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Numerical and experimental investigation on droplet dynamics and dispersion of a jet engine injector

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ABSTRACT

In the case of turbine combustors operating with liquid fuel the combustion process is governed by the liquid fuel atomization and its dispersion in the combustion chamber. By highly unsteady flow field conditions the transient interaction between the liquid and the gaseous phase is of interest, because it results in a temporal variation of air–fuel ratio which leads to a fluctuating temperature distribution. The objective of this research was the investigation of transient flow field phenomena (e.g. large coherent structures) on droplet dynamics and dispersion of an isothermal flow (of inert water droplets) as a necessary first step towards a full analysis of spray combustion in real-life devices. The advanced injector system for lean jet engine combustors PERM (Partial Evaporated Rapid Mixing) was applied, generating a dilute polydispersed spray in a swirled flow field. Experiments were performed using Phase Doppler Anemometry (PDA) and a patternator to determine the droplet polydispersity, concentration maps, and velocity profiles in the flow. An important finding is the effect of large-scale coherent structures due mainly to the precessing of the vortex core (PVC) of the swirling air jet on the particle dispersion patterns. The experimental results then serve as reference data to assess the accuracy of the Eulerian–Lagrangian computations using a Large Eddy Simulation (LES), a Unsteady Reynolds-Average Navier–Stokes Simulation (URANS) and two simplified (steady-state) simulations. There, a simplified droplet injection model was used and the required boundary conditions of injected droplet sizes were obtained from measurements. Important transient effects of deterministic droplet separation observed during experiments, could be perfectly replicated with this injection model. It is convincingly shown, through extensive computations, that the resolution of instantaneous vortical structures is indeed crucial; hence the LES, or a reasonably-well resolved URANS are preferred over the steady-state solutions with additional, stochastic-type, turbulent dispersion models.

1. Introduction

The air–fuel mass ratio (AFR) distribution in an engine combustor highly affects the distribution of temperature and species concentration. In the case of liquid fuel combustion, pressure variation changes the AFR distribution inside the combustor due to the change of forces acting on the droplets. Due to the changing in combustor pressure with the performance conditions the AFR distribution is also changing and the prediction of pressure scaling with empirical models becomes very difficult. So, the calculation of the combustion performance requires the three dimensional simulation of the combustion process at different performance (i.e. combustion pressure) conditions. One of the main tasks by the three dimensional simulation of the combustion process in the case of liquid fuel combustion is the realistic prediction of the fuel droplets dispersion.

Experimental studies on swirled spray flows have demonstrated that droplet dynamics become a complex combination of several phenomena like aerodynamic transport of droplets, turbulent mixing and centrifugal effects (Edwards and Rudoff, 1991; McDonell et al., 1988; Hardalupas et al., 1990; Bulzan, 1993). These studies revealed an occurrence of a predominant coherent structure within the flow field defined as the precessing vortex core (PVC). While the role of the PVC on combustion dynamics has been recently reviewed (Syred, 2006), its influence on droplet dynamics is still not completely clarified.

Optimization of engine combustors requires the ability of an accurate simulation of the two-phase flow. Unsatisfying results

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appear in steady-state simulations, leading to nonphysical flame structures (Kern, 2013; Andreini et al., 2013; De Meester, 2012). This could be the result of the missing influence of coherent structures on droplet dynamics and dispersion (Galeazzo et al., 2013) while the choice of turbulence closure model has a strong impact on the particle trajectory and dispersion characteristics (El-Asrag and Braun, 2015).

The AFR distribution depends on the local droplet mass load within a finite volume in the combustion chamber. This local droplet mass load being affected by the droplet size distribution and hence, on droplet atomization on one side and spray characteristics (e.g. droplet dynamics and dispersion) influence the pathway of each droplet on the other side. In the case of complicated injector systems as present in jet engines the atomization process is very expensive to calculate. Therefore, a simplified injection model was used neglecting the complex process of spray formation. The boundary conditions of droplet size at the injection point were taken from experimental data from an area located downstream, where atomization was already finished. The validity of this approach is demonstrated in this work. Additionally, the necessary accuracy in droplet dispersion modeling is investigated. For this task, four different simulations with decreasing degree of accounting for large turbulent eddies influencing droplet dispersion are carried out.

The aim of this work is to assess the impact of coherent structures and transient effects on droplet dynamics and dispersion within a flow field generated by a jet engine injector. For this task the Euler–Lagrange description (Jenny et al., 2012) was chosen which is one of the most promising approaches for this kind of problem (Riber et al., 2009; Sanjos et al., 2011). In this context the influence of coherent structures on droplet dispersion was considered with a Large Eddy Simulation (LES) and an Unsteady Reynolds-Averaged Navier–Stokes Simulation (URANS). Furthermore, a kind of a steady Reynolds-Averaged Navier–Stokes Simulation (RANS), which is unable to capture coherent structures, was also performed for comparison. To capture unresolved droplet dispersion in the steady-state approach a common droplet dispersion model was tested.

At ambient conditions without the presence of a flame, droplet dispersion modeling and the simplified injection model were validated against experimental data. This becomes important in order to provide a sufficient base for future spray combustion simulations in a jet engine combustor. Diameter, velocity and Droplet fluctuation Kinetic Energy (DKE) as well as liquid mass flow distributions were gained from measurements using a Phase Doppler Anemometry (PDA) and patternator technique.

This paper begins by laying out the theoretical background for the considered injector system. It will then go on to describe the setup and operating conditions of the test case. In the following, the determination of spray characteristics is summarized. After that the used mathematical method and the numerical setup as well as the injection model is described. Later the consideration of coherent structures in dispersion modeling of the simulations is documented. Finally, results including the validation are presented and discussed before the conclusions are made.

2. Experimental investigation

The investigated injector system for jet engines with lean combustion PERM (partial evaporation and rapid mixing), developed by GE Avio S.r.l. in cooperation with the Karlsruhe Institute of Technology in Marinov et al. (2012), is based on the prefilming air-blast atomization technology (Lefebvre, 1989). It produces a polydispersed spray with a large dilute spray zone.

The injector system consists of two radial swirlers (primary and secondary). They impose a tangential velocity component to the combustion air due to the tangential direction of inflow channels as shown in Fig. 1. This results in the creation of an inner recirculation zone (IRZ) which in return affects droplet dynamics. The formation of a dilute spray is schematically presented in Fig. 1. This complex process is documented in more detail by Marinov et al. (2012).

2.1. Setup and operating conditions

Experiments were performed at an atmospheric test rig, introduced in Wollgarten et al. (2013). This rig was unconfined to allow easier optical access and to avoid deflection of droplets at chamber walls (Marinov et al., 2012). The operating conditions, including the relative pressure drop as the pressure loss across the injector system, are summarized in Table 1.

As the use of kerosene is too dangerous, the liquid phase was replaced by demineralized water in order to investigate the spray characteristics, as successfully done in Wollgarten et al. (2013).

A characteristic Reynolds number of $Re = 160,000$, evaluated using the occurring mean bulk air velocity U_0 obtained from the mass balance and two times the nozzle exit radius R_0, demonstrates the high degree of turbulence generated by the injector system. The global swirl number of $S = 0.76$ was calculated from the nozzle geometry according to Gupta et al. (1984). This swirl number is high enough to allow a formation of a relevant inner recirculation zone (Gupta et al., 1984).

2.2. PDA settings

For the purpose of spray characteristic analysis PDA point by point measurements (Bachalo and Houser, 1984) were performed,

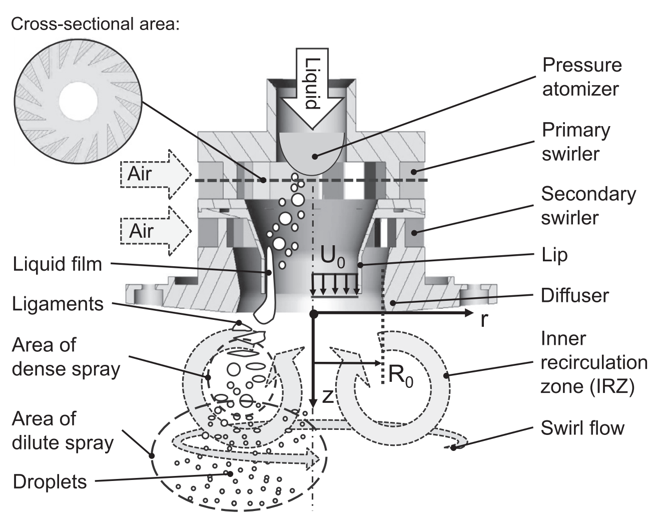

Fig. 1. Schematic representation of fluid flow from the gaseous and liquid phase produced by the injector system with: geometry components (labeled right), normalization values (R_0 and U_0), area of investigation (dilute spray zone), complex spray formation mechanism (labeled left) and cross section area of the primary swirler.

Table 1
Operating conditions of the two-phase flow investigation.

Operating condition	Value	Unit
Absolute pressure p_0	100,400	Pa
Relative pressure drop	3.5%	
Temperature	293	K
Air mass flow rate $\dot{m}_{total}$	0.0625	kg/s
Liquid mass flow rate	0.00232	kg/s
Effective injector exit area	640	mm^2