of spray.

Pressure swirl atomizers refer to low-speed spray devices designed to convert bulk liquid into fine drops. These drops then travel in gaseous media and result in spray formation. Obtaining energy from the pressure, the injection drops can attain a high velocity relative to the surrounding gas [10]. Introduction of the swirl atomizer helps to form a centrifugal force, facilitating a swirling motion and spreading liquids as a conical sheet after it leaves the orifice [11]. The pressure atomizers can be divided into 2 categories [12]: the hollow-cone and the solid-cone. Droplets generated through the former nozzles mainly concentrate at the outer edge of a conical spray pattern, while those produced by the latter always show a uniformly distribution over its impact area.

Compared with flat fan atomizers, pressure-swirl atomizers can generate a much finer and atomized liquid flow, producing spray patterns resemble a ring-shaped impact area. The liquid in the atomizer will be forced to a swirl chamber via some tangential ports to obtain a high angular momentum, and thus create an intensified vortex. During this process, the air-core blocks a part of the nozzle outlet orifice. The rotating liquid, under both axial and radial forces, emerges from the final orifice of the atomizer and spread into the shape of conical sheets. The sheet's thickness decreases as it expands with wave instability. Then the unstable sheet will disintegrate into ligaments and drops in the form of a well-defined cone-shaped spray. Disintegration of the sheet is mainly determined by the liquid discharge velocity and thus by the liquid

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injection pressure. The relative magnitude of the tangential and axial components of exit velocity influence the actual cone angle of the discharging nozzle [10]. The fine drops produced by the atomizers lead to sprays with a larger exposed total surface or contact area than other hydraulic nozzles. The increased contact area of the sprayed fluid with the exposing airflow makes them ideal for certain applications.

Chaker et al. [13,14] highlighted three key influential variables to determine drop size: air velocity, injection pressure and measurement location downstream of nozzle tip. Besides, the temperature and air humidity only exert a limited impact on the spray formation and the drop size. Durdina et al. applied Phase-Doppler Particle Analyser (PDPA) and Particle Image velocimetry (PIV) to explore the spray characteristics created through a pressure-swirl atomizer [15]. When the gauge pressure remains low, liquid mass would concentrate on the spray axis. When the injection pressure gets higher, however, mass flow maxima and local velocity in the spray periphery would become dominant, creating a full-cone spray. Chen et al. adopted experimental method to explore atomization and spray of both diesel fuels and some renewable alternatives [16]. They suggested that spray tip penetration is directly proportionate to the injection pressure, time duration, but inversely related to the ambient pressure. And the spray cone angle will become larger as the ambient pressure grows. Jain et al. experimentally investigate the impact of Reynolds number on the characteristics of a pressure swirl nozzle [17]. Based on the inviscid theory, they found that coefficient of discharge is independent of the Reynolds number. Both the spray cone angle and Sauter mean diameter decrease with the growth of Reynolds number. Hong et al. collected numerous experimental data related to a pressure-swirl atomizers with low nozzle opening coefficient and finally proposed a novel empirical model to accurately predict its discharge coefficient [18]. Dorfner et al. found that mean drop sizes in the spray grow with the surface tension of the liquid against the ambient medium, a result caused by a shift of the entire drop size spectrum towards larger diameters [19]. Moreover, the selective increase of numbers of large drops explains the larger mean drop sizes due to an increase of the liquid dynamic viscosity. Azami et al. came up with their modelling results of evaporation and spray penetration for alternative fuels [20]. They revealed that high initial temperature and velocity, on the one hand, accelerate evaporation rate. While on the other hand, it can lead to a shorter penetration and the high initial velocity produces a greater penetration.

Water spray used for evaporative cooling is commonly employed in building design to enhance thermal comfort in indoor environments. With validations against the wind tunnel experimental measurements, Montazeri et al. [21] demonstrated that the Lagrangian–Eulerian (3D steady RANS) approach can accurately predict the evaporative cooling by water spray. Their calculations show that the average deviations for dry and wet bulb temperature, the specific enthalpy are less than 3% in absolute values. They also furthered spray cooling study by conducting detailed analysis of various sprays under different physical conditions [22]. An interesting finding is that even if injecting water droplets with lower temperatures have better cooling performance than those with higher temperatures, the high-temperature water above the dry-bulb temperature of the air, can still provide sensible cooling. It is also shown that wider drop-size distributions can enhance sprays cooling performance.

Santolaya et al. [23] used PDPA to characterize the hollow-cone spray structure near field for different sheet disintegration regimes: perforations and surface wave instabilities. They concluded that a notably finer spray with a higher radial dispersion was obtained from wavy-sheet disintegration than that from perforated-sheet disintegration. Shim et al. [24] proposed a hybrid breakup model to predict fuel spray from a high-pressure swirl injector. The primary breakup was accounted for by the Linearized Instability Sheet Atomization (LISA) model while the secondary breakup process was modelled by the Aerodynamically Progressed Taylor Analogy Breakup (APTAB) model, which also accounts for the droplet deformation under aerodynamic external force. The predicted results agree well with experimental data obtained from Laser Induced Exciplex Fluorescence (LIEF) technique and the Phase Doppler Anemometry (PDA) system. Chang et al. [25] investigated the two-phase turbulent structure in an isothermal spray theoretically and experimentally. Turbulent dispersion effects were numerically simulated using a Monte Carlo method. They even employed turbulence modulation model but found it has negligibly small influences on the continuous-phase predictions. Theoretical calculations based on the Eulerian-Lagrangian formulism turn out to match well with the experimental results from PDPA measurements. Asheim et al. [26] developed a model to simulate droplets stochastically and accounts for “drop-drop" effects by permitting droplet collisions that result in coalescence or breakup. Their collision model predicted droplet velocities very well but overpredicted droplet trajectory angles and underpredicted droplet sizes, regardless of whether collisions were neglected or included.

According to existing literature, most researchers prefer to use experimental approach to investigate both the atomization and cross-flow or counter-flow spray of the pressure-swirl nozzles. Even some simulation work has been done previously [27–29], their primary focus was on the flow conditions inside the atomizers, which is critical to nozzle design. Nevertheless, the details of the structures and characteristics of co-flow sprays produced by pressure-swirl atomizers are not so readily available. Henceforth, the aim of the present study is to close this gap by providing a reliable spray model to capture the aerodynamic features of the full-cone spray produced by the pressure-swirl atomizer. Compared with the aforementioned researches, the work reported in this paper has two improvements: the first one is to model the spray from the more realistic liquid atomization process rather than construct an artificial spray based on the Rosin-Rammler approach. Even if the size distribution of drops at the inlet is usually assumed in the Rosin-Rammler form, this assumption suffers from poor accuracy due to the prediction uncertainties stemming from the lack of measured information at the inlet as well as the lack of spatial variation [25]. In order to address this problem, it is necessary to start the modelling the whole process from the very beginning, i.e., the liquid atomization. The second advancement is to investigate droplet characteristics by considering the effect of droplet collisions and coalescence on spray quality, which is usually neglected in many publications due to their complexity.

The pressure swirl atomizers are frequently applied to produce a spray comprising a large number of droplets, typically the order of diameter is in 10–1000 μm. The most challenging part of this work is the implementation of numerical simulations of droplet dynamics and heat and mass transfer process in a turbulent, two-phase flow. Specifically, the complex phenomena such as primary and secondary atomization, turbulent dispersion, droplet evaporation, droplet collisions and splashing in two-phase flow field need to be carefully treated to accurately represent the physical phenomenon. The paper is organized as follows: Section 2 presents necessary theoretical knowledge used in atomization and spray simulation, Section 3 gives a brief description about experimental approach carried out for the drop size and velocity measurements in sprays from pressure-swirl atomizers. Section 4 compares the simulation results with experimental data for model validation. Section 5 discusses both simulation and experimental findings in great depth. Finally Section 6 summarizes all the findings in this study.