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Experimental study on the influence of liquid and air boundary conditions on a planar air-blasted liquid sheet, Part I: Liquid and air thicknesses

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ABSTRACT

This experimental study is devoted to the influence of the air and liquid thicknesses on an air-blasted atomizer. The flow configuration corresponds to a planar liquid sheet sheared on both sides by two high velocity airflows. Using planar laser induced fluorescence, back lighting visualizations and light diffraction, flapping frequency, breakup length of the liquid sheet and droplet sizes resulting from the atomization process are measured. The results show that the influence of each fluid thickness depends on the investigated flow characteristic. Thus, breakup length is strongly correlated to liquid flow rate, whereas flapping frequency depends mainly on airflow conditions, characterized by the vorticity thickness. Concerning final droplet sizes, both previous parameters must be taken into account, leading to a correlation based on breakup length and oscillation frequency.

Introduction

Reduction of polluting emissions and improvement of the aircraft engine efficiency are currently the most important challenges for aeronautical research. To achieve these two goals, an optimization of the combustion processes is needed. In order to reduce costs linked to the development of the new combustion chambers, numerical simulations are required to check and validate the various possible options. For most aeronautical engines, kerosene is introduced into the chamber using airblast type injectors. For these devices, the energy needed to break the liquid phase into a cloud of small droplets prior to the combustion process, comes from the high shearing between the air and liquid phases. In this condition, the atomization process is divided into two successive steps called primary and secondary atomization, which must be taken into account in the simulations. These two steps combine a large range of scales, from micrometric droplets to millimetric liquid sheet length and even to centimetric combustion chamber dimensions. Up to date, DNS simulations may potentially predict the different processes involved accurately, if the boundary conditions are well defined and the meshing used is sufficiently small compared to the smallest entities computed (Shinjo and Umemura, 2010). In consequence, high computing costs and numerical resources are needed to calculate an entire combustion chamber. This is the reason why, in most industrial applications, the first step of the atomization process is not computed and models are used to reproduce the main features of the spray behavior. The boundary condition for the liquid fuel is imposed through the numerical injection of droplet parcels (Senoner, 2010). The characteristics of these droplets are deduced from size and velocity distributions a few millimeters away from the injector for given flow conditions (pressure, temperature and flow rates). With this approach, the great coupling between the gas and liquid phases during the first instants of liquid injection is not taken into account. In particular, the influence of the flow unsteadiness resulting from this coupling, which directly affects the flame behavior, is not reproduced in the simulations. In order to improve the quality of these calculations, it is therefore necessary to correctly simulate all of the atomization steps and particularly the primary breakup, where most part of the difficulty resides. In order to perform this kind of simulation with reasonable time costs and numerical resources, alternative numerical methods can be used. From these, a two-phase flow model has been developed by Blanchard et al. (2013a, 2013b), which is used to calculate the primary atomization process up to the detachment of the first liquid blocks from the liquid sheet. The following steps containing the breakup of these structures into droplets are modeled and then computed through well-known dispersed flow calculation methods (Eulerian or Lagrangian). To validate this alternative method and to develop models to couple the two-phase flow and the dispersed flow methods, experiments are needed.

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Table 1
Breakup length correlations.

Arai and Hashimoto (1986)	$\frac{L_b}{t_l/2} = 3.88\,(\frac{t_l/2}{t_{l1}})^{-0.5} We_{t_l/2}^{-0.5} Re_l^{0.6};\ t_{l1} = 0.2 \times 10^{-3} m$
Carvalho et al. (1998)	$\frac{L_b}{t_l} = 0.61\, MFR^{-0.64} Re_l^{0.36} We_{t_l}^{-0.53} + 3.89$
Carvalho et al. (2002)	$\frac{L_b}{t_l} = 6.51 MFR^{-0.68}$
Park et al. (2004)	$L_b \propto \frac{\rho_l}{\rho_g} \frac{u_l}{(u_g - u_l)} \frac{t_l}{2} We_{t_l/2}^{-1/2}$
Larricq (2006)	$\frac{L_b}{t_l} = 0.087\,\frac{\rho_l}{\rho_g} MFR^{-3/8} We_{t_l}^{-3/8};$
Fernandez (2010)	$\frac{L_b}{t_l} \propto ((\frac{\rho_l}{\rho_g})^{1/4} MFR^{1/2} We_{t_l}^{1/2} Re_l^{-1/4})^{-1};$

where L_b is breakup length, t_l the liquid thickness, u_g and u_l respectively the air and liquid velocities, ρ_g and ρ_l the air and liquid densities. We_{tl} is the Weber's number ($We_{tl} = \rho_g(u_g - u_l)^2 t_l/\gamma$ with γ the surface tension); Re_l the liquid Reynolds' number ($Re_l = \rho_l u_l t_l/\mu_l$ with μ_l the liquid dynamic viscosity) and MFR the momentum flux ratio ($MFR = \rho_g u_g^2/\rho_l u_l^2$).

For this purpose, a planar liquid sheet sheared by two co-flowing air streams is used. This configuration is classically used to represent the behavior of an annular injector (Berthoumieu and Lavergne, 2001) because the available optical access permits a more detailed description of the phenomena. Among the first working on this type of injector, Mansour and Chigier (1991) suggested a classification of the various atomization regimes depending on airflow conditions. This classification is based on a sudden frequency modification and the predominance of specific wave types (dilational and sinusoidal) highlighted by the work of Hagerty and Shea (1955). More recently, Fernandez (2010) and then Lozano et al. (2011) completed the Mansour and Chigier classification. In particular, Lozano's classification is composed of six different regimes, which are distinguished by frequency jumps and changes in the oscillation FFT spectra. These measurements are compared with visualizations and spray angle calculations, in order to characterize the regime transitions. Over the following years, several studies, experimental (Arai and Hashimoto, 1986), theoretical (Lozano et al., 2001) and numerical (Blanchard et al., 2013a, 2013b), were dedicated to this configuration. The influence of various flow parameters like air and liquid velocities was studied, highlighting a dimensionless number *MFR* (for momentum flux ratio) that characterizes the liquid sheet atomization. Other works investigated the influence of fluid properties like viscosity (Lefebvre, 1989; Sattelmayer and Wittig, 1986), density (Rizk and Lefebvre, 1982) or surface tension (Rizkalla and Lefebvre, 1975) on droplet size (Eroglu and Chigier, 1991; Stapper and Samuelsen, 1990). With the same goal, experimental studies were conducted at Onera on primary atomization parameters (Carentz, 2000) with different fluids (Larricq, 2006) and pressure conditions (Fernandez, 2010).

However, few studies have been conducted on the influence of flow thickness. Some precedent works revealed the influence of liquid thickness on the spray droplet size (Lefebvre, 1992), oscillation frequency (Lozano et al., 2005; Siegler et al., 2003) and break-up length (Arai and Hashimoto, 1986). Nevertheless, only few different liquid thicknesses were used. Few papers concerning the influence of air thickness were available. Modifications in the liquid sheet behavior were observed, but they cannot be directly linked to an airflow parameter (Lozano et al., 2005; Siegler et al., 2003).

Table 3
Sauter mean diameter correlations.

Arai and Hashimoto (1986)	$\frac{D_{32}}{t_l} \propto (\frac{t_l f}{u^*})^{-2}\ avec\ u^* = (\frac{\gamma}{\rho_l t_l/2})^{0.5}$
Lozano et al. (2001)	$\frac{D_{32} f \mu_g}{\gamma} = f(MFR)$
Fernandez (2010)	$St = \frac{f\sqrt{t_l t_g}}{u_{min}} = K \times We_{D_{32}}^{1/2} Oh_{l,t_l}^{3/2} \frac{\rho_l}{\rho_g}$ and $K = 4 \times 10^4$

where D_{32} is the Sauter mean diameter and $We_{D_{32}}$ the Weber number based on the D_{32} ($We_{D_{32}} = \rho_g(u_g - u_l)^2 D_{32}/\gamma$).
The other symbols are defined in Tables 1 and 2.

In order to understand the phenomena involved in primary atomization and to observe the influence of the flow conditions, the authors have focused their analysis on two main characteristics of the liquid sheet behavior: the breakup length and the flapping frequency. Furthermore, they characterize the final spray through the mean diameter D_{32} or *SMD* (Sauter mean diameter). Various correlations were proposed for these three quantities (they are presented in Table 1 for the breakup length, in Table 2 for the oscillation frequency and in Table 3 for the droplet size).

Yet, few of them take into consideration the liquid flow thickness and none of them takes into account the airflow configuration (convergent/divergent).

These correlations permit the dependence on the flow parameters of the studied liquid sheet characteristics to be defined. Some of them are indeed taken into consideration: linear dependence of frequency on air velocity for example. For other parameters, the various correlations show the same global tendency, but to a degree that depends on the author (breakup length with air or liquid velocity). These differences are presented in Table 4, where the exponents associated with the main parameters are presented for each correlation.

Experimental test-rig

This study has been performed on a simplified 2D liquid sheet, sheared on both faces by high velocity air (Fig. 1). The liquid sheet generator was designed at ONERA within the framework of a previous study on this topic (Fernandez et al., 2009; Larricq et al., 2005); it is an airfoil with an 89 mm chord and a NACA63-010 profile. A couple of perforations, at each injector side, allow the liquid to enter. Water was used at ambient temperature. The liquid sheet is formed on the trailing edge of the injector through a 40 mm width slit. Various

Table 2
Oscillation frequency correlations.

Arai and Hashimoto (1986)	$\frac{f t_l/2}{u^*} = a(\frac{t_l/2}{t_{l1}})^{0.5} We_{t_l}^{0.5} Re_l^{0.15} + b;\ u^* = (\frac{\gamma}{\rho_l t_l/2})^{\frac{1}{2}}$ *characteristic velocity*
Carvalho et al. (1998)	$St = \frac{f t_l}{u_l} = 0.366\, R^{0.09} MFR^{0.21} Re_l^{-0.15} We_{t_l}^{0.12}\ et\ R = \frac{u_{g1}}{u_{g2}}$
Berthoumieu and Carentz (2000)	$\frac{f t_l}{u_l} = 0.1\, MFR^{0.5}$
Lozano et al. (2001)	$St = \frac{f t_l}{u_g - u_{min}} = f(MFR)$
Carvalho et al. (2002)	$\frac{f t_l}{u_l} = 0.13 MFR^{0.38}$
Lozano et al. (2005), Siegler et al. (2003)	$St = \frac{f\sqrt{t_l t_g}}{u_g - u_{min}} = f(MR)$
Larricq (2006)	$\frac{f t_l}{u_l} = 0.0034 \times (\frac{\rho_g (u_g - u_{min})^2}{\rho_l u_l^2})^{1/2} (\frac{\delta}{\delta_\omega})$
Fernandez (2010)	$St = \frac{f\sqrt{t_l t_g}}{u_{min}} \propto Oh_{l,t_l}^{\frac{3}{2}} Re_{g,C} (\frac{\delta}{\delta_\omega});\ u_{min} = 2 \times 10^{-4}\ \frac{\gamma \rho_l}{\mu_l \rho_g};\ Re_{g,C} = \frac{\rho_g u_g C}{\mu_g}$

where *f* is the oscillation frequency, *a* and *b* two constants (0.0084 and 0.02), u_{min} the minimal air velocity to initiate oscillation, δ the boundary layer thickness, δ_ω the vorticity thickness, μ_l the air dynamic viscosity and *C* the chord of this injector. $Oh_{l,tl}$ is the Ohnesorge number ($Oh_{l,tl} = \mu_l/(\rho_l t_l \gamma)^{1/2}$).
The other symbols are defined in Table 1.