Characterization of fuel oil atomizers at industrial scale

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Abstract

Nowadays heavy fuel oils represent a significant source of energy available for different applications, either for processes or for power generation. The combustion performance for this type of material considering efficiency, pollutant emissions, etc. is very much influenced by the atomization process and by the oxidant used in combustion. Oxy-combustion can provide advantages with heavy fuels oils such as reducing the vaporization time, as well as reducing the environmental impact, improving the operational economy in terms of reduced fuel consumption or increasing the productivity due to more efficient heat transfer particularly for processes such as glass and steel making.

This paper reports the methodology and main aspects considered to evaluate and optimize the design of an air assisted atomizer for industrial scale, from the operational conditions set up and spray characterization measurements reliability, to the impact for the particular application on oxy-combustion. To carry out the study, the available facilities have fundamental impact on the results; therefore particular emphasis is dedicated to work at optimized conditions. A description of the atomization bench, associated diagnostics and furnace is made as well as an analysis of their reliability in such environment.

The results show the spray characteristics and dimensionless SMD for various operating conditions and for two atomizer designs. Corresponding flame characteristics are also reported as well as thermal efficiency and NOx emissions. In general, the methodology used allowed to optimize the atomizer design, with a reduction by 3 times of the atomizing air flow rate for the same droplet size. This optimization has resulted in a significant improvement of the furnace thermal efficiency and in an important reduction of NOx emission by 20%, proving the reliability of heavy fuel oil spray characterization at industrial scale.

Introduction

Over the last years, with significantly increasing energy costs and more stringent legislation concerning NOx emissions and other pollutants harmful to the environment, oxy-combustion has become a more viable alternative for furnace operators. The benefits of oxy-combustion are well known, and include reduced environmental impact, improved operational economy in terms of reduced fuel consumption and increased productivity due to more efficient heat transfer for processes such as glass and steel making. This particular technology provides the high temperature requested for the process, with minimum energy consumption and less impact on the environment. Furthermore, flue gases from oxy-liquid combustion can be treated in a more economic and efficient way due to high concentration of the chemical species. This also represents an advantage for CO_2 sequestration projects.

It is very well known that heavy fuel oil combustion performance considering efficiency, pollutant emissions, etc. is very much influenced by the atomization process [1]. Vaporization of droplets is also a very important phase in the liquid fuel combustion mechanism which basically influences flame stability. In oxy-combustion of liquid fuel, this step is very short compared to combustion with air [2], which provides another advantage for using heavy fuels or even waste materials with low volatile content as an energy source with this technology.

Within this frame, Air Liquide R&D is involved in the development of various types of atomizers dedicated to oxy-combustion. Since atomization quality depends on the operating conditions, design of the atomizers, fuel oil properties such as viscosity, density, etc. [3, 4] understanding of the atomization phenomenon and the techniques used to analyse and characterize the sprays are essential to develop efficient atomizers. Furthermore open literature reveals a lack of information on heavy fuel oil atomization characteristics. In general, published information present data using different fluids with similar viscosities, basically due to the problems to use this type of fluid at laboratory or industrial scale. The link between the spray properties, flame characteristics and combustion efficiency at semi-industrial scale [5, 6] is also important and should be considered for a full evaluation. In this frame, Air Liquide decided to build an atomization bench with associated diagnostics such as drop-size measurement instrument and strobe light imaging to operate in non-reactive condition. The main idea is to pro-

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vide the first step in the evaluation of fuel oil sprays for various types of atomizers. Further evaluation in a reactive environment using combustion facilities will provide the following step to optimize the design, as well as to provide data for modelling needs.

This paper reports the methodology and main aspects used to optimize an assisted atomizer design, from the operational conditions set up and spray characterization measurements reliability, to the impact for the particular application on oxy-combustion.

Facilities and Methodology

ALISA atomization bench

The atomisation bench shown in Figure 1 consists of a fuel oil storage tank, a closed atomization chamber, an oil separator/collector system, as well as an oil/air supply system with controls for flow rate, pressure and temperature. Heavy fuel oil temperature is maintained to a minimum around 55°C in the storage tank and then preheated to the atomisation temperature up to 110°C using an electric heater. The nozzle sprays the oil in the atomization chamber which has a cross-section of 2m x 2m. The waste fuel is collected in the tank to be further disposed. An exhaust fan controls the gases and small droplets in the chamber inducing an air stream at 10 m/s. This velocity insures that the spray is not disturbed. The exhaust gases then pass through a cyclone to separate the oil droplets from the air stream before being sent to the chimney. For the oil line, there is a loop recirculation to maintain oil temperature constant when the atomiser is not used.

In order to test a wide range of atomizer specifications with good accuracy, two oil supply lines are available: a first one operates at fuel oil flow rate up to 200 kg/h and service pressure up to 30 bar .The other one operates at fuel oil flow rate up to 1100 kg/h and service pressure up to 100 bar. Air assisted atomization can be used at pressure up to 10 bar and flow rate up to 150 kg/h.

The oil gun is set up on two axes robot allowing motion in to the two directions with a precision of 1mm.

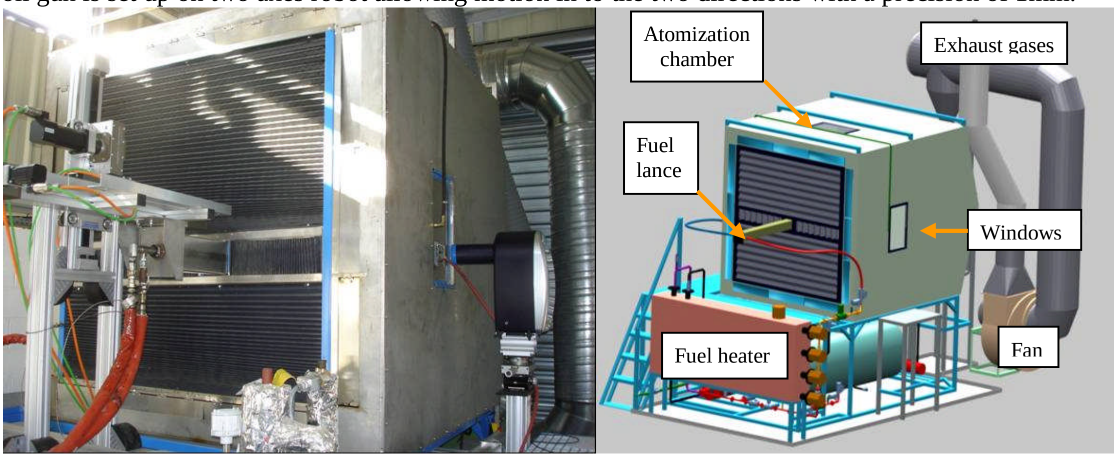

Figure 1: Atomization bench

Optical accesses have been installed on each side of the atomization chamber to allow the access of laser beams and collection of signal for laser diagnostics.

Measurements of heavy fuels droplet size distribution

Drop-size measurement is performed with Malvern Spraytec 2007 Particle Sizer. The principle and the limitations of the instrument are well documented in the literature [7-19].

The main phenomena which impact the measurements are vignetting, multiple scattering and beam steering. These aspects were considered carefully for the Malvern operation during these tests.

According to Hamidi & Swithenbank [11], vignetting occurs if the particles to be measured are too far away from the receiving lens, because the diffracted light of the smallest particles, causing the largest diffraction angle, may be cut off from the lens' finite aperture. Basically, this working distance can be assessed by geometrical calculation [18] and has a maximum of 1.5 times the focal length of lens. In the present work, a 750 mm focal lens was mounted on the Malvern allowing a working distance of 1 meter. As the spray studied has a radius much lower than 250 mm in the measurement area, the receiver is placed at 750 mm away of the spray axis to avoid vignetting. The light energy distribution measured did not reveal any cut of the signal on the outer diode.

According to Hirleman [14], multiple scattering basically occurs in dense spray where interparticle spacing is so small that the scattering characteristics of a particle depend on the position and size of adjacent particles, or in large spray where the optical path is so large that a significant number of photons are scattered more than once before reaching the detector. Many studies investigated this phenomenon [9, 12, 13, 14] and they concluded that the impact on measured droplet size depends on transmission rate and spray characteristics. For transmission rate lower than 40-50%, the droplet size reported by Malvern instrument is affected by multiple scattering with more impact for the smallest particles. As a solution to this problem, a correction algorithm derived from Hirleman's model [14, 15] has been implemented in Malvern software, but recent work of Triballier *et al.* [16] has shown that this correction is not always efficient. In the present work the sprays are dense and broad (~100 mm) because of the high flow rates typical of industrial scale. To limit the impact of surrounding environment of the spray to the measurement and transmission, a light guide was used to conduct the beam near the edge of the spray without penetration inside the spray to avoid disturbance [10]. The measurements have been performed far away of the nozzle exit in the fully atomized zone where transmission rate varies between 30 and 50% at the centreline of the spray. The Malvern correction has been compared to the correction of Dodge [9] and Gülder [13]. The comparison shows a good agreement between the different approaches with an averaged difference for the corrected SMD around of 2 to 4%. The maximum discrepancy of 6% is observed for the largest droplets or transmission rate, reaching the limits of the models of Dodge and Gülder.

Beam steering effect is the manifestation of light scattered due to an index gradient in the gas phase. The mathematical inversion interprets this additional signal as big droplet since beam steering deviates light at small angles. With the previous version of Malvern software, many investigators propose a scheme to reject data from the inner diode affected by beam steering and replace it with data extrapolated from the outer elements [17]. This kind of extrapolation is now automatic in the latest version of Malvern instrument as the Spraytec 2007, when signal from inner diodes are ignored. In the present work, the presence of fuel oil vapour in air around droplets results in beam steering phenomenon clearly identified by the peaks of light energy on the inner diode of receiver. After mathematical inversion, this additional signal results in a second distribution peak in the big-drop population separated from the first one. As recommended by Malvern and described in recent work using Spraytec 2007 [18, 19], the intensity collected by the first diodes is ignored and automatically replaced by data extrapolated from outer diode according to the Malvern algorithm. The number of diode ignored is defined so that the second distribution peak disappears.

To ensure reproducibility and accuracy of the measurements, more than 30 scattered light energy samples were acquired for each operating condition and averaged to calculate the resulting drop-size distribution and the Sauter Mean Diameter (SMD), Dv50 and Dv90. Reproducibility of these calculated diameters have been evaluated for each nozzle tested and reported around 3%.

Spray structure imaging

Strobe light imaging is a powerful optical non-intrusive technique for observation of spray structure. For this particular study an impulsive Nd-YAG laser, a train of optics, and a CCD camera synchronized to the strobe light have been used. The Nd-YAG laser operated at 532 nm generate light pulse of 10ns at a low frequency of 15Hz. Light is conveyed by optic fibre towards lens used to control the beam expansion to the region of interest. The light scattered by the droplets is collected thanks to a numerical CCD camera AVT Pike. The camera has a resolution of 2048x2048 pixels and is equipped with a 50 mm f/1.4 objective. Laser pulse, camera opening and data acquisition in a computer are synchronized together to catch the spray image during ten nanoseconds. This is short in comparison with the characteristic time of atomisation, which is basically of the order of magnitude of millisecond. Using this technique the spray structure is visualized and the liquid core length, spray angle, penetration and homogeneity could be evaluated from the image giving information on the atomization mode and performance of the atomizers. The information on spray angle, obtained thanks to this technique, permits to determine the maximal radial position possible to perform drop-size measurement.

ALICE pilot furnace

The atomizers are tested in experimental reactive conditions using a pilot furnace shown in Figure 2.

The combustion chamber is 6 m long, 2 m wide and 1.5 m high. This unit is designed for very high temperature applications, using different types of fuels in oxy-combustion mode such as gas, propane and fuels oils. The operational parameters such as thermal input, temperature profile, excess oxygen, etc. can be managed by the control system and all data relating to the tests such as fuel flow rate, oxygen flow rate, temperatures, pressures, concentration of chemical species in the exhaust gases, etc. are saved in a data acquisition system. The heat transfer profile is controlled by 13 water coils distributed along the furnace's axis. The exhaust gases are evacuated through the chimney using an electrically controlled motored damper located inside the chimney. This allows running the furnace at different pressures in order to control the air in leakages in the combustion chamber.

This facility also has several ports to have access for flame visualization or sampling. Furthermore, 3 permanent cameras are located in the walls of the unit to observe the flame at different positions.

The unit is run until the thermal stabilization is reached. After this, all measurements are recorded each 10 seconds, to allow evaluation of the accuracy and reproducibility of the data and at the same time to provide a good average for better results reliability.

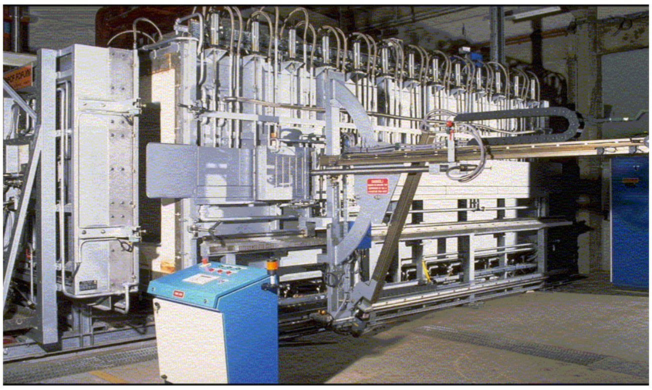

Figure 2: ALICE pilot furnace

The accuracy and reliability of the results is very much important for this study. Therefore, all the results are corrected having into account the incertitude for the main instruments involved in the measurements. The Table 1 shows the incertitude of the main instruments for each system used.

ALICE	Incertitude	ALISA	Incertitude
Oxygen flow rate	1%	Atomisation temperature	± 2°C
Fuel oil flow rate	1%	Fuel oil flow rate up to 200 kg/h	0.6%
Furnace roof temperature	± 10°C	Pressure for line up to 200 kg/h	± 0.3 bar
Water flow rate	± 0.1 m^3/h	Fuel oil flow rate up to 1100 kg/h	± 0.2 bar
Temperature water flow rate	± 0.1 °C	Pressure for line up to 1100 kg/h	± 1.0 bar
NOx and O2 in exhaust gases	3 %	Atomiser position	± 1 mm

Table 1 : Specifications for incertitude of the different instruments

Methodology description

The methodology for spray characterization used is schematically shown in Figure 3. The first step is to characterize the spray from well-known injectors, making an evaluation of the operational parameters which impact the most on the droplet size distribution, angle, penetration and jet break up length. After this step, several prototypes are designed and tested in ALISA atomization bench to benchmark their capacities in comparison with the previously defined specifications. If the prototype's results match to the specifications, the tests at reactive conditions should be performed. If prototype's results don't match to the specifications, design is improved and then tested again in non reactive conditions. Due to this comparative method, the results are presented as a deviation from the targeted performances for SMD, Dv90 and Air/fuel ratio. The targets are named SMD_0, $Dv90_0$ and $(A/F)_0$. Ratios lower than 1.0 for droplet sizes or air/fuel ratio represent better atomizer performance.

The atomizers used are twin fluid atomizers using air as the atomizing fluid. The reference one is commercialized by Air Liquide for many years and has proven its reliability and efficiency in many applications. This atomizer is named Atomizer A and has a nominal fuel oil flow rate of 100 kg/h. The new atomizer proposed for the same nominal fuel oil flow rate is called Atomizer B. Fuel oil specifications are shown in Table 2.

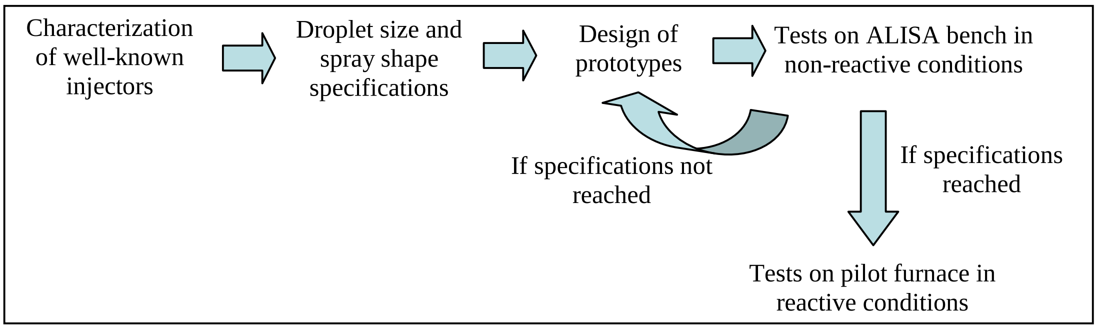

Figure 3: Schematic representation of the methodology used

Elemental Analysis		Properties	
Carbon (% w/w)	87.9	Viscosity @ 50°C (cSt)	522.4
Hydrogen(% w/w)	10.36	Viscosity @ 100°C (cSt)	34.89
Sulphur (% w/w)	0.96	Viscosity @ 150°C (cSt)	8.859
Nitrogen (% w/w)	0.39	Density @ 25°C (kg/m^3)	1000.1
Oxygen (% w/w)	0.33	High Calorific Value (MJ/Kg)	42.290

Table 2 : Fuel oil specifications

Results and Discussion

Spray measurements

The strobe light imaging technique is the first step used to characterize the atomizers. Figure 4 presents a series of spray views from atomizer A at nominal oil flow rate and A/F = 3.5(A/F)$_0$. The photo shows a disintegration mode between fibre and superpulsating regime [20, 21]. Indeed, the spray is characterized by a peeling of the main liquid core and, close to the nozzle exit, by a formation of fibres and ligaments before the liquid core is fully broken up. The series of instantaneous pictures shows sometimes a truncated liquid core with length variation from 10 to 15 times the liquid diameter.

Figure 5 presents the spray picture of the atomizer B at nominal oil flow rate at A/F = 1.0(A/F)$_0$. This shows a different atomization mechanism. The liquid core jet is very short, approximately 10 times the liquid diameter, and rapidly splits first into very short ligaments extending tangentially and then into a fine droplets cloud. However, some bigger droplets are formed especially at the periphery of the spray, on the contrary of the first atomizer A where the biggest droplets seem to be more concentrated on spray axis.

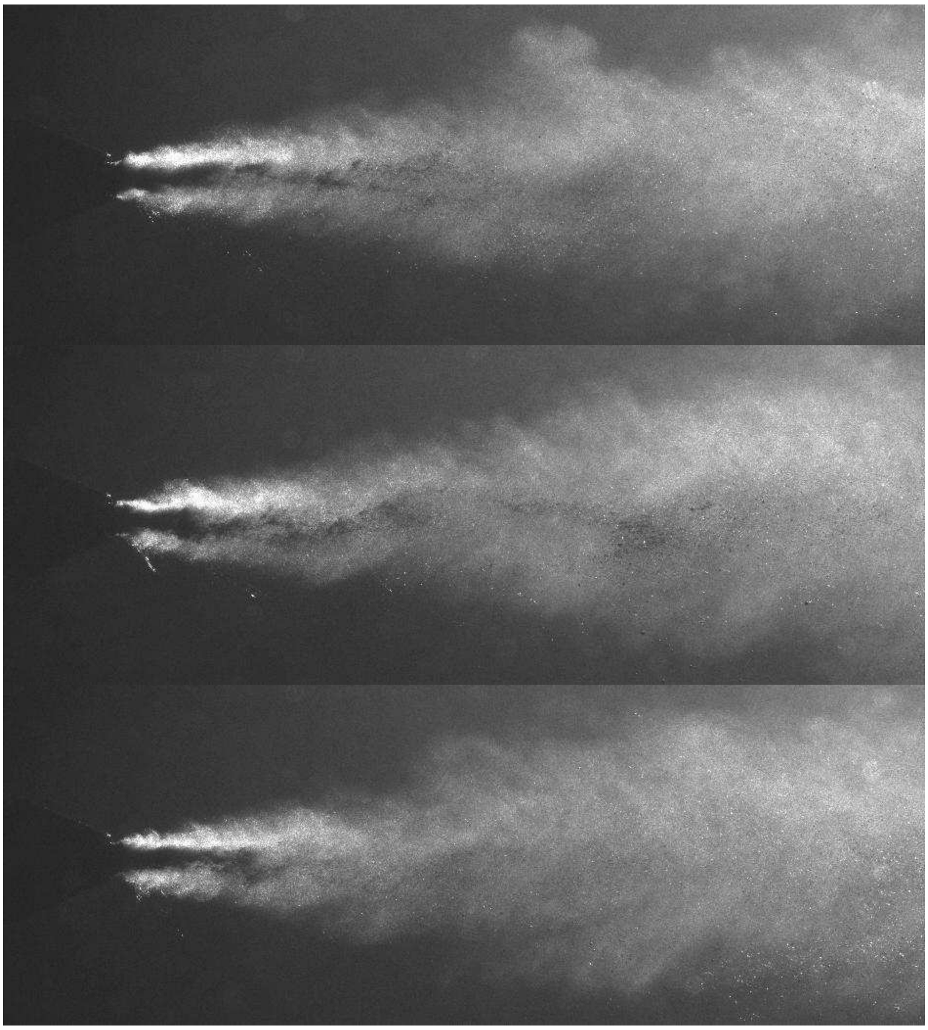

Figure 4: Characteristics of primary atomization zone for atomizer A

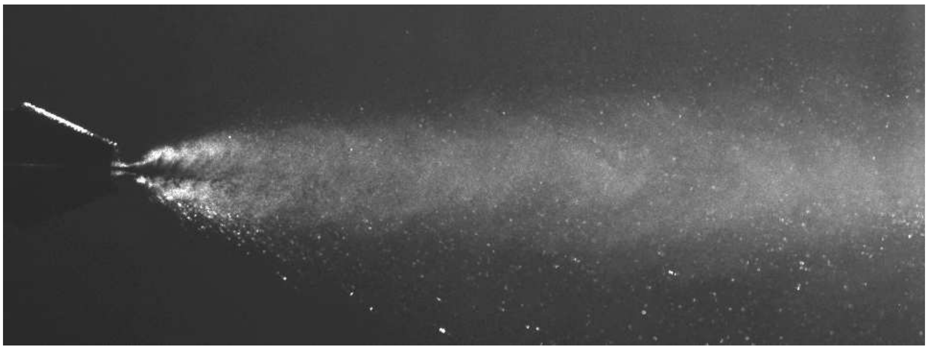

Figure 5: Characteristics of primary atomization zone for the improved atomizer B

Measurements of droplet size distribution are performed at 600 mm downstream on the nozzle exit, where the fuel oil is already fully developed, and at the centreline. Figure 6 and 7 show respectively the results for the SMD ratio, and Dv90 ratio as a function of the air/fuel ratio. As expected, the measurements show that an increase of air/fuel ratio produce a significant decrease in the droplet size for both atomizers. In particular, at the same A/F ratio, atomizer B produces a spray with lower SMD than atomizer A. In fact, to achieve the same droplet size atomizer B uses an atomizing air flow rate 3 times lower than atomizer A

Dv90 ratio values present a strong dispersion due to the treatment of beam steering on the first inner diode signal corresponding to the bigger diameter. However, the graph shows that the biggest droplets from atomizer B are smaller than the biggest droplets from atomizer A at the same A/F ratio.

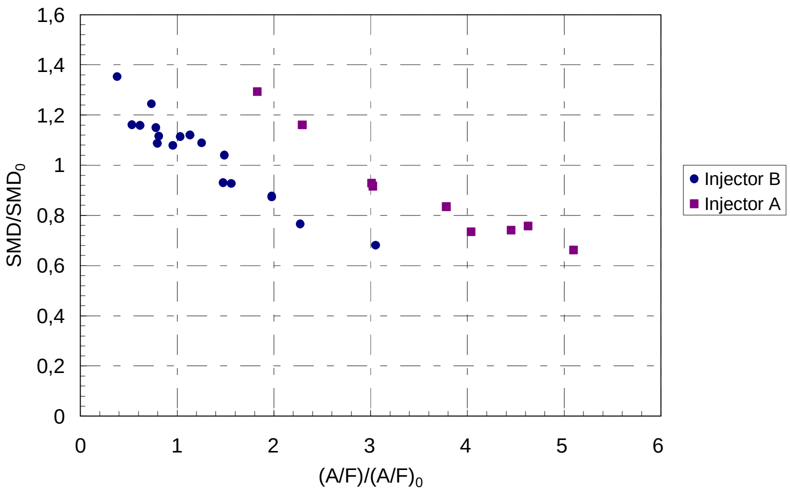

Figure 6: SMD versus Air/Fuel ratio

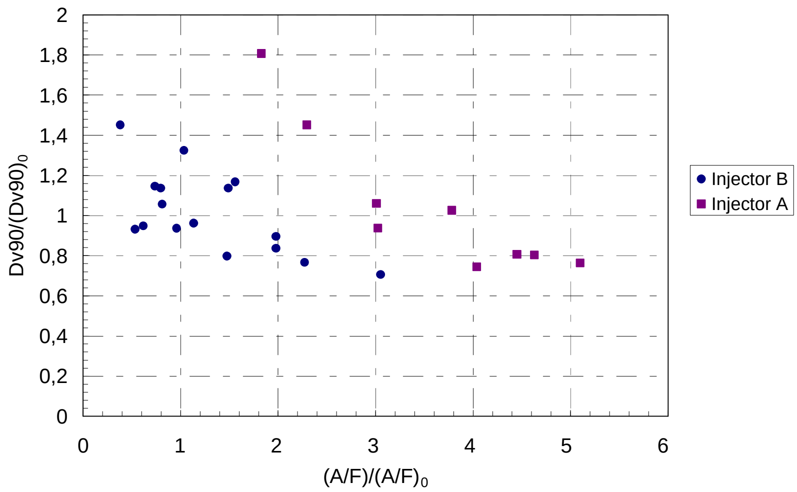

Figure 7: Dv90 versus Air/Fuel ratio

Combustion measurements

After trials in non reactive conditions, injectors A & B have been tested in oxycombustion conditions using the same burner, thermal input and excess oxygen. Therefore for these trials, only the impact of atomizing air flow rate on flame shape, pollutant emissions as well as thermal efficiency have been evaluated for the two atomizers. Flame shapes of injectors A & B are similar, they are straight, very stable, well attached to the burner throat and have similar length. Moreover, atomizer B produce a flame in a vaporization regime [22] in the whole range of A/F ratio explored. On the contrary, atomizer A for A/F lower than 2, when atomization has a poor quality, produces a flame near a brush regime [22] with droplets burning individually at the end of the flame. At this particular condition, the non-reactive tests showed that the spray presents a high Dv90 ratio, which is never reached with atomizer B even at lowest atomizing air flow ratio.

Figure 8 presents NOx emissions measured at furnace exit at 3% excess oxygen and as a function of the A/F ratio for the two atomizers. A clear reduction of NOx emissions by 20% is observed between the optimized atomizer B and the original design A. Thus, the reduction of required atomizing air flow rate to reach the same spray quality than original design A has led to a significant reduction of NOx emissions.

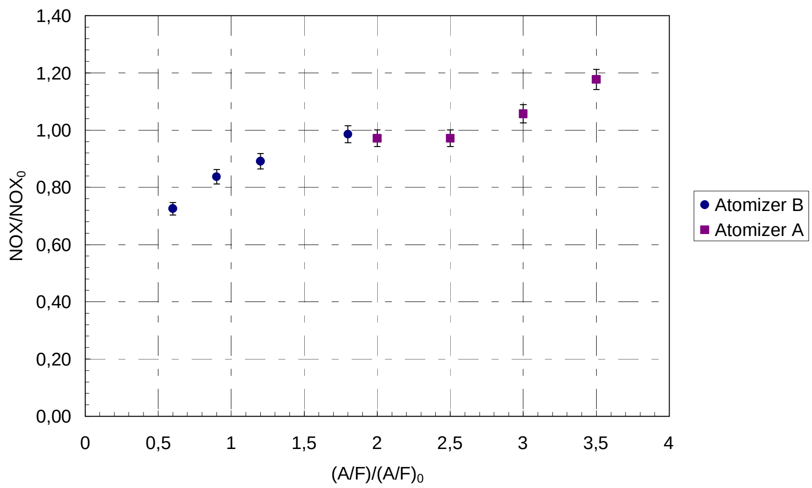

Figure 8 : NOx emissions for atomizers A & B at excess O_2=3%

Figure 9 presents the thermal furnace efficiency calculated by averaging the mean heat transfer to the load all along the furnace, divided by the power input. The uncertainty included in the graph represents the statistical uncertainty calculated as the standard deviation of the measurements. The prototype B exhibits 1% increase of the thermal furnace efficiency. This is linked to the significant reduction of the atomizing air and associated thermal ballast of nitrogen, compared to the atomizer A for the same droplet size distribution.

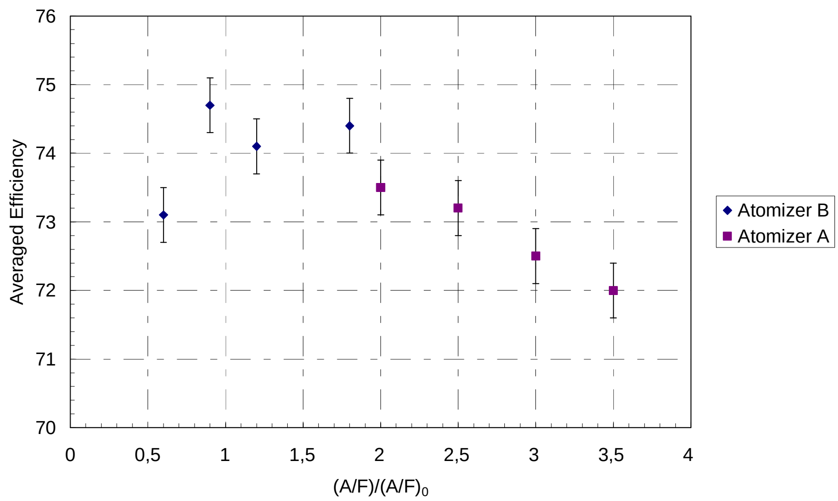

Figure 9 : Average of furnace thermal efficiency for atomizers A & B

Conclusions

The spray imaging technique and droplet size distribution using Malvern Spraytec 2007 allowed qualifying the spray of liquid fuel; not only from the droplet size distribution point of view, but also from the spray structure and break up mechanism of liquid jets. Tests results done in this environment produced data which qualified the atomizer performance and provided a preliminary assessment of their performance in combustion. Using these techniques, the atomizer B produced a spray with smallest droplet sizes in comparison with atomizer A. This has a significant impact on oxy-combustion tests of the various atomizers in particular regarding thermal efficiency and NO_X emissions. Atomizer B, which produced smallest droplet sizes at lowest atomizing air flow rate, has a better performance in oxy-combustion than atomizer A.

The methodology used to evaluate the different atomizers, together with the proper operation of the facilities used, allowed performing reliable measurements to assess the impact of sprays on oxy-combustion of liquid fuels, and optimized the atomizer design. In particular, atomizer B exhibits a reduction of the air atomizing flow rate by 3 times in comparison with the atomizing flow rate for the atomizer A. Therefore, using the atomizer B produced an increase of at least 1 point in the furnace thermal efficiency with NOx emissions reduction of 20%.

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