Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field

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Abstract

Liquid-fuelled turbomachines for propulsion and power made great improvements in terms of overall efficiency and reduction of pollutant emissions over the last two decades. The main technology trends were a better atomisation using airblast injectors, a stronger pressure ratio and a higher combustor inlet air temperature acting on both refined spray and rapid evaporation (see Lefebvre [1] and Faeth [2, 3]), and an operation in the lean combustion domain to obtain the right balance between thermal efficiency and pollutant emissions.

However, at such levels of pressure and temperature, the slightest injection fluctuation may have a dramatic effect on the combustion stability, with the risk to trigger a thermoacoustic instability, interfere with the performance of the machine and/or provoke structural damages. The combustor is tuned during the design phase iterating with a trial-and-error session so that combustion remains steady at operation. But transients or unexpected events such as a partially plugged injector may still trigger a combustion instability. The research effort focuses on a better understanding of the physics of the injection, in order to provide design guidelines based on a rational approach, and also develop active control strategies able to maintain steady state combustion.

This study reports on the combined effects of a modulated injection of liquid in presence of a strong thermoacoustic resonance. One combustion control strategy consists in acting in real time on the liquid injection, in order to act in phase-opposition with the acoustic pressure and thus damp the instability. The influence of the unsteady atomisation process and two-phase flow transport are taken into account. The idea is to assess the levels of fluctuation on the injection and time-shifts required to damp as much as possible the pulsating spray effect. A 1D particle transport model called IN-PULSE has been designed for this purpose and is hereby presented.

Introduction

The research program performed at TU Graz on "Evaluation of active control strategies regarding airblast atomisation" in cooperation with DLR Cologne is financed by the Austrian Science Fund (FWF).

The aim is to assess methods for optimising the fuel spray to off-design operation of a gas-turbine. Active control through the injection can in theory damp a combustion instability if the latest occurs [4], or fine-tune the spray so that the optimum between efficiency and emissions is maintained at steady operation as well as during transients. A methodology based on particle transport simulation is presented to assess the effectiveness of real-time actuation strategies of the injection.

Numerical simulation of the air-blast atomisation process is thoroughly researched (Trontin et al. [5]) with a detailed description of the turbulent two-phase flow in the vicinity of the injector. However, the problem is multi-parametric: fully-resolved two-phase flow with two-way coupling, evaporation, species diffusion, combustion. So that the computational costs are high and the computational measurement volume is limited in size. A simplified modelling for detailed parametrical study on airblast actuation is hereby presented, for a non-reactive flow. The effect of inlet condition modulation (air and/or liquid) on the spray in the far field is assessed in 1D. The atomisation is introduced as fully atomised in the computational model, with a detailed size distribution. The test case used for model validation fits this modelling since it was performed with real fuel (kerosene Jet A1) at room temperature (no evaporation) and intermediate pressure. Low-scale turbulence and diffusion are neglected.

A lagrangian model for particle transport issued from an airblast and called IN-PULSE uses droplet size correlations from basic experiments realised at DLR Cologne ([6, 7]). It is designed to evaluate the spray characteristics in the far field as a function of the inlet boundary conditions. The particles are discrete in size, covering the size range of interest. Air and liquid phase can be steady or unsteady state, as well as the particle size PDF can be modulated at the inlet condition.

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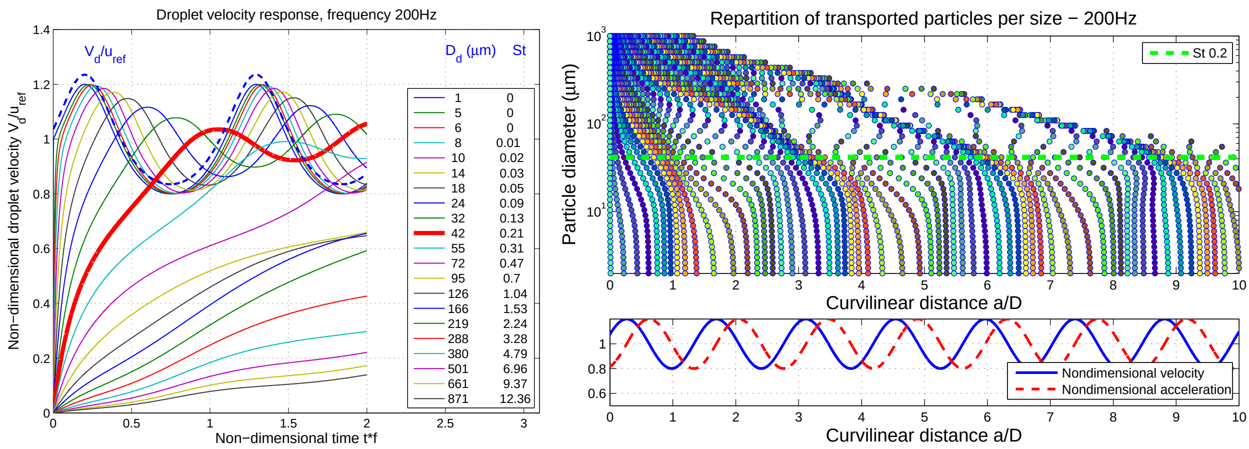


Figure 1: IN-PULSE demo: response of single droplets in time (left) and space (right) as a function of their size when released in an unsteady air flowfield

The specifics of the programm IN-PULSE are described. The experimental test case, as well as the correlations are presented. Several scenari are studied: pulse air injection, pulse liquid injection, intermittent injection. Further developments of IN-PULSE towards its integration in CFD codes with evaporation and combustion assessments are planned.

Materials and Methods

Numerical model

IN-PULSE (Modèle analytique d'INjection PULSéE en turbine à gaz) was primarily programmed by author to describe the physics of an airblast atomisation with modulated air flow rate [8, 9]. Its algorithm is designed to let vary on-demand the inlet conditions (air steady or pulsed, liquid steady or pulsed, intermittent flow, "shaked injector"), and to report on the resulting spray conditions at the desired spray depth at a given frequency. In its latest version, IN-PULSE reports not only on the particle size distribution, but also on the liquid mass flow rate or flux at any depth in the spray. Other global parameters of interest are the Mean Sauter Diameter $D32$, the mean particle velocity (derived from the momentum balance), the Weber number We and the Stokes number St.

The particle transport model is based on the simplified BBO equation [10]. This model assumes isolated, spherical, non-deformable particles, that are non-rotating on themselves. In a steady or unsteady air flow, the droplet acceleration is expressed as a sum of specific force per mass ratios. These forces are the viscous drag force, the added mass force, the historical term of the droplet, and contributions from the pressure gradient and gravity. Given the operation of an air-blast injector, the viscous drag force is an order of magnitude larger than the others, so that:

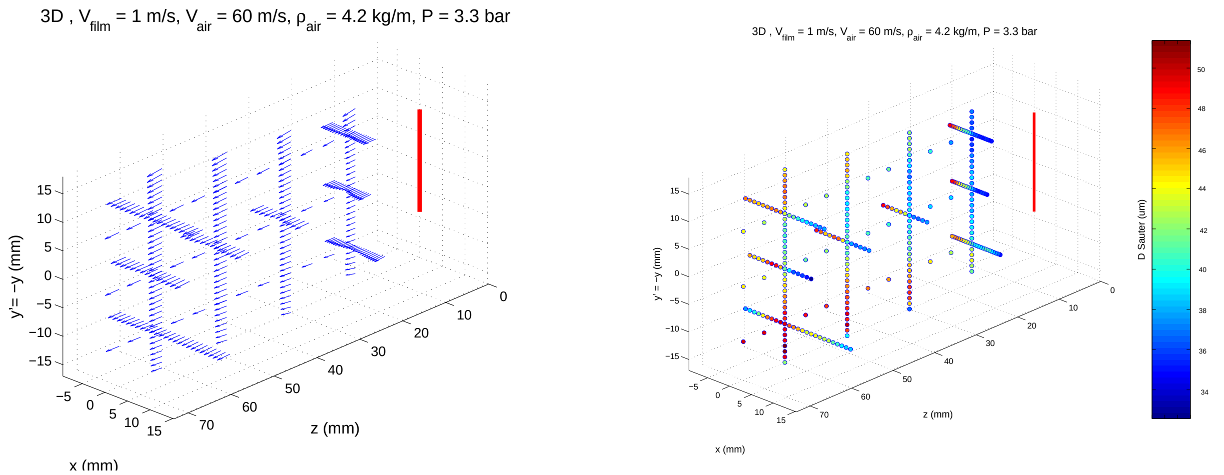
$$\frac{d\vec{V_p}}{dt} = \frac{3}{4}\,\frac{\rho_g}{\rho_p}\frac{C_d}{D_p}\,(V_g - V_p)\,|V_g - V_p| \tag{1}$$

The transporting phase is dry air, the liquid is kerosene Jet A1, and the correlations for physical fluid properties are taken from [11, 12]. We consider in this study a non-evaporating spray, the evaporation module based on the d^2 law is deactivated (see [9] for a test case with evaporation).

An example on the use of IN-PULSE is shown in Fig. 1. On the left plot, the response of the droplet velocity to a pulse air flow is represented. On the right plot, droplets of several diameters are iteratively emitted at the origin, and then follow the pulsed flow. The conditions here are an air flow of 30 m/s (with a 20 % modulation) at atmospheric conditions on a kerosene spray. Giuliani et al. [8] showed the importance of unsteady transport effect of a pulsed air flow on the construction of dense zones in the spray. These are essentially made up of small particles with a low Stokes number constructing a coherent ensemble, as shown in Fig. 1, left.

Reference test case

Realistic droplet size and velocity probability density functions of atomised kerosene are required so that IN-PULSE performs assessment with correct orders of magnitude. The correlations presented hereby are issued from a post-process of data obtained by author at DLR Cologne [6, 7] in the frame of the MoPAA project (Measurement of Prefilming Airblast Atomisation, a joint DLR-ONERA study).



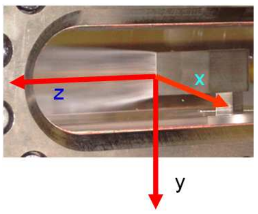


Figure 2: PDA Measurements on the flat prefilmer. Top left: particle velocities. Top right: D32 measurements. Left: injector and resulting spray, with coordinate system.

The DLR spray test rig is designed for non-reactive fuel spray analysis under realistic levels of pressure and temperature for gas turbine operation. Technical details can be found in [13]. The maximum parameters are: air pressure up to 20 bar, air mass flow rate up to 1.3 kg/s, air temperature up to 920 K and kerosene flow rate up to 10 g/s. The test cell has a square section of 40*40 mm.

The flat liquid atomiser used has a prefilmer length of 4 mm, over an height of 18 mm (see Fig. 2, left). Kerosene is injected through a slot of 300 μm. The spray in the centerline is assumed to be two-dimensional, where the effect of the injector's tip vortices are minimal, as can be seen on the 3D plots for velocity (middle plot), and $D32$ (right plot). Its body is profiled to minimise blockage. 2-component particle size and velocity measurements were realised with a Dantec 57X10 PDA.

In the following, measurements performed on the centerline at 15 mm downstream the injector are considered. This is an optimal distance from the injector between particle size measurements with an acceptable validation rate of spherical particles and the high spray density responsible for a high data rate. This measurement point also catches very small droplets that evaporate further downstream. Traverses were performed along the X-axis to integrate the overall droplet size distribution and check that the centerline measurement is representative of the spray: the traverse $D32$ matches the single point $D32$ with a 3 % confidence interval.

Lefebvre [1] notes that no universal droplet size distribution model can be offered for air-blast atomisation since the latter is injector-design dependent. A statistical approach is therefore necessary. Usually, a Rosin-Rammler PDF (RR) is used to fit the volume distribution. In this study, we considered two other distributions: Gamma PDF (Γ) for the droplet volume distribution, and Log-Normal PDF (LN) for the size distribution. Least root square fitting methods were used. Compared to the RR distribution, better qualitative results were found to match the volume distribution using a Γ PDF (compare the columns $D32_{measured}$ and $D32_{\Gamma}$ in table 1). A LN PDF was observed to perform the most representative particle size distribution fitting. However, when computing the $D32$, due to its algebra the LN PDF tends to overrate the big droplets' number, ending with errors up to 20 %. On the other hand, both Γ and RR PDFs overrate the small droplet number, but this has little effect on the $D32$. One example of distribution fit is displayed in figure 3.

In the following, we consider the Γ PDFs results as a basis for a correlation. Table 1 covers several measurement points realised at 15 mm of the injector lip, at ambient temperature. The film load was varied from 0.225 to 0.45 g/mm, not affecting the SMD but having an impact on the spray width (see [7]). The Weber number varied from 80 to 750. The parameters a and b of the Γ distribution are reported so that:

$$PDF_D = \frac{1}{b^a\,\Gamma(a)} D^{(a-1)} e^{\frac{D}{b}} \qquad \text{with} \qquad \Gamma(a) = \int_0^\infty e^{-t} t^{a-1} dt \tag{2}$$

where D is expressed in μm.

Based on this study, a linear correlation for a and b was established, matching the measured $D32$ with a 5 % confidence interval for Weber numbers from 80 to 410, and 15 % for We up to 730:

$$a = -0.026 V_g + 7.5 \qquad\qquad b = -1.24P - 0.045(V_g - 60) + 11.8 \tag{3}$$

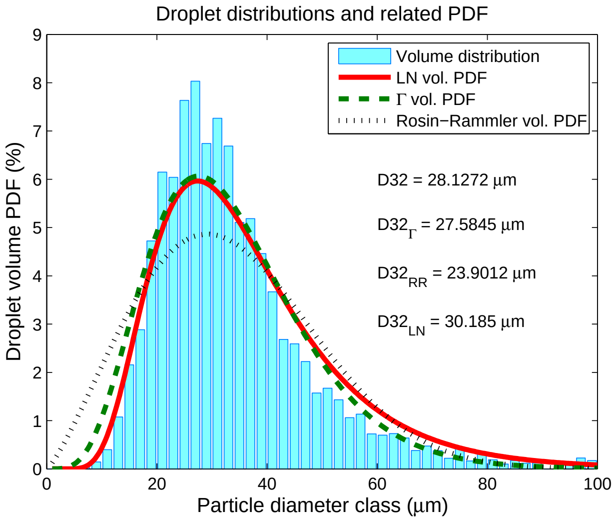


Figure 3: PDF fits compared with PDA measurement, and $D32$ comparison

Table 1: Particle size measurement: parameters, $D32$, Γ fit and correlation check

We	Air pressure P (bar)	Air velocity V_g (m/s)	Gamma fit a	(Γ parameters) b	$D32$ measured (μm)	$D32_\Gamma$ (μm)	D32 correlation (μm)
87	1.6	60	5.68	10.03	46.64	46.89	48.49
98	1.8	60	5.85	9.54	46.09	46.23	47.27
180	3.3	60	5.87	8.1	39.7	39.4	38.08
410	3.3	90	4.46	6.07	27.62	27.08	26.45
733	3.3	120	4.4	5.44	19.44	18.48	16.93

where V_g is expressed in m/s and P in bar.

Definition of the parametric study

As a first assumption, the liquid is introduced as already fully atomised in the computational domain, with a PDF on its size repartition as determined previously. At elevated We numbers (above approx. 200 in this study), the atomisation scales are reduced and primary and secondary break-up mechanism take place simultaneously, leading to sheet stripping. Thus it may be assumed that the atomisation process at elevated pressure and velocity is compact and local.

Each emitted scalar in the computational domain represents a droplet size class, weighted with the probability density corresponding to the same diameter. It appears iteratively with zero velocity at the injector's lip, is logged in position and velocity at each time step and is then counted in the far field by a probe.

The simulation is set at air velocity V_g=60 m/s, pressure P=3.3 bar, ambient temperature T=283 K. The mass flow rate remains symbolic (a normalised total value "100" is injected in the computational domain at each time step). Provided the flow is steady state, the simulation is supposed to reproduce the PDA measurement, as shown in Fig. 4 for model validation. Both measured size and volume distribution are represented on the left. The velocities per droplet size scatter at the extremes because of the lack of data for extremely small and big droplets. The terminal velocity of 60 m/s is not achieved yet 15 mm downstream the injector. On the right hand side, the simulation is produced. The trends and features are well reproduced, especially the particle velocity per size where the highest volume distribution is situated, where the particles are still in the acceleration phase. The $D32$ differs by 4 %, the mean velocity differs by 2.8 %.

The modulated flow inlet condition on the air is introduced, with hydrodynamics similar to the description by Giuliani et al. [8]. Due to the presence of a thermoacoustic coupling, pressure fluctuations at the air inlet can effectively modulate the air inflow. This modulation is advected as a wave at half the inlet velocity, so that the gas phase (without damping factors) can be expressed as:

$$V_g(z,t) = \bar{V}_g \left(1 + A \sin\left(2\pi f \left(t - \frac{2z}{\bar{V}_g}\right)\right)\right) \quad (4)$$

IN-PULSE can assess 1) the effect of pulsed air on the steady atomisation 2) the effect of modulated atomisation at the atomiser's

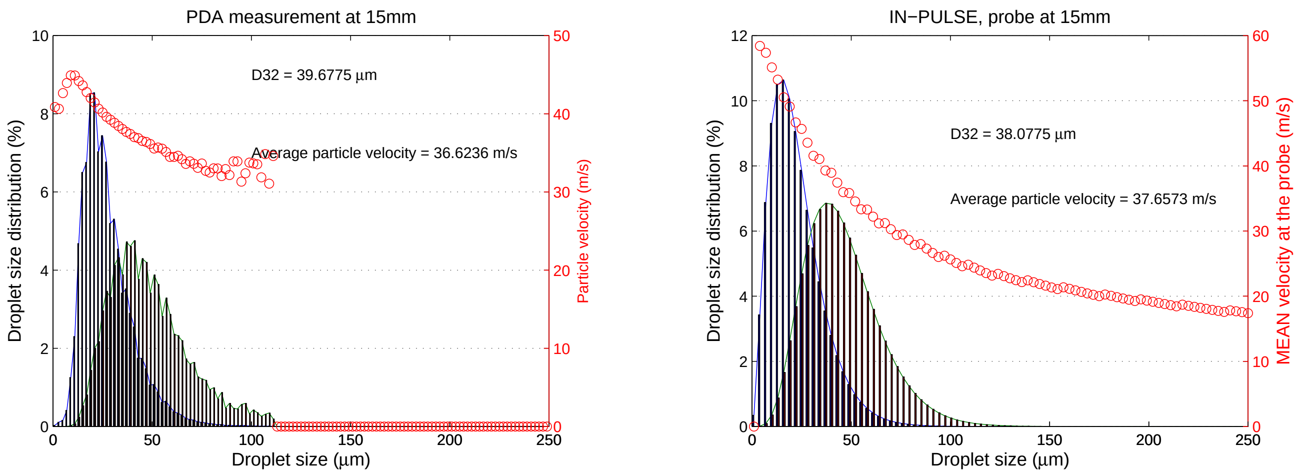


Figure 4: Comparison between PDA measurement and simulation. Particle size distribution, volume distribution and velocity per droplet size measured 15 mm down the injector are shown

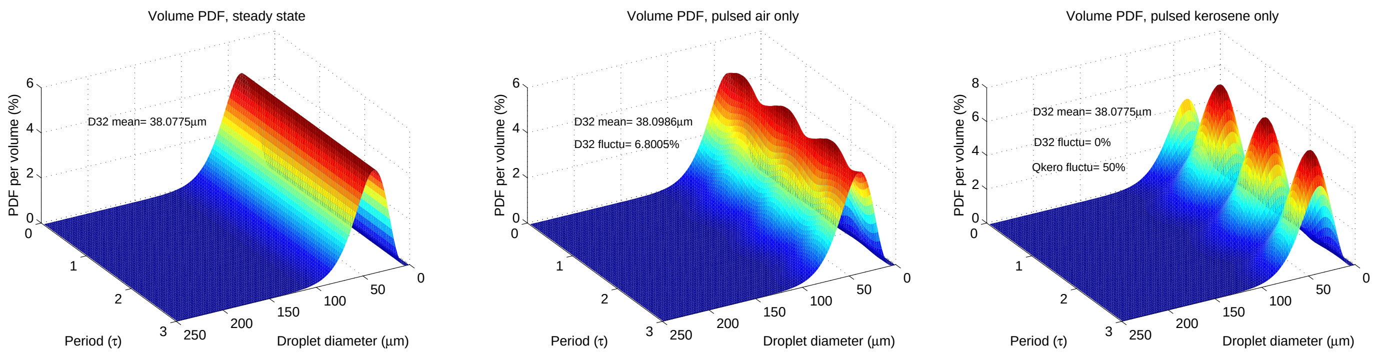


Figure 5: Possible inlet conditions for the introduction of the atomised phase: steady state (left), constant kerosene flow with modulated PDF (middle), and pulsed kerosene flow (right)

lip (resulting in a fluctuating D32 at constant liquid flow rate) 3) the effect of intermittent kerosene injection (fluctuation of Q_{kero} at constant D32) 4) any combination of the latter with phase-defined shifts. The inlet conditions of the time-resolved volume PDF for steady-state atomisation, modulated atomisation by air and pulsed kerosene flow are shown in figure 5.

Results and Discussion

In figure 6, an air modulation of A =10 % is applied on the case study point (60 m/s, 3.3 bar). We suppose the atomisation response to be linear to the pulsation, so that a and b undergo a similar fluctuation level as the air velocity. For Eckstein et al. [14], film disintegration in presence of an oscillating air flow can be described as a quasi-stationary process. Müller et al. [15] restrict this observation to the low-frequency domain. The range of interest is therefore [50 - 500Hz], which is also about the current technological limit for precise phase-resolved injection actuation. The air pulsation frequency is set at 100 Hz. The probe is placed at Z =60 mm from the injector.

Each parameter measured at the probe is compared with its inlet condition. Attention is paid to the time shifts and the amplitudes of fluctuations. On the left plot, the effect of pulsed air on the atomisation is reproduced: particle velocity, liquid mass flow rate and $D32$ are strongly influenced by the air flow and act synchronously. The lowest $D32$ corresponds to the highest number of particles, confirming the observation on dense droplet zones done in figure 1. A 10 % air flow modulation combined to modulated atomisation at the inlet generates a 7 % liquid flow modulation, a 6 % D32 fluctuation and a 20 % droplet count fluctuation.

The idea is to damp the flow rate fluctuation at the probe level. Given the prefilmer configuration there is little chance to act on the atomisation process itself. The most realistic actuation relies on a phase-shifted pulsation of kerosene, considering the same fluctuation level as measured previously (7 %). The best condition is achieved for a phase-shift of $3\pi/4$ (eq. to a time lag of 7.5 ms) between air and liquid, where the fluctuation at probe level drops to 0.5 %. Note that in the phase-opposed situation, a worst case is met where the

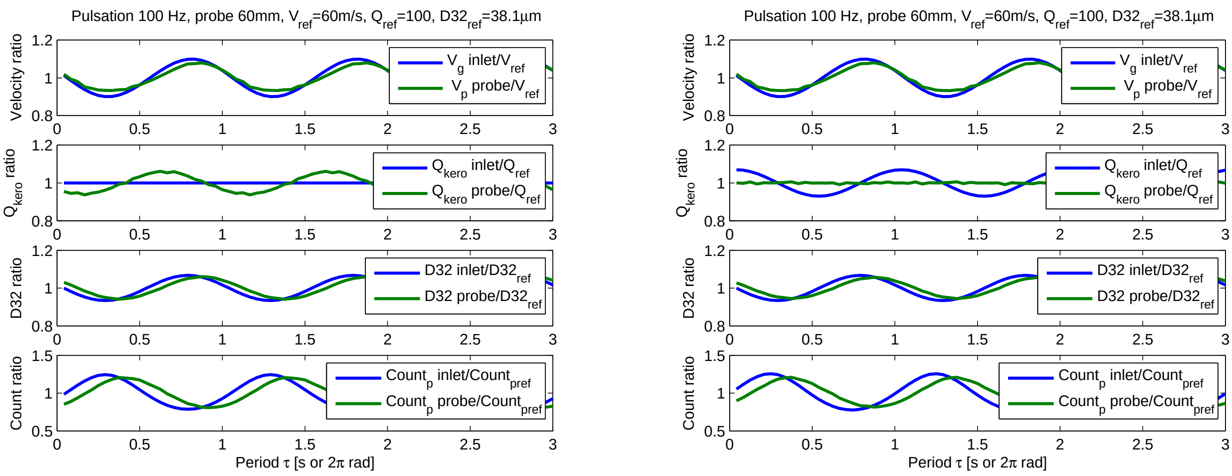


Figure 6: IN-PULSE application: probe measurements on an air blasted spray at Z =60 mm. Left: effect of an air pulsation on the spray parameters. Right: damping of Q_{kero} based on a modulated liquid injection.

amplitudes add-up with Q_{kero} rising to 14 %. The other parameters (velocity, D32 and droplet count) remain quasi unchanged as long as no actuation on the atomisation process is attempted.

The fluctuation of D32 and liquid flux is frequency dependant. Particular attention must be paid to where in space stability is wished (for instance the front flame position). Precise control requires a high phase-resolution. Damping factors and non-linear coefficients can also be used to fine-tune the model to a test case.

Conclusions

The model IN-PULSE was adapted to reproduce the spray characteristics in the far field as a function of the inlet conditions. A correlation on the atomisation of an airblast with prefilmer was used to assess realistic inlet conditions. Based on these, order of magnitudes on the required actuation can be computed, so that IN-PULSE can be used as a simple predictive and/or dimensioning tool for combustion instability risk analysis.

The immediate potential for improvement lies in a more detailed modelling on the introduction of the liquid phase in the computational domain. Concerning the droplet size PDF, further attempts to represent with more precision the low St particles will be done based on the use of truncated LN distribution. In the near future, IN-PULSE will become a user-defined function of a numerical code, to facilitate similar studies for liquid actuation assessment in 2D and 3D, with evaporation, and under reactive conditions.

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Nomenclature

	Main scripts	
Γ	Gamma distribution	
ρ	Density	[kg/m^3]
a, b	Gamma distribution parameters	
Cd	Drag coefficient	
D	Particle diameter	[μm]
D32	Mean Sauter diameter	[μm]

Q	Mass flow rate	[kg/s]
V	Velocity	[m/s]
	Abbreviations	
BBO	Basset-Boussinesq-Oseen equation	
FWF	Austrian science fund	
LN	Log-normal distribution	
PDF	Probability density function	
RR	Rosin-Rammler aka Weibull distribution	
	Subscripts	
g	Gas phase, or air	
kero	kerosene	
p	Particle	

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