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Air–liquid interactions in a pressure-swirl spray

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ABSTRACT

The energy transfer between a liquid hollow cone spray and the surrounding air has been studied using both imaging and phase-Doppler techniques. The spray was produced by a pressure-swirl atomizer discharging Jet A-1 fuel at inlet over pressures of $\Delta p = 0.5$, 1.0 and 1.5 MPa into quiescent ambient air.

The liquid exits the nozzle as a conical film which thins as it spreads and develops long- and short-wave sinusoidal instabilities with breakup occurring, at the length smaller than that predicted by the inviscid model, to form film fragments and ultimately droplets downstream the spray.

The single shot imaging characterised the spray regions of near-nozzle flow, the breakup processes and the developed spray. The phase-Doppler system resolved the three components of velocity and size for the droplet flow as measured on radial profiles for four axial distances from the nozzle exit.

A Stokes number, *Stk*, analysis of the droplets' response times to the airflow time-scales showed that droplets < 5 μm followed the airflow faithfully and so were used to estimate the local airflow velocity. This allowed a comparison of both the droplet and airflow fields in terms of their mean and fluctuating velocity components to be made.

The formation of the hollow cone spray and the interaction of the fragments and droplets with the air, through viscous drag, induce complex entrained airflows. The airflow was found to be highly anisotropic, fluctuating preferentially in the downstream direction, and spatially varying within three distinct spray regions. The air drag establishes a positive size–velocity correlation of droplets; their *Stk* reduces with axial distance and increases with droplet size and Δp; so that $Stk \approx 1$ for 20–40 μm droplets and the largest droplets (80–160 μm, $Stk > 10$) move ballistically.

The spatially resolved mean and turbulent kinetic energies of the air and spectra of the droplet velocity fluctuations are detailed in the paper. These findings are relevant to scientists and engineers modelling the complex two-phase flows.

1. Introduction

Pressure-swirl (PS) atomizers have been widely used for decades in industrial, domestic, agricultural and other applications. Their principle lies in the conversion of the pressure energy of the pumped liquid into kinetic energy to create a high-speed swirling conical film of liquid which discharges into the surrounding gas (usually air). The film breaks up primarily due to stretching and then to aerodynamic shear forces [1]. The initial difference between the velocity of the liquid and gas phase induces a strong dynamic liquid–gas interactions. It plays a substantial role in the entire atomization process and influences, or even causes, secondary effects during the spray formation. The high-momentum liquid fragments induce an entrained air motion, which consequently controls the flow of smaller liquid volumes and results in dispersion and reposition of small droplets downstream [2], where droplet collisions [3] and droplet clustering [4] have been seen to occur. The combined contribution of the above regulate the fundamental sprays characteristics, such as spray dispersion angle and droplet size and velocity distributions [5]. The mutual interaction of the dispersed phase and the gaseous phase is important in both reacting and nonreacting flows where the droplet characteristics and their response to the airflow pattern have, for example, an effect on the flame shape and stability, sooting characteristics, and emission of combustion products [6]. Also, the character of the turbulence has consequences in the mass transfer applications where the atomization process frequently appears. For example, in

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reactive and evaporating sprays it causes augmentation of the reactions and mass transfer.

PS sprays contain a wide range of droplet sizes exhibiting different dynamic behaviour. The liquid–gas interaction spatially redistributes the spray droplets due to the size-dependent droplet inertia, momentum, and drag. It was shown for PS atomizers, in the absence of significant external airflow fields, that large droplets tend to maintain the high velocity of the liquid sheet whereas small droplets couple with the local-induced airflow [7–9]. Spraying into co- and cross-flowing air additionally modifies the droplet trajectories with an important effect of droplet size on the outcome [10,11].

The interaction with the surrounding gas can lead to the local formation of instantaneous clusters of droplets in the flow [12,13]. Rouson and Eaton [14] used a direct numerical simulation (DNS) to document two extremes in the dispersed particles' response to turbulence. High-*Stk* particles respond only slightly to turbulent eddies, and their motion lacks mechanisms for non-random clustering. Low-*Stk* particles act as flow tracers and the medium-*Stk* particles tend to segregate into clusters. Katoshevski et al. [15] investigated droplet trajectories and showed distinctive characteristics of grouping and non-grouping cases with the effect of droplet size on the grouping pattern. Further works, experimentally [16] and numerically [17,18] evidenced that particles in a swirl-free turbulent flow exhibit non-uniform spatial distribution. The degree of non-uniformity is induced by particle–turbulence interaction on the particle scale and depends on particle inertia. The turbulence-driven radial droplet dispersion and reposition can possibly be controlled by the susceptibility for particles to shift in the direction of decreasing turbulence levels (turbophoresis) and by the concentration gradient of the particles, as observed in the DNS study by Lee and Lee [19]. The droplet clustering phenomena was documented in PS sprays [4–5,20]. Droplets, concentrated in clusters (or packets) make the spray spatially and temporally non-uniform [21], which is an important issue in combustion applications; the combustion of these clusters can lead to periodic variations in the heat-release rate and pressure in the combustor and, in turn, may result in various problems such as combustion noise or combustion-driven oscillations and low combustion efficiency [22].[1]

To summarise the above findings, the dynamic liquid–gas interaction is of principal importance in the PS spray formation process as it affects the atomization as well as the further life of droplets in the consequent processes. The deduction is that the liquid–gas interaction produces the near-field turbulent airflow, and that the air drag establishes a strong positive size–velocity correlation. The turbulent flow can lead to preferential clustering. It is of practical and fundamental interest to elucidate what is the role of ambient air in the motion of the sprayed liquid and what droplet sizes are affected by the drag effect.

The turbulent characteristics of the liquid-induced entrained airflow (spatially resolved turbulent kinetic energy (TKE) and mean kinetic energy (MKE), isotropy and homogeneity, frequency characteristics) and the size range of air-affected droplets can be determined by the analysis of the size-discriminated droplet and gas flow fields and used to elucidate the role of the entrained air in the spray development downstream. Amongst a number of studies on PS sprays, only few deal with the phase-resolved velocity fields; therefore, a detailed measurement of the velocity of both the phases is still required. The ambient flow field is often traced using artificial seeding particles [3,6,24–26] or probed with conventional methods [27]. Since PS sprays contain droplets in a wide size range then the smallest ones could serve as natural tracers. De la Rosa et al. [6] studied the effect of swirl on the velocity and turbulence fields of PS sprays and observed that, in general, droplets up to 5 μm in diameter responded well to the fluctuations of the air velocity; the turbulence intensity for 5 μm droplets and the air differed only slightly. They concluded that droplets smaller than 5 μm follow the air motion reasonably well. Also, Sanchez et al. [28] used spray droplets sized under 5 μm as tracers of the gas velocity. However, the concept of the smallest droplets used as natural tracers requires a detailed analysis to be proved and optimised in our case.

This study focuses on a small PS atomizer, intended for a gas turbine. The air–liquid interaction phenomena are addressed and estimates of the spatially resolved flow fields of air and liquid within the spray are made. The turbulence characteristics (spatial, directional and spectral) are qualitatively described, and the main values are quantified. It is based on measurements of droplet size and the three-component droplet velocity using phase-Doppler Anemometry (PDA). The results elucidate the transfer process of kinetic energy from the liquid (droplets) to the air MKE and TKE, the size range of the droplets affected by the air drag and the structure of the turbulent airflow field and the sprayed liquid.

This study aims to improve the current understanding of the PS spray morphology by a comprehensive investigation of the gas-liquid energy transfer with a link amongst different related phenomena that was not found in earlier works. It experimentally provides gas and liquid thermodynamic characteristics of the spraying process and discusses them in the context of previous references. These can be used to validate numerical simulations and show the modellers which phenomena are important to be included in their CFD models to compute realistic simulations.

The focus of the study is the idealised case of a liquid discharged into a quiescent air. It is proposed to extend this study to the cases typical of combusting sprays such as co- and cross-flowing air [10,11,29,30] or controlled external turbulence [31].

Several important phenomena of the spraying process such as secondary droplet breakup, droplet collisions, and liquid evaporation are closely linked to, or influenced by the air–liquid interaction. These phenomena require attention and are not covered by this paper with the aim to keep it focused and not too lengthy. So the results presented here will be used as a base for the following work on these topics.

2. Experimental

This investigation of the air–liquid interaction in the PS spray applies experimental data acquired by optical probing of spray produced by a PS atomizer in the Spray laboratory at the Brno University of Technology. Following paragraphs describe the essential experimental apparatus used including the atomizer under test, the cold-spray test bench with the fluid supply system, PDA and a digital camera with illumination systems.

2.1. Atomizer and test bench

A small PS atomizer, developed for an aircraft engine, was operated continuously in cold-flow (non-reacting) conditions and sprayed aviation fuel Jet A-1 (kerosene) at room temperature, 20 °C, into the quiescent air. The fuel with a density $\rho_l = 795$ kg/m^3, viscosity $\mu_l = 0.0016$ kg/(m·s) and surface tension $\sigma = 0.029$ kg/s^2 was provided at inlet gauge pressures of $\Delta p = 0.5$, 1.0, and 1.5 MPa. All the tests were conducted with one fuel batch. The atomizer was fixed to a 3D computer controlled traverse. Alignment

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[1] Note for completeness that several further mechanisms and forces (e.g. diffusiophoresis, photophoresis, Brownian diffusion) apply in the disperse particle–gas systems, but these act on the particles sized comparably with the gas mean free path (0.07 μm in our case) [23] and are not apparent in the sprays where droplets above 1 μm are produced.