Cold Flow PIV and Spray Visualization Experiments Applied to the Development of ALSTOM Dual Fuel Gas Turbine Burners

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Abstract The development of liquid fuel injectors for dual fuel gas turbine burners involves complex processes like spray formation and evaporation of single and multi phase fluids under high temperature and pressure conditions. Since for such complex phenomena satisfactory numerical modeling methods are still under development, experiments play a key role in the development process. Gas turbine testing or full-scale experiments on single burner and gas turbine conditions are generally expensive and come only at a later development stage, therefore a simplified experiment allowing early feedback to the development process would be very beneficial. An experimental tool is presented here that allows the investigation of fuel injection sprays under simplified conditions by simulating the high pressure with the use of a high-density fluid (air/SF_6 mixture). This allows the experiment to be carried out at ambient pressure, where standard optical measuring techniques can be applied, such as PIV and laser-based spray visualization (Mie scattering).

By comparing spray images and velocity fields of different injector variants and correlating this information with the results from combustion tests, it was possible to identify some spray features which have an impact on combustion behavior, and in particular on pulsation. Based on this empirical method selection criteria were therefore defined and are now applied to the screening of possible injector variants. This allows the down-selection of the most promising variants for further testing and a cost and risk reduction for the further development steps. A few examples of successful application of this method to the development of oil injectors for ALSTOM dual fuel gas turbine burners are shown, where the injection momentum and the amount of assist air could be optimized by SF_6 testing.

1. Introduction

Dual fuel gas turbine burners must have the capability to burn either natural gas or oil with the same hardware, therefore several geometrical and aerodynamic constraints apply when developing oil injectors for such burners. This results into complex interactions between spray and combustion air, which influence the combustion behavior of the burner in oil operation [1]. It is therefore important to characterize the spray behavior for different injector geometry and operating conditions and try to correlate it with the corresponding combustion behavior, in order to support and optimize the burner development process.

ALSTOM has been since long developing dual fuel gas turbine burners, through a standard burner development process. This includes, before the engine validation stage, a series of numerical investigations such as CFD and thermoacoustic modeling, accompanied by experiments both in cold conditions (water / wind tunnels) and with combustion (single / multi-burner under atmospheric / high pressure conditions).

For oil combustion, involving processes like spray formation and evaporation of single and multi phase fluids, experiments are an important step to understand the underlying physics and to support the development of new injectors. In the first development stages, a flexible and costeffective experimental investigation tool would be the preferred choice to provide a first insight into the problem and key parameters for the development of numerical models. An alternative is therefore needed to combustion tests, which under atmospheric pressure are not fully representative - since the atomization process is strongly dependent on pressure – and under high pressure conditions are associated with high costs and strong limitations of the optical access.

In ALSTOM's labs a wind tunnel was therefore designed and built for spray investigation purposes. By running this tunnel with a mixture of air and sulfur hexafluoride (SF_6), which has a density about 6 times higher than air, it is possible to simulate pressures of up to 8 bar under typical gas turbine pre-heating temperatures while operating the rig under cold and atmospheric pressure conditions. These operating conditions allow the required optical accessibility, flexibility and cost-effectiveness to be obtained.

The importance of using such a test rig, which is able to simulate an increased pressure as well as the interaction with the burner flow field, was confirmed by tests carried out with injection into still air/SF_6 mixture (pressure effect alone) or into flowing air withoutr SF_6 (burner flow effect alone). These tests showed the strong influence of each of these two effects on the spray features, so that only by combining the two a representative characterization of the spray produced under gas turbine conditions can be achieved.

The principle of the experimental method applied, including a discussion of the key parameters and a description of the test rig and measurement techniques is described in the next section. In the following section, the test results and their application to the gas turbine burner development process are presented, then the main conclusions are summarized in the last section.

2. Experimental Methods

Principle

The conditions of the combustion air within a gas turbine combustor typically range around 10-30 bar and 300-500°C. For liquid fuel operation of a gas turbine, a fuel or an emulsion (e.g. diesel oil or an emulsion with demineralized water) massflow of above 100 g/s have to be injected under those conditions into the burners, which are typically operated with more than 1 kg/s of air. As a result, it is clear that spray investigations under such gas turbine relevant conditions are extremely complex and expensive, due to the energy needed to run the rig and to the required robustness of the test rig and hardware, which allows in turn only limited optical access.

As described in the introduction, the main idea to simplify the testing procedure is the simulation of high-pressure conditions by the use of high density fluids. A closed-loop wind tunnel was built for this purpose and run with a mixture of air and SF_6, a gas with a density of about 6 kg/m^3 at standard ambient conditions. The air/SF_6 mixture is normally set to obtain a density of around 3.5 kg/m^3, as a compromise between achieved density and flow velocity (limitation of the wind tunnel fan). This corresponds to simulated pressures of up to 8 bar under typical gas turbine pre-heating temperatures.

The liquid fuel is simulated by a water/ethanol mixture, whose proportions can be adjusted to match the scaling parameters to those of the oil/water emulsion used in the gas turbine. For testing the mixture density is typically in the range of 900 kg/m3, the resulting viscosity was measured as approximately $2.9\cdot10^{-6}$ m2/s while the surface tension was estimated to be around $2.2\cdot10^{-2}$ N/m. The Reynolds number of the main air flow is of the order of magnitude of 10^5, i.e. smaller than in the gas turbine, but still fully turbulent.

Several strategies exist for scaling down the flow conditions from engine to test rig (see e.g.

[2]), depending on which spray process is important to be correctly modeled and therefore which parameter has to be conserved. In the tests described here, only a qualitative empirical analysis of the spray pattern and velocity field is performed at the present stage, so it was decided to use as the main scaling criterium the momentum flux ratio between liquid and gaseous phase, which is kept in the test rig equal to the one under gas turbine conditions, i.e.:

$$\frac{\dot{m}_L U_L}{\dot{m}_G U_G} = const \qquad (1)$$

where m is the massflow, U the velocity, while the subscripts L and G stand for liquid and gaseous phase, respectively.

Further detailed studies are ongoing based on more generic testing, which should improve the scaling strategy for future tests.

Test Rig

The SF_6 wind tunnel is sketched in Figure 1: a fan is keeping the air/SF_6 mixture circulating in a closed loop through a pipe with massflow and density measurement systems, a plenum for flow settlement and straightening, and the test section. The upstream part of the test section, in which the burner is mounted, simulates the combustor hood, while the part downstream of the burner represent the combustion chamber. Downstream of the test section a water cooler is installed to keep the air/SF_6 temperature constant during the test, together with a droplet separator used to prevent the droplets from running through the fan and back to the test section.

The liquid phase is also running in closed loop, since the droplet separator is recovering the liquid dispersed in the gaseous mixture and conveying it back to a reserve tank. From here, a high pressure pump is injecting the liquid through the fuel lance into the burner.

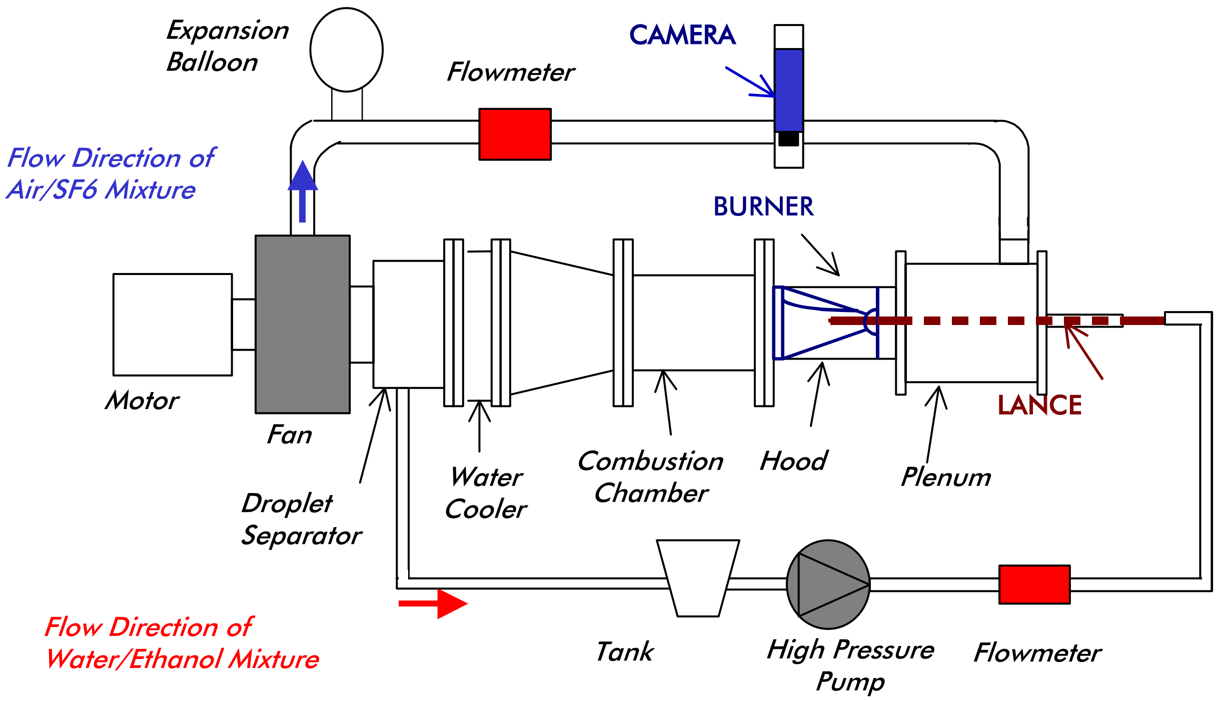

Figure 1 **Sketch of SF_6 test rig**

The most critical requirement on all wind tunnel components is tightness, since operation at constant density has to be ensured for the whole duration of a test and the consumption of SF_6 gas has to be minimized for health, environmental, and cost reasons. A special tightening device to enable the exchange of the lance with the oil injector without loss of SF_6 gas was therefore designed and implemented.

The test rig has full optical access through glass walls, while the burners are provided with plexiglass windows, to allow laser light sheet illumination and camera view for PIV tests.

Measurement technique

A commercial PIV system with double-pulse Nd-YAG laser is used for the measurements. As shown in Figure 2, the laser light sheet is created by a cylinder lens and enters the burner through a side window, illuminating an axial cross-section of the flowfield in correspondence of the injection point at the tip of the fuel lance. The camera is placed perpendicularly to the light sheet and views the measurement plane through a wide plexiglass window.

Due to the flow features, droplets are often impinging on the windows of the model and on the test rig walls, thereby posing a serious threat to the image quality. However, with the setup used images of acceptable quality for PIV tests can still be obtained (see Figure 2 and Figure 3.d). Without seeding, no information can be obtained on the velocity field of the gaseous phase, but by using the liquid droplets as tracers, PIV can yield the velocity field of the liquid phase (see Figure 3.e-f).

At the same time, the raw images produced for PIV processing represent Mie scattering of the droplets and can therefore be used for spray visualization and characterization through appropriate image processing. Generally, an average spray image over time is the most representative to characterize the spray (see Figure 3.a), but also the RMS fluctuations of the instantaneous images around this average image (either absolute, see Figure 3.b, or relative to the average image, see Figure 3.c) may provide some insight in the spray behavior. Additionally, sample instantaneous spray images can be used to observe details of spray formation and droplet distribution (see Figure 3.d).

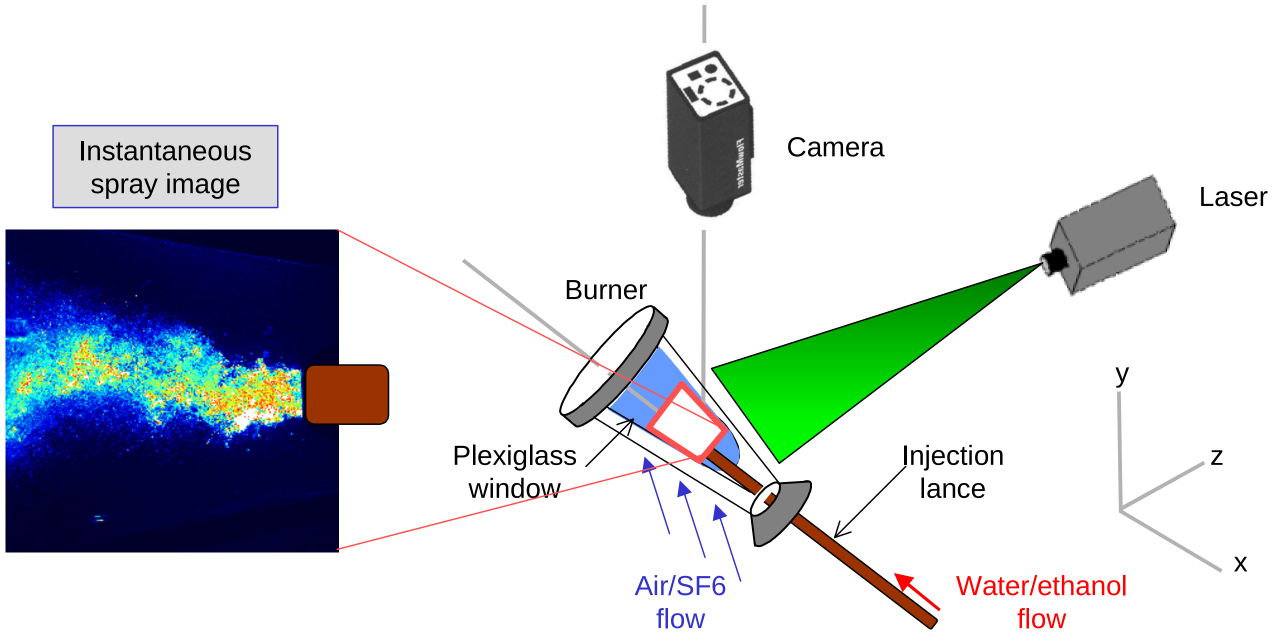

Figure 2 **Schematics of PIV measurement within gas turbine burner**

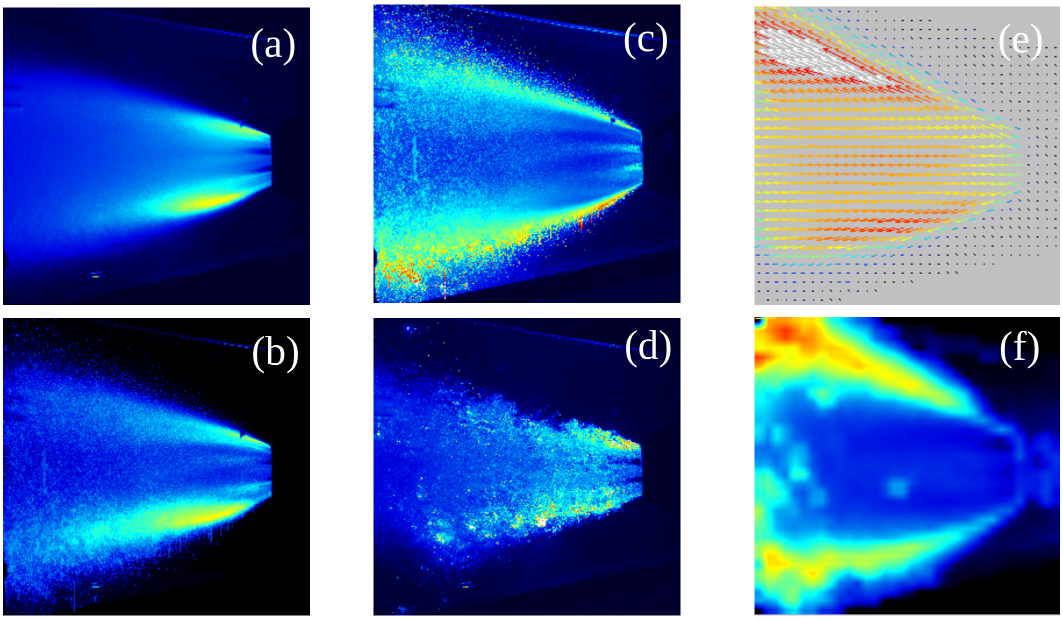

Figure 3 **Sample results from PIV / spray visualization test: average spray image (a), RMS spray image (b), RMS/average spray image (c), sample instantaneous spray image (d), average velocity vector field (e), and RMS velocity field (f).**

3. Results And Discussion

Injectors for wet oil operation generally show little influence of injector geometry on NOx emissions, the NOx level being mostly related to the effect of the water in the emulsion on flame kinetics. Instead, strong differences can be observed in the pulsation levels measured under the same operating conditions with different injectors. The present study therefore concentrates on the correlation between spray features and pulsation behavior.

In wet oil operation of dual fuel burners, flame stabilization and thus combustor pulsation behavior change according to the operating conditions and in particular as a function of the water-to-oil massflow ratio in the emulsion. Since a certain amount of water is needed to reduce NOx emissions, the main target for a dual fuel burner during wet oil operation is to be able to operate with low pulsations in order to extend components lifetime, while limiting water consumption. Tests were therefore carried out with different injection massflows in order to model the different water contents of the emulsion used under gas turbine conditions. Generally, however, it was observed that trends among different nozzle designs are conserved when varying the injection massflow. For simplicity, then, only one reference injection massflow, corresponding to the typical water content used at engine base load, is considered in the results and discussion presented here.

Different liquid fuel injectors have been tested in the SF_6 test rig, and both the spray pattern (average image and RMS fluctuations, see Figure 3.a-c) and its velocity field (see Figure 3.e-f) were used to characterize the spray of each injector. At first, a variety of injectors that had already been tested in the gas turbine or in combustion rigs at engine operating conditions were investigated, in order to build a representative database. By empirically correlating the spray information with the results from combustion tests, it was possible to identify some spray features that have an impact on combustion behavior and provide criteria for the selection of new injector variants.

A sample of results from the database of injectors tested both in engine conditions and in the SF_6 rig is shown in Figure 4. Over the whole range of water contents, the three injectors can be ranked, best to worst in terms of pulsation behavior, in the order C, B, A. Among the macroscopic spray features, the spray opening angle and the spray density along the axis appear to play a key role in the correlation with pulsation behavior (see also [3]). For the tested geometry, given a fixed injection position, a decrease in pulsation intensities appears being associated with larger spray angles. Also, the better variants show a different distribution of image intensity (which can somehow be correlated with spray density), with the higher intensity regions moving away from the center towards the edges of the spray, especially in the region further downstream of the injection point. The velocity fields do not show such a clear change of spray angle, because even a few droplets outside of the main spray cone are sufficient to produce velocity vectors in that region. The better variants are here associated with higher velocity values, especially in the core region of the spray. This is possibly due to the better atomization, causing smaller droplets to be more easily accelerated by the high velocity air stream.

A possible explanation of the improved pulsation behavior with injectors producing a wider angle and leaner core could be related to a change in flame shape / position together with the larger time-lag spread that results when feeding not only the root of the flame along the burner axis but a wider region in radial direction.

It is important to notice that the interaction of the spray with the surrounding burner flow has a strong impact on the spray characteristics under engine-relevant conditions, due to which it is not possible to derive a simple correlation between the geometry of the injector and the final spray features (e.g. the assumption that a large injection angle will generate a large spray angle is not necessarily true when including the effect of the burner flow). This is one of the key reasons for the need of an investigation method such as the present one, i.e. able to include the effect of such interaction.

The criteria derived from this analysis have been applied in the optimization of existing injectors in order to support the latest upgrades of ALSTOM's EV burner technology (see [4] and [5]), as well as to help understanding the pulsation behavior observed in combustion tests at engine conditions.

An example of the latter application is given in the following. An injector designed with a certain momentum flux was found to have a better pulsation behavior than a reference injector (see top graph of Figure 5). In order to reduce the fuel pressure requirements, a second variant of the injector was designed, with reduced pressure drop and therefore lower injection velocity and lower momentum flux. In a second test it was then observed that the pulsation behavior had become worse than with the reference injector, so that the injector could not even be operated at low water contents (see bottom graph of Figure 5). As the present method was applied to investigate the phenomenon, it revealed that the high momentum injector did indeed show an increased spray angle

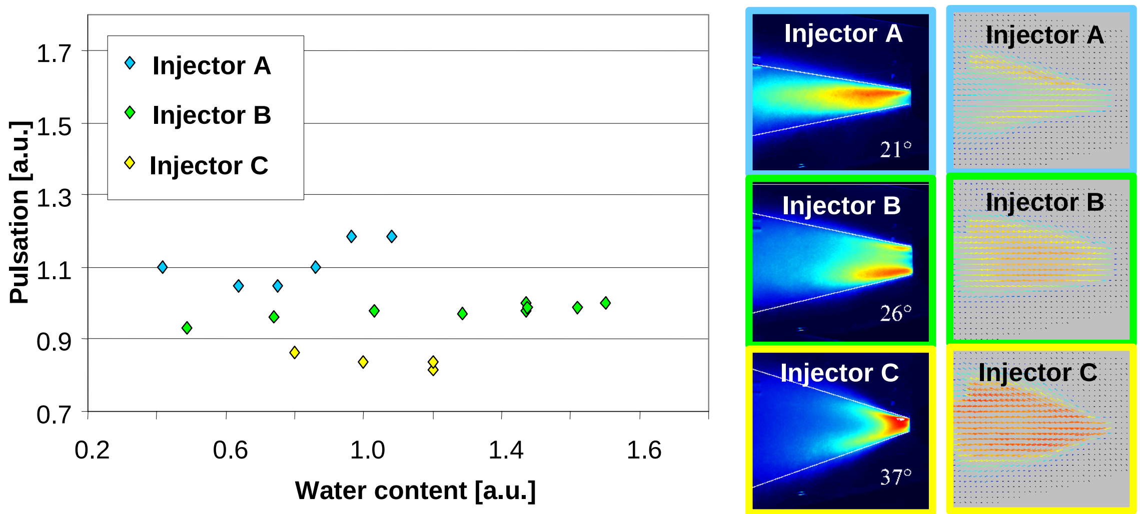

Figure 4 **Correlation between pulsation behavior and spray features: pulsation behavior (left), average spray images (center), and average velocity fields (right).**

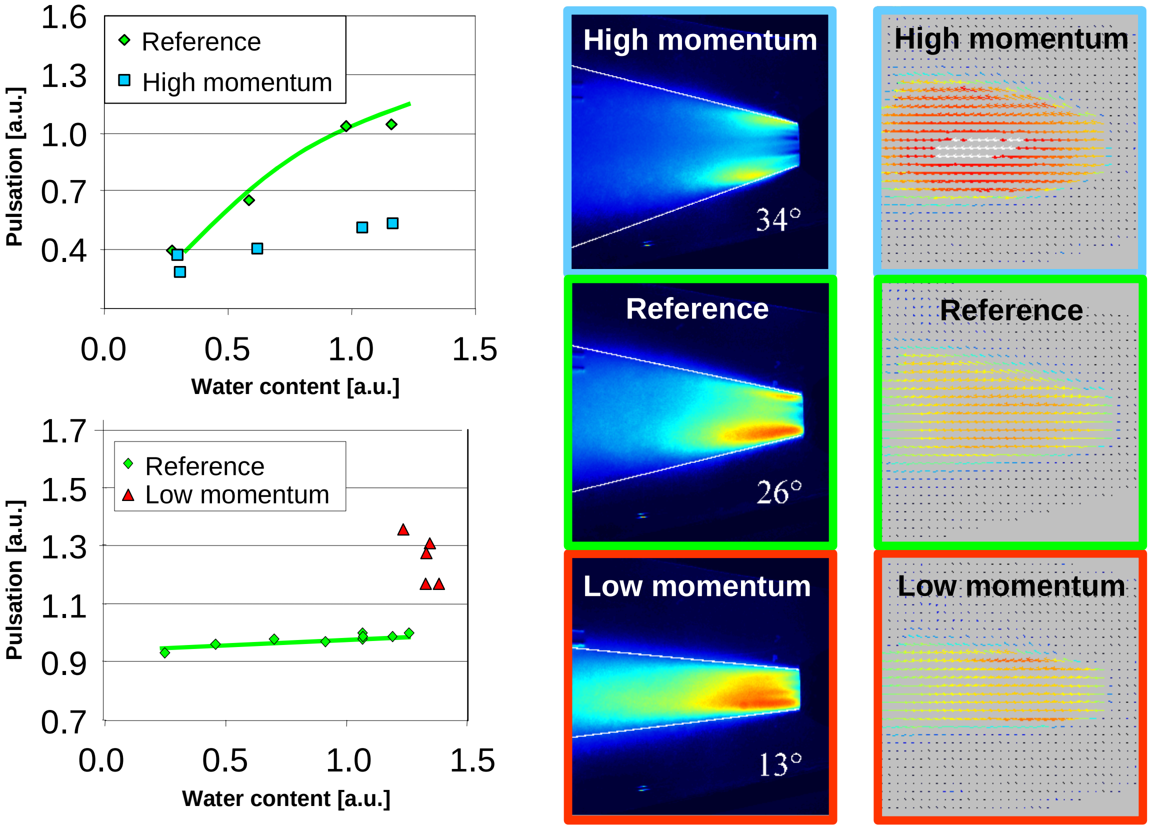

Figure 5 **Effect of injection jet momentum: pulsation behavior (left), average spray images (center), and average velocity fields (right). Please note that the two tests displayed in the top and bottom graph were carried out at different conditions, therefore the reference line does not show the same values in both cases.**

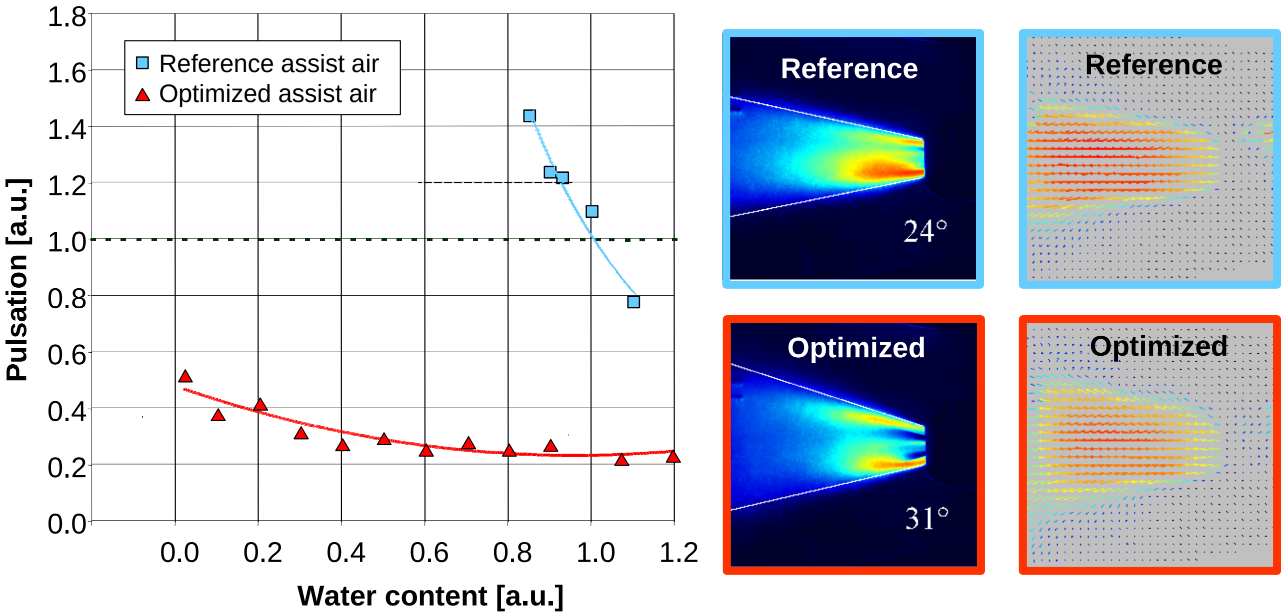

Figure 6 **Effect of assist air: pulsation behavior (left), average spray images (center), and average velocity fields (right).**

and a spray intensity concentrated more at the edges than at the core of the cone, which have been identified above as hints for a better pulsation behavior. The low momentum variant, instead, shows a clear collapse of the spray along the axis, which corresponds to the high measured pulsation. The spray tests thus proved that the momentum reduction had been excessive and the empirical correlation could be used to predict the critical momentum (and therefore fuel pressure drop) required to obtain an acceptable pulsation behavior.

A further example of the application of the method is the optimization of the amount of assist air for an air-assisted atomizer. Since the assist air may have an influence on the whole burner flow field, and therefore on its performance both in oil and gas operation, a solution was needed with the minimum changes in the amount of assist air with respect to the reference injector. Starting from a reference injector, the amount of assist air could be easily varied in small steps during tests in the SF_6 rig, thereby observing the spray features. The tests could therefore be used to identify the optimum variant as the one with the smallest change in assist air required to achieve the targeted spray features. As discussed above, these are a sufficiently large spray angle and reduced spray intensity along the axis (see Figure 6).

Thanks to this screening, only few tests were subsequently needed in the high pressure combustion rig in order to validate the improved variant, and a considerable cost saving could be achieved before the engine validation, which confirmed the strong pulsation reduction (see graph on Figure 6).

4. CONCLUSIONS

Since the interaction of liquid fuel sprays with gas turbine burners under engine conditions is extremely complex and expensive to investigate, a simplified testing method has been developed based on spray visualization and measurement experiments under cold, scaled conditions. The scaling criteria are far from being comprehensive and are presently taking into account only a limited number of parameters. Still, by combining information from the existing engine experience and from the main macroscopic spray features, it was possible to develop a methodology to assess the potential of liquid fuel injectors in terms of pulsation behavior.

The validity of this empirical method was confirmed by tests performed on the engine and the method was successfully applied for the screening of possible injector variants and the down-selection of the most promising ones for further testing, thereby achieving a cost and risk reduction for the further development steps.

5. REFERENCES

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