Evaluation of active control strategies regarding airblast atomisation

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Abstract

The fine control of fuel injection stability in gas turbine combustors is a key point in the development sustainable technologies for propulsion and power. It may improve the overall efficiency, facilitate smooth operation as well as reduce pollutant emissions. It is also the most feasible solution able to damp combustion instabilities if the latter occur. The concept of active control of combustion via the injection is meant to ensure combustion stability on the whole operation envelope, extend the flammability limit in the lean domain, and produce a better atomisation at part load conditions. However, the practical aspects of this control remain technical challenges. The question is then to assess which control method on atomisation is effective, has a low-energy cost, and is technically feasible and robust enough for an embedded application in a gas turbine. The aim of this ground research project financed by the Austrian Science Fund is therefore to evaluate active control strategies regarding airblast atomisation, based on a numerical approach. A particle transport numerical model was developed to assess the effect of different modulated parameters on the resulting spray [Giuliani et al. Effect of the initial droplet size distribution of the liquid phase combined with transport phenomena on the resulting airblast spray in the far field. ICLASS 2009-133]. The injection geometry is an air-blast, the injected liquid is kerosene. The parameters that can be modulated in real time are the air mass flow rate, the liquid mass flow rate, the atomisation PDF and the injector tip position. Several fluctuations can be applied simultaneously, with or without phase-shift between each other. This paper reports on the first assessments performed on an isothermal and non-evaporating test case. This approach offers a better understanding on the physics involved in the airblast injection when modulating one of its operation parameters.

Introduction

The current trends for gas turbine combustion technology involve rising inlet pressure and temperature levels, combined to an augmentation of the thrust-to-weight ratio. The combustor tends to be more compact and operate at high levels of density of thermal energy. At some point, it is crucial to ensure that steady state combustion is maintained over the full operation envelope. The focus is put on the standard aeroengine injection system: the airblast injector [1].

However, problems of unsteady combustion or combustion instability arise at near blow-out limit, or under exceptional circumstances leading to an aero-thermo-acoustic coupling [2]. Among the technical solutions for advanced combustion management, real-time controlled injection is a candidate that possibly can maintain steady state combustion by changing the injection operation using quasi-static operation changes, or dynamic drive [3, 4]. A research programme supported by the Austrian Research Fonds was started 2008 at the TU Graz to assess the effectiveness of some dynamic control strategies for airblast injection.

Among the important parameters of the injection, the transport effect taking place from the location of liquid fuel injection up to the front plate plays an important role on sustaining the mechanisms of combustion instability. Especially when long residence times are involved such as in the case of premixing and prevaporisation for lean combustion, augmenting the degree of interaction between the air turbulence and the fuel. The question asked is, in case of strong perturbation (e.g. a combustion instability), what are the effective parameters of injection that can be driven so that the effect of combustion instability on the injection is being reduced and eventually damped.

The modelling of air-blast atomisation process for numerical simulations and injector design guidelines is extensively researched (Trontin et al. [5]). The focus is put on 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, turbulence, evaporation, species diffusion, combustion. The computational costs are high and the measurement domain and test case duration are limited in size. Therefore the number of test cases to be performed on a given geometry is limited.

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A simplified 1D tool was developed with the purpose to facilitate the parametric analysis, perform a large number of test cases in a limited time and provide assessments on airblast atomisation control strategies under a generic form. The IN-PULSE model [6, 7] contains basically three modules:

1. an airblast atomisation module issued from correlations on a generic airblast prefilmer of DLR Cologne,
2. a 2-phase flow transport module based on the Basset-Boussinesq-Oseen equation (that can include an evaporation module based on the D-square law, turned off for this specific non-evaporative case study) and
3. an assessment module providing the specifics of the spray at a given depth.

These parameters are the air mass flow rate (or velocity), the air pressure, the liquid mass flow rate, the atomisation PDF and the nozzle tip position. All these parameters can be steady-state or modulated at a given frequency and amplitude. The single effect of a dynamic parameter can be studied, as well as a combination of several dynamic parameters with a control on the phase-shifts.

This work reports on the analysis of several types of actuation at realistic levels of airblast operation, in the non-evaporative and non-reactive case.

The IN-PULSE model

2-phase flow transport module

The ambition when developing IN-PULSE (Modèle analytique d'INjection PULSéE en turbine à gaz, Analytical model for modulated injection in a gas turbine), basically a Matlab-encoded Lagrangian model, was to facilitate the understanding of transport mechanisms of particles transported by a pulse jet. One motivation was the refined physics of the injection facing a strong combustion instability, and the understanding of the role of the injection within this loop. The assumptions of the transport model follow: the particle appear in the computational domain in the atomised state, at a negligible velocity compared to the air velocity, the acceleration of spherical particles is mostly a function of the drag force exerted by the air on them (so called Basset-Boussinesq-Oseen or BBO equation), non-evaporating case to ease experimental validation at ambient conditions, diluted spray conditions so that a one-way coupling assumption is acceptable, and no collision between particles. More details can be found in [8, 6, 7].

In presence of an air flow modulation, the spray gets a discontinuous pattern with formation of droplet fronts. These fronts are convected at about half the air injection velocity. Different interpretations have been offered. For Eckstein et al. [9], film disintegration in presence of an oscillating air flow can be described as a quasi-steady process, where the droplet size distribution is dictated by the air velocity. If the air velocity (and/or pressure) fluctuates, the droplet size distribution varies as a response to the latter. The fronts are therefore related to a strong change in droplets size and transported at an average velocity. Müller et al. [10] restrict this observation to the low-frequency domain. For Giuliani et al. [8], the principal driving phenomenon is the segregation of the droplets as a function of their size and of the pulsation frequency of the entraining pulsed air (Fig.1).

The patterns of these mechanisms simulated by an early version of IN-PULSE were validated by Fraunhofer diffraction measurements [11]. However, in that case the instrument used (Malvern particle sizer) had a low cut-off frequency (600Hz) so that higher frequencies could not be investigated. Becker et al. [12] used a time-resolved reconstruction algorithm of PDA measurements to observe spray discontinuities up to 3 kHz organised per particle diameter classes - but noted the large uncertainty specific to the particle validation rate.

Airblast atomisation model

The atomisation process is simplified by the introduction of the fully atomised spray in the computational domain. The point is to reconstitute a realistic aspect of the particle size distribution at several positions along the axis of the spray. Therefore an atomisation model defined over a large operational domain is required. This model is issued from a post-process of PDA data obtained in the frame of the MoPAA project (Measurement of Prefilming Airblast Atomisation, a joint DLR-ONERA study between 2001 and 2004, [13]) on the kerosene spray test rig at DLR Cologne.

During this study performed on a model flat prefilmer (see also Baharaju [14]), it was established that - provided the conditions of a diluted spray are respected - the Sauter mean diameter $D32$ is driven by the air flow conditions, and the effect of the mass flow rate of kerosene $\dot{Q}_{kero}$ has quasi no influence.

During a statistical analysis, it was found out that the droplet size distributions have a best fit with a Γ distribution, and that this distribution could be parameterised over the covered operation range. More details on this study are available in [7]. The probability density function (PDF) as well as the parameters a and b of the Γ distribution follow:

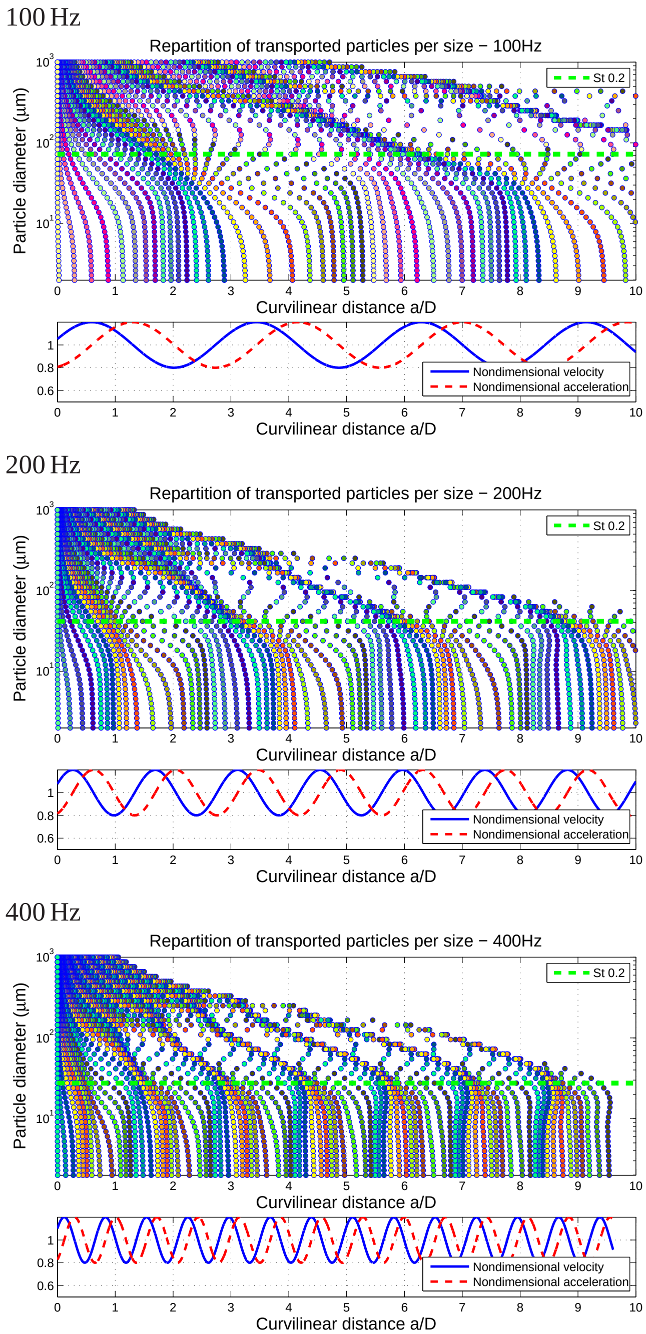

Figure 1. Response of droplets transported in a pulsed air flow as a function of their size and of the air pulsation frequency. Three frequencies are represented: 100, 200 and 400 Hz pulsation frequency. The particle diameters cover the [1 μm-1 mm] range and are arranged along a logarithmic scale. The curvilinear distance a/D is the trajectory length of the particle since its emission divided by a characteristic length of the simulation (D=50 mm). Particles of the same colour have been emitted at the same time. The Stockes number $St = 0.2$ notes the upper particle diameter that constitutes a droplet front. A snapshot of the velocity field as a function of the length is represented for each frequency.

$$PDF_D = \frac{1}{b^a\,\Gamma(a)} D^{(a-1)} e^{\frac{D}{b}} \quad (1)$$

$$\text{with} \quad \Gamma(a) = \int_0^\infty e^{-t} t^{a-1} dt \quad (2)$$

$$a = -0.026 V_g + 7.5 \quad (3)$$

$$b = -1.24P - 0.045(V_g - 60) + 11.8 \quad (4)$$

where D is the droplet diameter expressed in μm, V_g is the air velocity expressed in m/s and P the air pressure in bar. a and b are valid for a Weber number We situated in an interval [80 to 750].

Combined to the transport model, this correlation allows to simulate the average particle size distribution as measured by a PDA at any distance from the injector, assuming a 1-D flow hypothesis. Fig.2 represents two simulations on the same spray conditions (the droplet size distribution remains unchanged because of the conservation

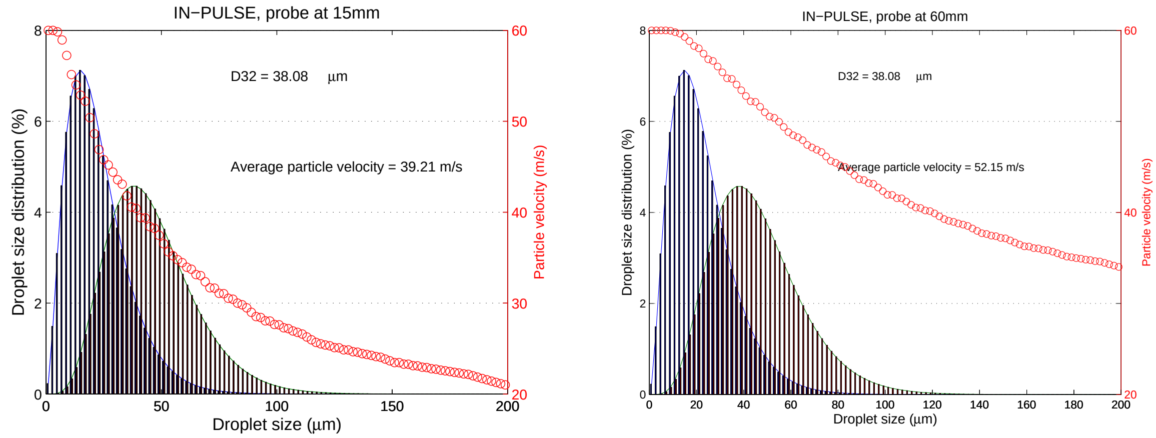

Figure 2. Particle size distribution, volume distribution and velocity per droplet size for two probe positions 15 and 60 mm downstream of the injector

of liquid fuel mass flow rate at non-evaporative conditions) at two different positions along the axis. One can see the gain in velocity of the large particles from near-field to far-field conditions. Even in the far field, most of them have not yet achieved the terminal velocity of 60 m/s.

Assessment module

Fig.2 is obtained using the assessment module. This tool firstly sets the initial atomisation conditions and manages the quantities being varied (e.g. flux of kerosene mass flow rate at a given depth, and its phase-shift in comparison with other modulations, see Fig.3). Its function is to coordinate the number of particles in each diameter class with their transport velocity. It also performs at each time step a particle count at a virtual probe position, situated at a given distance from the injector. Since the model is 1D and the test case is non-evaporative, the measured flux of kerosine mass flow rate at a given probe position is similar to the liquid mass flow rate. It will therefore be named $\dot{Q}_{kero}$ in the following.

An example of assessment is shown in Fig.4. In the test case (top plot), a strong air pulsation of 10 % at the inlet combines with an atomisation fluctuation (hypothesis of Giuliani et al. and Eckstein et al. are combined - resulting in a "worst case" scenario regarding injection stability) and results in a discontinuous spray. At probe position 15 mm, the fluctuation of $\dot{Q}_{kero}$ reaches 11 % amplitude with a phase-shift of about three quarter of a cycle compared to the air pulsation status at the injection. In the middle plot, an attempt to provide a regular spray at probe position is done, by letting $\dot{Q}_{kero}$ oscillate at the injection by 10 %, with a three-quarter phase-shift in comparison with the air pulsation. This has a positive effect since the kerosene flow modulation at probe position reduces to 3 % vs. 11 % without flow control. However, if the spray is satisfactorily stabilised at 15 mm downstream of the injector, transport effects and pulse kerosene mass flow rate tend to build up other patterns at different positions. For instance, at 60 mm, the mass flow rate fluctuation reaches 19 % when using kerosene flow control vs. 27 % without kerosene flow control.

In the rest of the study, since multiparametric control is unlikely to exist while too complicated, the study concentrates on the effect of a given parameter modulated at a time as a response to an air pulsation.

Parametric study

Droplet size distribution

The droplet size distribution is a function of the operating conditions. For the purpose of this study, three consistent operation points are analysed: a part load point at low pressure and velocity conditions, a design point centred on the MoPAA analysis matrix [13] and a full-load point corresponding to elevated velocity and pressure conditions. These conditions are reported in table Tab.1 and Fig.5 shows the droplet size repartition, computed according to Eq.1.

Air pulsation

The air pulsation is characteristic of the presence of a combustion instability. It may also be used for control purpose provided the feed line is equipped with an actuator that modulates a part of the flow. For this study, the

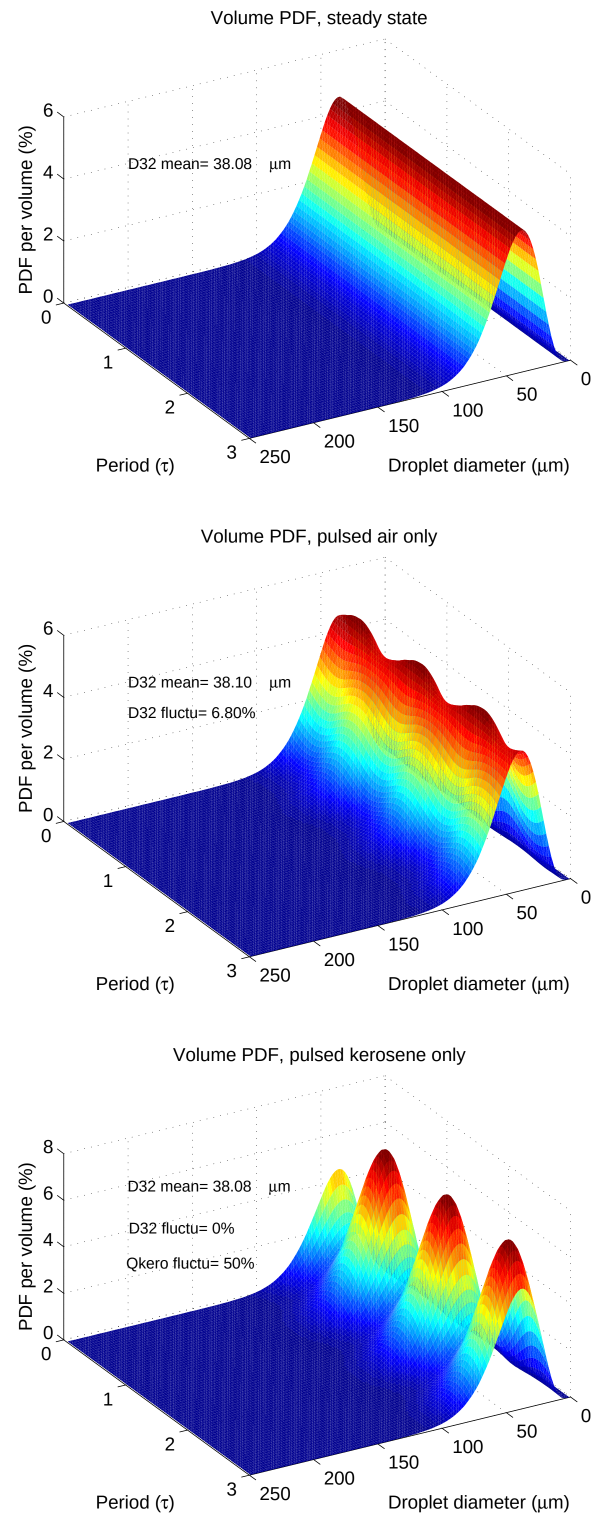

Figure 3. Possible inlet conditions for the introduction of the atomised phase. The atomisation PDF is represented per diameter class and over time: steady state (top), constant $\dot{Q}_{kero}$ at the inlet condition with modulated PDF (middle), and pulsed $\dot{Q}_{kero}$ at the inlet condition (bottom)

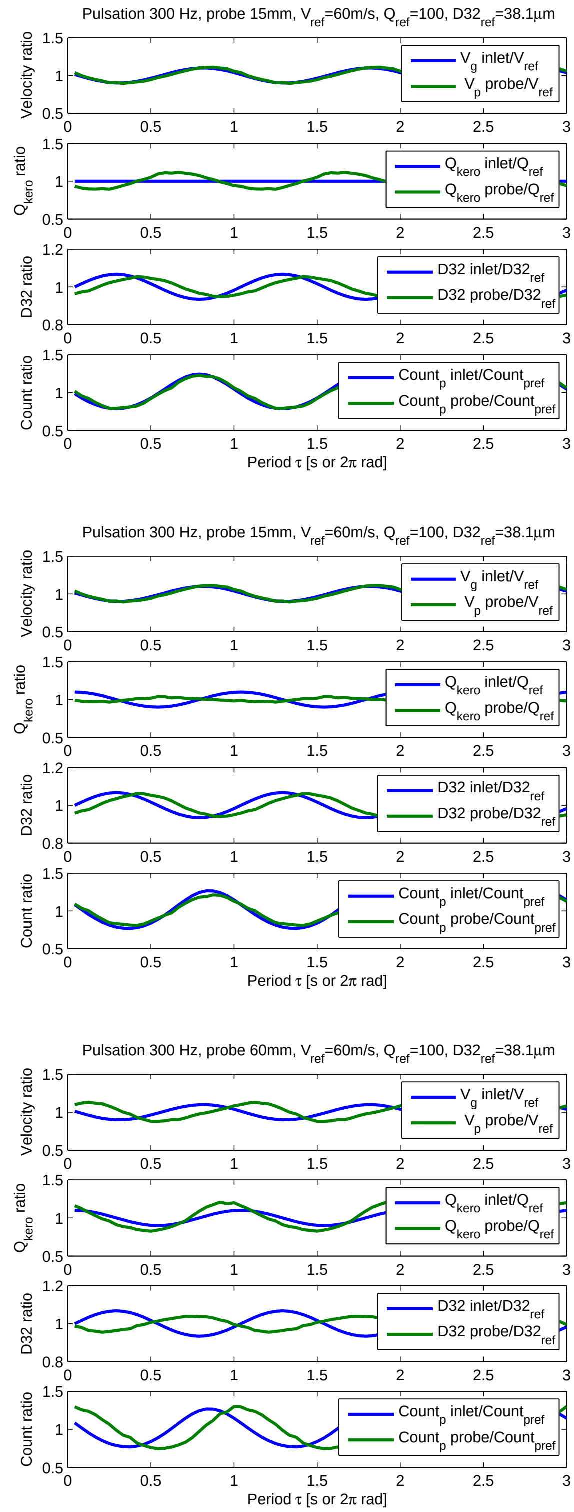

Figure 4. Three assessments on atomisation stability control: top is the reference case, unsteady because of an air pulsation. Middle is an attempt to stabilise the latter with help of pulsed kerosene flow rate at position 15 mm. Bottom displays the effect of control at position 60 mm.

Table 1. Operating conditions for atomisation

		Part load	Design point	Full load
Air velocity	[m/s]	51	60	69
Air pressure	[bar]	1	1,6	3,3
$D32$	[μm]	56,73	48,49	34,37

pulsed air velocity is composed of a mean value, plus a fluctuating value that travels at half the reference value and a stochastic value reproducing lower turbulence scales. The velocity airfield for any spray depth z at time t is then:

$$\begin{aligned} V_g(z,t) &= \bar{V_g} + \widetilde{V_g} + V_g^{'} \\ &= \bar{V_g}\left(1 + A\sin\left(2\pi f\left(t - \frac{2z}{\bar{V_g}}\right)\right)\right) + V_g^{'} \end{aligned} \quad (5)$$

Given the short ranges of dimensions that are studied, no damping factor is introduced on the periodic part, and the turbulence term $V_g^{'}$ is also neglected.

Experimentally, air pulsation is obtained with help of a resonator to achieve very low air flow modulations usually below one percent of the mean value. Each resonator has its own tessitura, simplified here under the form of a sine wave. Forced modulation (pulsation) is possible using special actuators such as the ONERA siren [8], in which case very strong modulations can be achieved (up to 20 %). For this study, an air pulsation level A=10 % is analysed.

This overdoes by far the effect of a thermo-acoustic coupling - but highlights the frequency domain where this coupling may take place in case a source term and resonance frequency exist. For control purpose, one can also foresee that one burner is fed by an air line plugged to such a device, controlled in frequency and phase.

$D32$ *fluctuation*

According to the hypothesis of Eckstein et al., the atomisation responds linearly to the velocity changes, so that the velocity term can be implemented in Eq.1 over a pulsation period. That would lead to a worst case where a particle size fluctuation adds up to droplet size segregation due to transport in an unsteady flow.

For control purpose, the possibility is given to modify both amplitude and phase in comparison to the air flow modulation. Technically, that would be possible - over limited frequency ranges though - by controlling the air boundary layer turbulence at will at the airblast's lip. Experiments using pulsed air sheet or mechanical motion with the help of MEMS or piezo-elements have already been attempted [15].

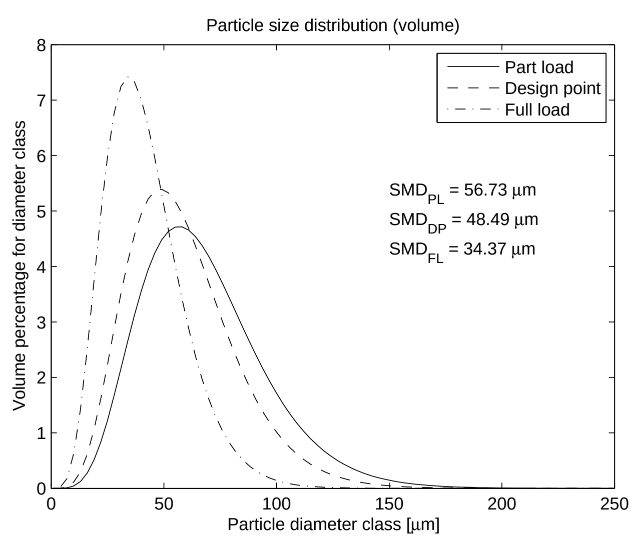

Figure 5. Droplet size distribution for part load, design point and full load operation

In this study, the $D32$ fluctuation is related to the air pulsation level (10 %).

Liquid fuel mass flow rate modulation

This philosophy is at the moment the most likely to be employed for combustion control. Pulse fuel valves are standard devices in the automotive world (usually up to 200 Hz).

In this study, levels of kerosene flow modulation up to 20 % are foreseen.

The shaker option

One control strategy is to move quickly back and forth the airblast's lip at a given frequency with phase control. Some applications for the study of spray formation in stagnant air are known [16].

While electropneumatic devices can operate in the low frequency range over large scales (of the magnitude of the millimetre), piezoelectric systems can cover the high frequencies but over a much lower amplitude. In this study, inertia forces within the liquid induced by the shake motion are neglected compared to the aerodynamic forces. The only change compared to other simulations is the cyclic position of release of a particle within the computational domain.

In this study, vibrations amplitudes up to max. 2 mm peak-to-peak are foreseen.

Results

The assessments have been performed on the frequency domain [0-6 kHz]. The resolution augments in the low frequency domain, which is particularly of interest for most of the gas turbine combustors.

Attention is paid not only to the fluctuation in particle size, here materialised by the $D32$, but also to the fluctuation of fuel mass flow rate $\dot{Q}_{kero}$. This quantity is also very important for modelling the equivalence ratio fluctuations in the evaporative case. However, since the liquid flux fluctuation is hard to measure precisely - with a PDA for instance because of the data rate and validation rate settings that miss or reject quite a lot of data - only few papers refer directly to it.

Effect of the air pulsation

Fig.6 shows the effect of a 10 % air velocity fluctuation (with advection) on the spray, for two positions and the two extreme loads. The common features are a broadband spectral signature, showing significant levels of resonance over the studied domain, with most of the "peaks" situated in the [0-2 kHz] interval (we call peak a maximum - the low frequency resolution because of the limited number of computations could not reveal the precise position nor the shape of the maximum). The peaks of fluctuation go from 22 % to 45 % for $\dot{Q}_{kero}$, while lower levels of fluctuation are achieved on the $D32$: 7 % to 16 %. There, the ratio between amplitude of modulation of $\dot{Q}_{kero}$ and $D32$ is about 3. Since the air velocity fluctuation is advected, droplet size segregation builds up with the distance to the front plate, which explains the largest levels of fluctuations observed in the far field.

Fig.6 also shows that the peak frequency of $\dot{Q}_{kero}$ is situated at a lower frequency than the peak of $D32$ fluctuation. This is related to the statistical definition of the $D32$ itself that covers a large amount of small droplets, hence going towards the high frequency domain. Another specific diameter (e.g. DV10, DV50 or DV90) would probably have a different signature.

Role of the droplet size distribution

Still related to Fig.6 - position 15 mm, one sees the extreme change in signature near the injection. Full load atomisation produces droplets with a much smaller Stokes number, having thus the tendency to respond strongly to the air turbulence. A finer modulated spray has a broader frequency range, and achieves higher amplitudes. The peak is pushed in the high frequency domain because of the larger amount of small particles in a refined spray. As a consequence, if a fine spray is adequate for rapid evaporation and mixing processes, it also can strongly sustain unsteady processes such as a combustion instability over a broad frequency range and especially in the high frequency domain. This problem has been observed for instance in rocketry with "screeching" noises related to radial instabilities [17]. On the opposite, a rough spray limits the risk of resonance to a low frequency interval (e.g. "humming" noise at part load operation).

Effect of a modulation in kerosene flow

Fig.7 shows the effect of a modulation of $\dot{Q}_{kero}$ at the inlet on the resulting spray, when the air flow is at steady state. A common feature is the maximum $\dot{Q}_{kero}$ fluctuation at low frequencies, achieving quasi the setpoint value 20 %, and its rapid decay towards the high frequencies. A refined spray offers a larger frequency bandwidth

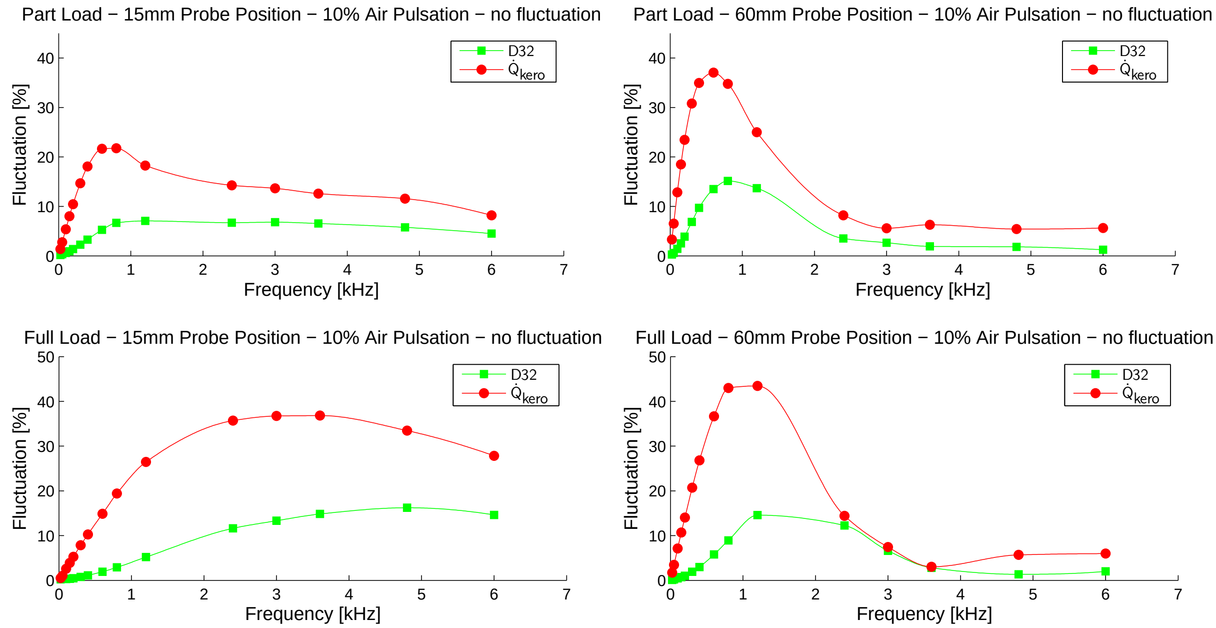

Figure 6. Fluctuation levels of $\dot{Q}_{kero}$ and $D32$ due to a 10 % air pulsation. Top: part load distributions for probe positions 15 mm and 60 mm. Bottom: full load conditions, same probes.

of efficiency (here up to 3 kHz at full load). Kerosene flow fluctuation rises also a fluctuation of $D32$, shifted in frequency towards the high frequency domain, at similar ratio of levels as observed in Fig.6.

When moving away from the injector, the frequency bandwidth shrinks towards the low-frequency domain (results not shown).

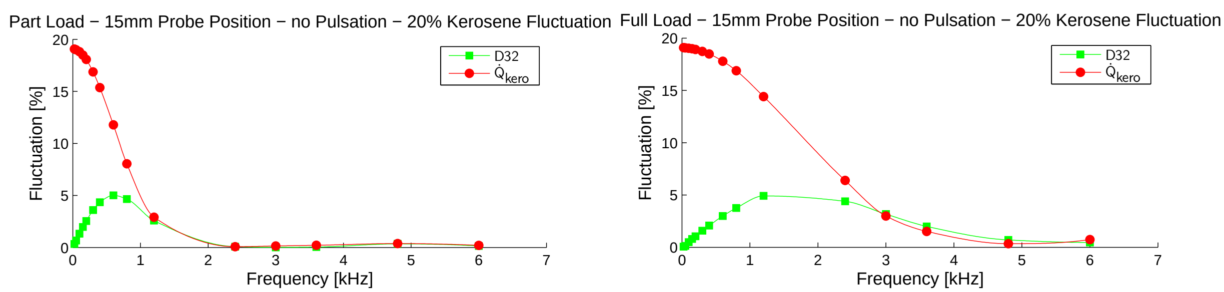

Figure 7. Effect of a 20 % fuel flow pulsation for probe position 15 mm. Left: part load. Right: full load condition.

Effect on a modulation of the atomisation

Fig.8 shows the effect of driving the atomisation when the air is at steady-state. Common features are a bimodal distribution in the $D32$ fluctuation, that is at its greatest in the low frequency domain, then decays, then shortly rises up again to rapidly disappear in the high frequency domain.

The amplitudes of $\dot{Q}_{kero}$ when modulating the atomisation are lower, in terms of ratio, to the ones observed before. However, in comparison to the kerosene mass flow rate pulsation, the frequency domain where the fluctuation is significant is doubled. The finer the spray (compare the part and full load signatures), the more efficient is this method.

Effect of shaking

The results obtained with shaking the injector are shown in Fig.9. The amplitudes of modulation, peak position and frequency bandwidth are very much similar to those provided by a $D32$ modulation. The main difference with both latter controls is the similarity of shape with the air pulsation: both $D32$ and $\dot{Q}_{kero}$ modulation rise up

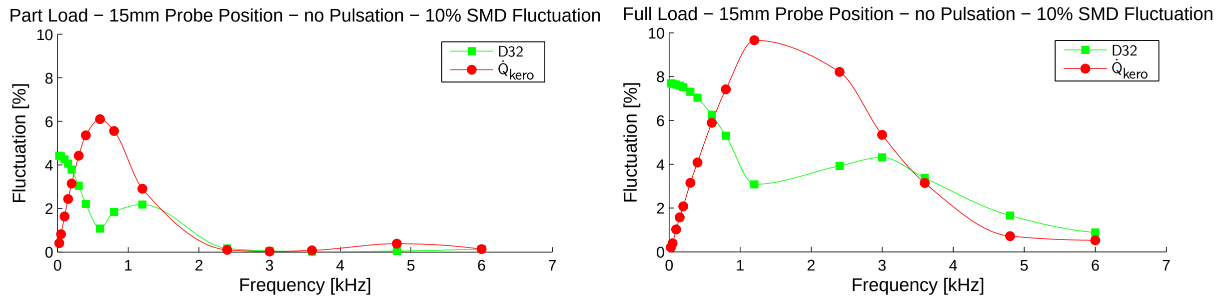

Figure 8. Effect of a 10 % $D32$ fluctuation at probe position 15 mm. Left: part load. Right: full load condition.

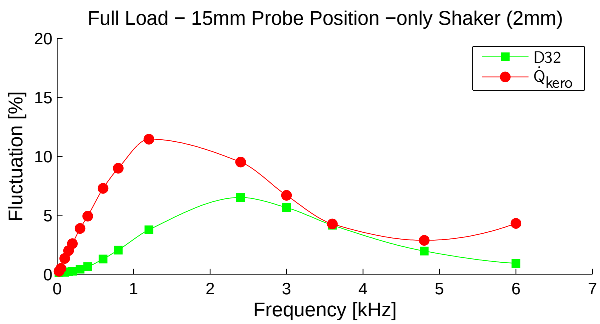

Figure 9. Effect of a shaking injector with amplitude 2 mm peak-to-peak at probe position 15 mm and at full load condition.

from zero in the low frequency domain, achieve a peak mostly function of the droplet size distribution, and decay towards high frequencies.

Discussion on control issues

Fig.10 shows a tentative to damp a spray modulated by a 10 % air pulsation by means of a kerosene pulsation, which is the most suitable technique to face the fluctuation levels involved. As can be seen on this figure (top), this strategy is efficient to some extent in the interval [0.4 4 kHz] where the fuel fluctuation curve with phase-shift $\phi = \dfrac{3\pi}{2}$ is situated below the reference curve. Damping could even be better than shown when adjusting the fuel pulsation amplitude and the phase-shift for a specific frequency. The bottom plot shows the fluctuation in terms of $D32$, that does not systematically reproduces the trends of $\dot{Q}_{kero}$ fluctuation for a given phase-shift.

This example reminds that actuation is to be used only when necessary. For instance, the actuation via the fuel disturbs the spray in the interval [0-0.4 kHz] more than the air pulsation. Furthermore, when activated the phase-shift shall be set precisely, since $\dot{Q}_{kero}$ fluctuation adding-up to the existing problem can make the things much worse at the wrong phase-shifts (see the curves at $\phi = \dfrac{\pi}{2}$ and π). If a phase-shift can currently be well-managed at low frequencies, precise control above the kHz region may be a problem.

Again, the situation displayed in Fig.10 is typical of the probe position, and of the spray particle size distribution.

Conclusions

A set of simple simulations was performed using the software IN-PULSE to assess the perturbation of a spray in terms of particle size and transported liquid mass flow rate. The exercise was limited to a non-evaporative case. Although this is not representative of the real injection in a gas turbine, it may allow to understand in a first step how fluctuation of equivalence ratio via the injection is produced. The effects of an air pulsation, fuel flow rate modulation, droplet size modulation and fluctuation of fuel placement were assessed. When properly chosen and used, each of these strategies can partially damp a combustion instability. Among the complexities of the problem, the roles of the particle size distribution and distance to the injection were highlighted.

Future research at TU Graz will focus on similar exercises at elevated temperature, including evaporation and mixing processes. Parallel to that, a program on an injector with variable geometry for precise combustion control is getting started. The next step will be to feed back experimental results in IN-PULSE, by fine-tuning the damping

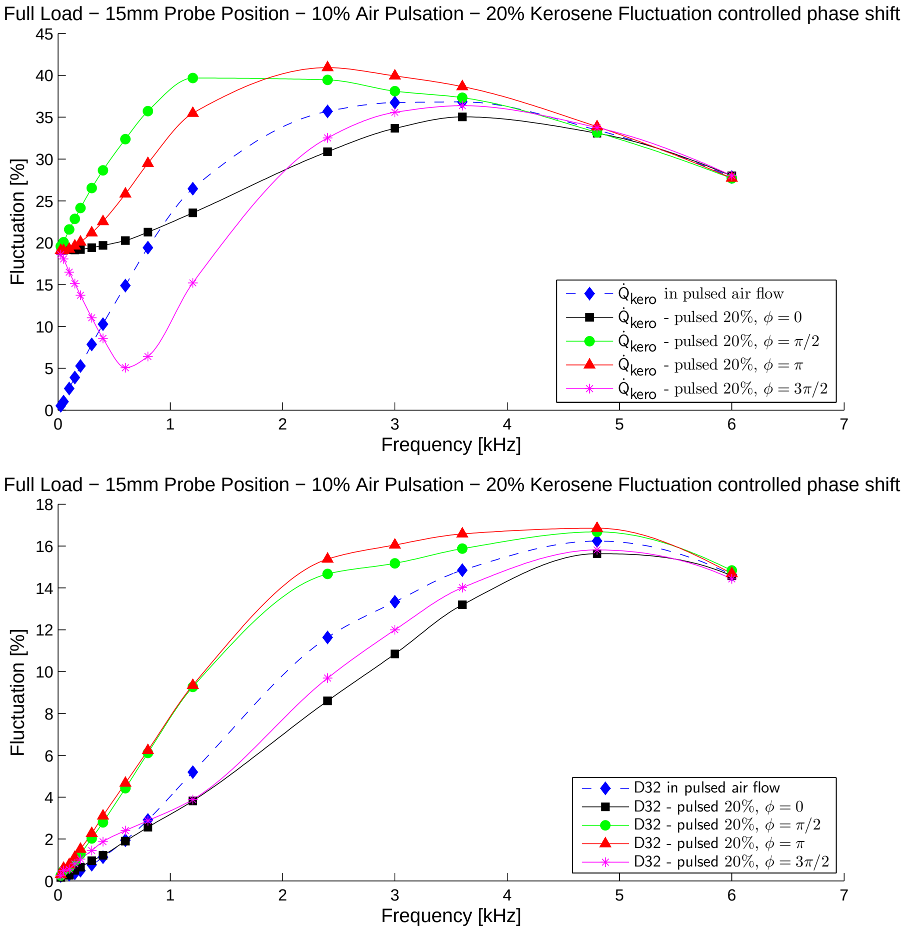

Figure 10. Combining a spray modulated by a 10 % air pulsation with a kerosene pulsation for four different phase-shifts. Top: fluctuation of $\dot{Q}_{kero}$. Bottom: fluctuation of $D32$. Full load operation. Probe at 15 mm.

factors that were neglected in this study (e.g. decay on the air modulation amplitude as a function of the distance to the front plate). The last step of the research programme will be to run 3D simulations of two-phase flow where the architecture of the Lagrangian module for particle transport will be inspired from our experience with IN-PULSE. This shall facilitate similar assessments on injection control for specific combustor designs.

Nomenclature

Main scripts

a,b	Gamma distribution parameters
D	Droplet diameter or diameter class [μm]
D32	Mean Sauter Diameter (or SMD) [μm]
P	Pressure [bar]
$\dot{Q}_{kero}$	Kerosene mass flow rate [kg/s]
t	Time [s]
V_g	Air velocity [m/s]
$\overline{V_g}$	Mean air velocity [m/s]
$\widetilde{V_g}$	Periodic component of the air velocity [m/s]
$V_g^{'}$	Stochastic component of the air velocity [m/s]
We	Weber number [-]
z	Distance to the injection [m]
ϕ	Phase angle [rad]
Γ	Gamma distribution

Acronyms

BBO	Basset-Boussinesq-Oseen equation
DLR	German Aerospace Centre
FWF	Austrian science fund
IN-PULSE	Modèle analytique d'INjection PULSéE en turbine à gaz
MEMS	Microelectromechanical Systems
MoPAA	Measurement of Prefilming Airblast Atomisation
ONERA	The French Aerospace Lab
PDA	Phase Doppler Anemometer
PDF	Probability Density Function
TU Graz	Graz University of Technology

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