ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-1-14

THE EFFECT OF THE INNER FLOW ON THE PERFORMANCE OF A TWIN-FLUID NOZZLE WITH AN INTERNAL MIXING CHAMBER

F. Barreras[1], A. Lozano[1], G. Ferreira[1], E. Lincheta[2]

[1] Laboratory for Research in Combustion Technologies (LITEC/CSIC)
María de Luna 10, 50018, Zaragoza, Spain
[2] Centro de Estudios de Combustión y Energía (CECYEN)
Universidad de Matanzas, km 3½ Autopista a Varadero, Matanzas, Cuba

ABSTRACT

For the last years, studies have been conducted by our research group in order to determine an optimal configuration of a twin fluid nozzle with an internal mixing chamber, especially suitable to atomize high viscosity fuel oils in large capacity steam boilers. It has been measured that this type of nozzle is advantageous compared to the traditional "Y" type twin-fluid approach because it can produce smaller droplets with a lower gas mass flow rate. However some recent results have called into question some hypotheses that had been derived from previous experiments. In particular, the assumption that choked gas flow was desirable to improve the atomization performance might not be always true. In the same way, with the specific geometry under study, swirl inside the mixing chamber might be a negligible factor in order to obtain smaller droplets. The more important point appears to be to assure a thorough mixing inside the nozzle to achieve a homogeneous bubbly flow. To obtain it, the roles of the mixing chamber design and size and the diameter of the gas inlet have to be clarified.

INTRODUCTION

For the last years, our research group has been working on the design of nozzles to improve the atomization of highly viscous fluids, specifically aimed at its application in power plant boilers to efficiently burn heavy hydrocarbons. These nozzles are twin-fluid, and their main novelty when compared to traditional "Y" type models is the introduction of a mixing chamber. "Y" type nozzles are well known [1,2], and commonly used in most industrial boilers and furnaces to atomize liquid fuels in large-scale facilities. In them, each one of the independent exit orifices is connected to a liquid and gas conduct that join together prior to the discharge. As will be explained in the next Section, our alternative design contemplates a common mixing chamber that communicates with all the exit orifices. Besides a notorious improvement in the nozzle maintenance that will become evident when its structure is presented in detail, this geometry results advantageous compared to the "Y" models because it has been demonstrated that, for the same liquid mass flow, it requires a lower atomizing fluid mass flow rate simultaneously yielding a cloud of droplets with a lower *SMD*. This is a very interesting effect because in many industrial processes, and particularly in combustion applications, the atomizing fluid typically used is steam exiting at a relative large velocity. If a high steam flow rate is required for an adequate atomization, it can result in an excessive cooling of the reaction zone, contributing to flame instabilities and even local extinction. In this case, very long, flickering, unstable and sooty flames are generated, that can even reach the boiler walls. This situation produces the emission of large quantities of pollutant gases and solid particles. Minimizing the addition of steam increases the combustion efficiency, even more if the reduction in the required auxiliary fluid flow is accompanied by a decrease in the mean diameters of the generated droplets.

The objective of this work is to optimize the nozzle design attending to geometrical parameters and operation conditions. However, to achieve this goal, it is essential to understand the flow conditions inside the nozzle, because they determine in a large extent the characteristics of the resulting spray. Among them, a key point is the gas/liquid mixing in the nozzle internal chamber.

EXPERIMENTAL FACILITY

The facility where the present experiments have been performed has been already described in previous papers [3-5]. Nevertheless, some of its characteristics will be summarized here to put into context the results that will be presented. Similarly a brief description of the nozzle characteristics is also pertinent.

The nozzle under study, designed for a full load of 1 tm/h, is formed by two different pieces [6]. The outer part is a conical hollow piece, with 8 cylindrical 3.5 mm diameter exit holes, designed to receive the inner part. When assembled, both pieces form a body with an inner mixing chamber as depicted in Fig. 1. The inner part (see Fig. 2) has a truncated-cone shape with 6 swirl slots with rectangular cross section, and a central orifice where the air is supplied to the internal mixing chamber. In the initial design, the piece height was 16 mm, enabling a mixing chamber height of 6 mm; the liquid ports were slanted θ=20° respect to the axis of the nozzle, and the diameter of the air discharge orifice (d_d) was 4 mm. All these geometrical parameters have been varied in different sets of experiments. In this way, inner pieces 12 mm high have also been tested, with and without slanting angle, and with discharge orifice diameters ranging from 1mm to 9 mm.

For all the experiments the same external piece has been used, but with different cone angles in the side that conforms the mixing chamber floor.

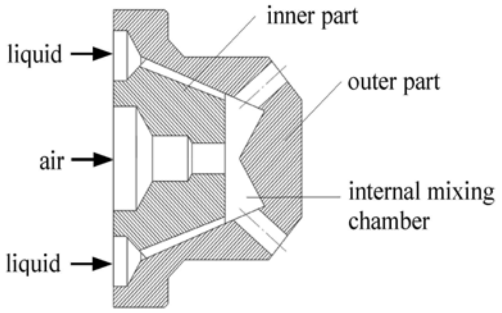

Fig. 1. Twin-fluid nozzle used in the present study.

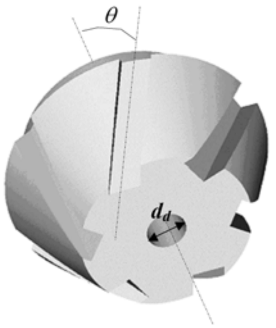

Fig. 2. Sketch of the internal piece of the nozzle.

The nozzles have been tested in the test rig shown in Fig. 3, using air and water as atomizing and atomized fluid respectively. Volumetric flow rate and inlet gauge pressure were controlled for both flows. Air was supplied with a multistage compressor capable of circulating a maximum flow rate of 100 Nm^3/h at 8 bar, and a centrifugal pump was used to supply the water. The experimental conditions have covered the range of the actual conditions at the power plant, a nominal fuel oil flow of 1 t/h with a maximum pressure of 6 bar, and a maximum steam pressure (atomizing fluid) of 7 bar. In the experiments, for a constant water flow, different air flows have been established. For each experimental condition, inlet water and air gauge pressures have been simultaneously measured. Air flow has been measured with a rotameter ranging from 9 to 90 Nm^3/h, with a precision of 2 Nm^3/h, while the gauge used to measure its inlet pressure was capable to detect variations from 0 to 10 bar with a precision of 0.1 bar. On the other hand, water flow has been measured with a flow meter with a range extending from 100 to 1500 l/h and a precision of 50 l/h. The corresponding manometer used to measure the inlet water pressure has a range from 0 to 6 bar, and a precision of 0.1 bar. Both water and air were collected in an extraction container. Water was re-circulated with a centrifugal pump to the main tank, and an air extraction fan was connected in order to guarantee stable flow conditions

The quality of the spray has been primarily determined from *SMD* measurements. They have been obtained with a Malvern Spraytec difractometer coupled to the experimental rig. To avoid an excessive obscuration, a spray selector was attached to the nozzle. This device allows the free flow from only one nozzle exit orifice, redirecting the water exiting from the other orifices out of the laser path without blocking them [4]. The position of the selector relative to the nozzle is illustrated in Fig. 4

Fig. 3. Photo of the experimental facility: 1- air line, 2- water line, 3- displacement and positioning system, 4- nozzle assembly, 5- container, 6- air extraction tube.

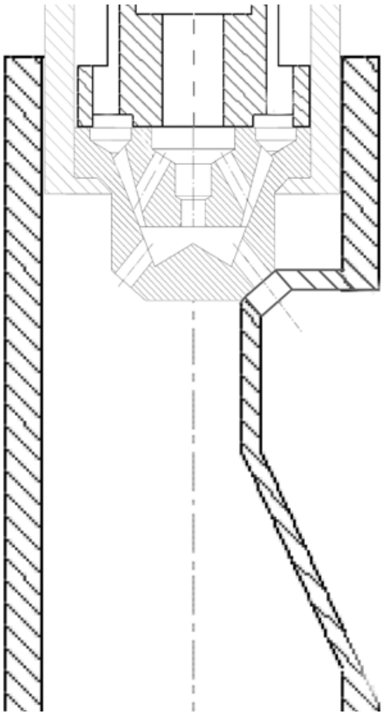

Fig. 4. Illustration of the spray selector attached to the nozzle

RESULTS AND DISCUSSION

As pointed out in the previous paragraph, in order to determine the best nozzle geometry, different modifications have been tested throughout these last years. In a first step, the slant angle of the liquid inlet channels was modified to determine the influence of the entrance swirl to the mixing chamber. In a limiting case, the channels were machined without slant angle, i.e., parallel to the cone generatrix. Quite surprisingly, the effect was very weak (see Fig. 5), and the spray characteristics were very similar for all the inner pieces. As a matter of fact, the extreme case with no slant angle does not degrade the spray characteristics. The most likely reason for this effect is that the main process determining the atomization is the inner mixing of air and water. Even if the liquid is rotating inside the chamber, the path followed before entering the exit holes must be too small for the swirl to affect the nozzle performance. Under these circumstances, the nozzle could not be assimilated to a swirling type.

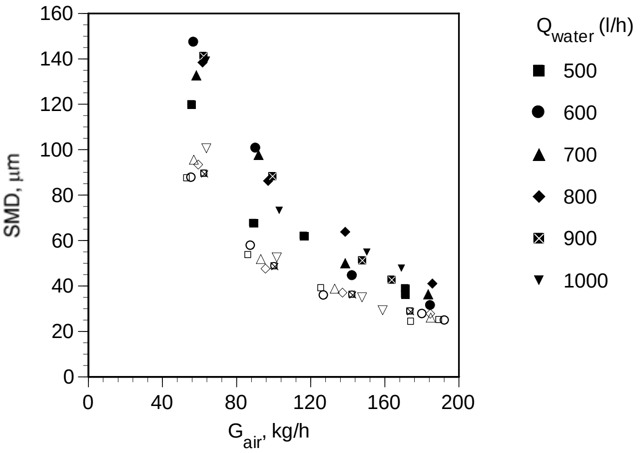

Fig. 5. Influence of the slant of the liquid ports on the SMD. Black symbols: slant angle of 20°; hollow symbols: no slant.

As the mixing inside the inner chamber appeared to be the most relevant process to determine the spray quality, another set of experiments were performed, varying the chamber geometry. In particular, two sets of inner pieces were tested, with different heights, 12 mm and 16 mm. The shorter pieces resulted in a larger mixing chamber, while the longer pieces yielded a smaller one. In each case, different air inlet central channel diameters were tried, measuring the spray droplet size distribution for a range of air and liquid flow rates.

Figure 6 presents some results obtained for an air inlet diameter of 4 mm. In the figure, the solid symbols correspond to the 16 mm inner piece, while to hollow ones correspond to the 12 mm piece. In both cases, there is a clear decrease in the *SMD* as the air mass flow rate increases, but the influence of the chamber height appears to be minor. For these particular measurements, the smaller chamber seems to produce smaller droplets. The effect could be related to a higher chamber pressure, easing the gas-liquid mixing. Figure 7 shows a similar plot, but in this case, for an air inlet channel diameter of 6 mm. Again, solid symbols stand for the 16 mm piece, and hollow ones represent the shorter inner piece. In this case, for equivalent operation conditions, a larger mixing chamber seems to result in a finer spray. The difference, however, almost disappears as the air mass flow rate increases, indicating that for the actual conditions in a power plant, this aspect of the chamber design might not be essential.

In the same line of reasoning, some more experiments were developed, modifying in this case the end wall of the mixing chamber (the one where the exit holes are located). The angle of the cone in the wall was varied (150° and 120°), and a nozzle without cone was also studied. From previous visualization experiments [5], the flow inside the nozzle was supposed to form a toroidal structure (Fig. 8). For this reason, it was assumed that the cone angle could serve to reduce the transversal diameter of this structure. Yet at this point, after having observed that neither the inlet liquid channel slant angle, nor the chamber height had a strong influence on the mean spray *SMD*, it was not unreasonable to imagine that these variations were not going to substantially modify the spray characteristics. Effectively, even although the flow structure inside the nozzle could be altered, the repercussions on the measured *SMD* were also minor.

The following aspect that was analyzed was the influence of the diameter of the central air channel, which conforms the gas inlet to the mixing chamber. To this end, diameters ranging from 1 mm to 9 mm were tested, while maintaining a fixed nozzle geometry. Some previous measurements, obtained just for two cases (4 mm and 8 mm), had lead us to think that larger channel diameters would result in increasingly large droplet *SMD*. Nevertheless, some more experiments were still required to decide if there was an optimum configuration. Following some other authors [7], we had hypothesized that gas choked flow inside the nozzle was preferable to improve the atomization performance. We thought that this was a reasonable condition because it maximizes the gas velocity at the mixing chamber entrance,

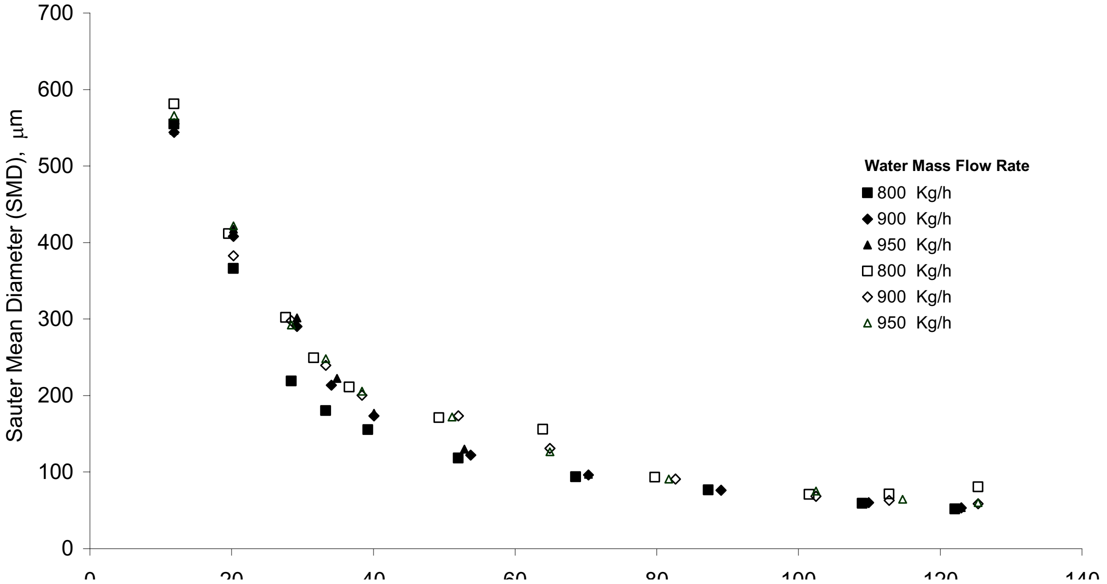

Fig. 6. *SMD* as a function of air mass flow rate for an air inlet channel diameter of 4 mm, and 16 mm inner pieces (solid symbols) and 12 mm inner pieces (hollow symbols)

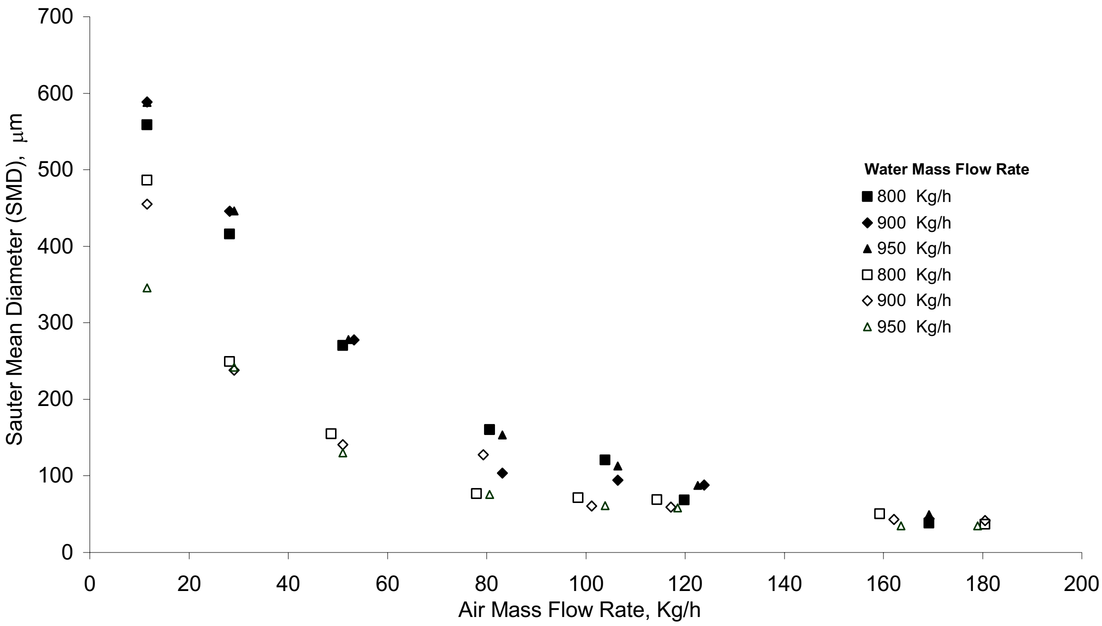

Fig. 7. *SMD* as a function of air mass flow rate for an air inlet channel diameter of 6 mm, and 16 mm inner pieces (solid symbols) and 12 mm inner pieces (hollow symbols)

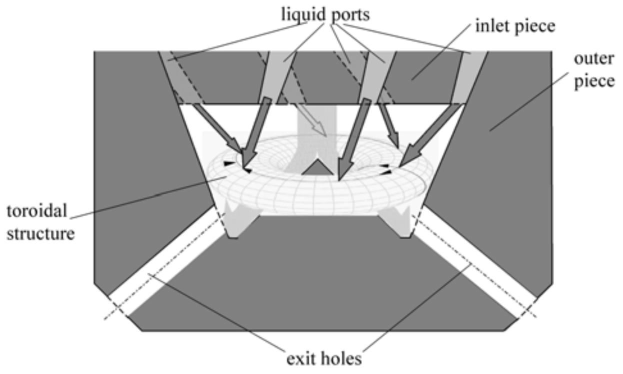

Fig. 8. Sketch of the formation of a toroid by the two-phase flow interaction at the internal chamber

and hence, should enhance the gas-liquid shearing and mixing. Results are displayed in Fig. 9 for a single water mass flow rate of 950 kg/h. Very small inlet diameter values are not interesting, because the maximum air mass flow rates that can be attained without surpassing the high pressure limit of 7 bar are too low. On the other hand, it can be seen that increasingly large diameters, are not beneficial either, as the *SMD* seems to increase for a fixed air mass flow rate. Under these circumstances, these two extremes will be analyzed in more detail, trying to find an optimal air channel inlet geometry.

The smallest *SMD* for the droplets generated with a 2.5 mm gas orifice is not inferior to 100 µm, although this value is reached for a quite low mass flow rate. Nevertheless, smaller *SMD*s would be desirable. To achieve them, the air mass flow rate has to be increased, and to this end, larger diameter channels are required. If the air pressure is fixed to a maximum value, the mean spray droplet diameters obtained for the different air channels are displayed in Fig. 10, where for practical operational reasons the air gauge pressure has been maintained to 5 bar. For channel diameters ranging from 2.5 mm to 6 mm, it is clear that a minimum *SMD* is obtained for a value around 5 mm. The measurements for 7 mm, 8 mm and 9 mm do not seem to follow the same trend, although the results for the 7 and 9 are not better than those for 5 mm. The *SMD* measured for the 8 mm channel is smaller, but with a much higher air mass flow rate. It has to be noted that in this last case together with the 9 mm channel, the flow is not choked, as opposite to the rest of the cases analyzed. The effect in the velocity reduction might be compensated by the fact that the entering gas fills a larger area, "squeezing" the liquid mass against the nozzle walls and thinning the liquid sheet, resulting also in a more homogeneous mixture. In any case, as already stated, the increase in gas flow suggests limiting the air channel diameter.

What strikes as a quite unexpected result is that very small droplets are obtained when the inner nozzle piece is completely removed, feeding the two fluids directly into the outer part through concentric channels. In this case, the entrance channel is even broader, the flow is not choked, the liquid swirl is not forced and the mixing chamber is substantially enlarged. Most of the reasoning used to explain the observations for the complete nozzle tests cannot be applied to this situation. The lower air velocity at the chamber entrance should deteriorate the gas-liquid mixing inside it resulting in a poorer performance. The only explanation that we can offer for the moment is that, without the inner piece, the two-phase flow inside the nozzle responds to a different topology. To analyze this possibility and as a first step, the mixing chamber pressure has been measured for different operation conditions. Figures 11 and 12 show the chamber pressure as a function of the air mass flow rate for the different air inlet channel diameters and two water mass flow rates, 500 kg/h for Fig. 11 and 800 kg/h for Fig. 12. In general it can be observed that the pressure increases both for increasing air and water mass flow rates, and is nearly independent of the air channel diameter. For the nozzle operated with the internal piece, the pressure dependence on air flow rate is nearly linear. For the 500 kg/h water flow rate, this behavior is not maintained when the inner piece is extracted. With this configuration and liquid flow rate, the dependence seems to be quadratic, with values that are noticeably lower for low air flow rates, although they seem to converge as they air mass flow rate increases. However, when the water flow rate is raised to 800 kg/h, the behavior of the chamber pressure is nearly identical with and without inner piece. In consequence, no hypothesis can be derived from these measurements and further research will be required. Confirmation of this nice operation working only with the outer piece would be a very interesting situation, because it would greatly simplify the nozzle geometry and its manufacturing process. The final design could be similar to those studied by Graziadio et al. [8,9] for coal slurries and coal/water mixtures that are also formed by a single piece with multiple exit holes. In order to validate these results, some more experiments should be completed, particularly to ascertain the flow structure inside the nozzle. A scaled up transparent model will be used to visualize the flow inside the mixing chamber without internal piece, to compare the images with others already available [5] acquired with the complete nozzle assembly.

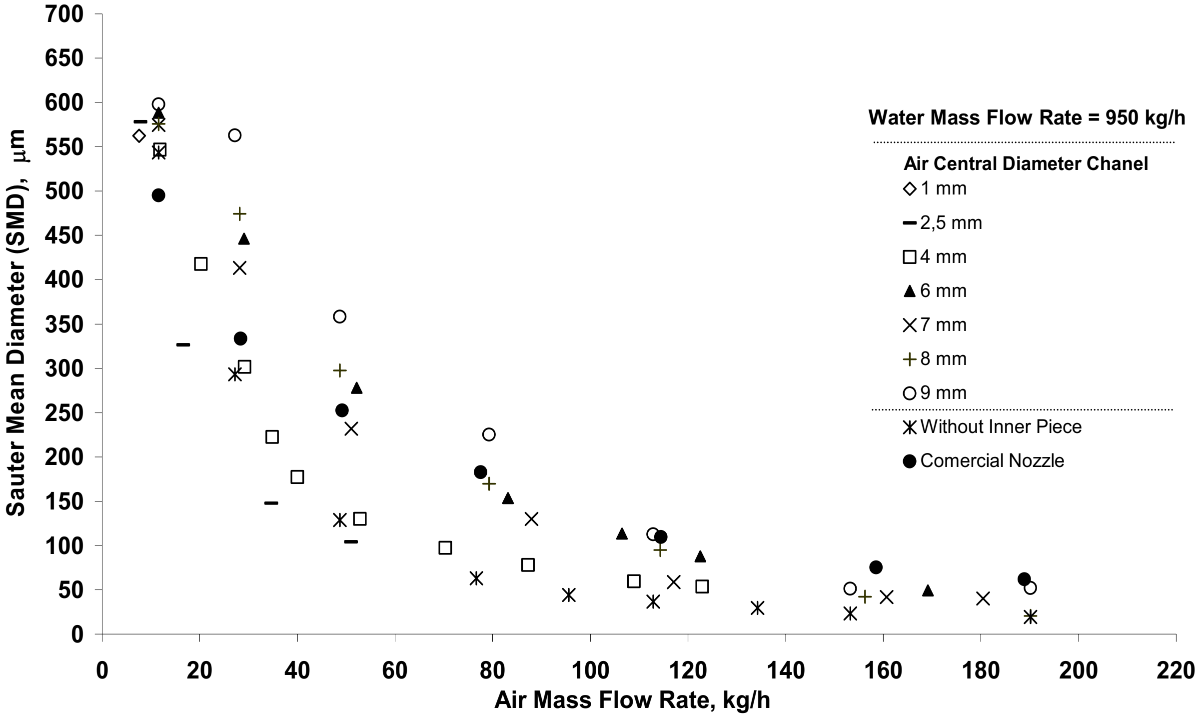

Fig. 9. *SMD* as a function of air mass flow rate for different air inlet channel diameters, and a fixed water mass flow rate of 950 kg/h

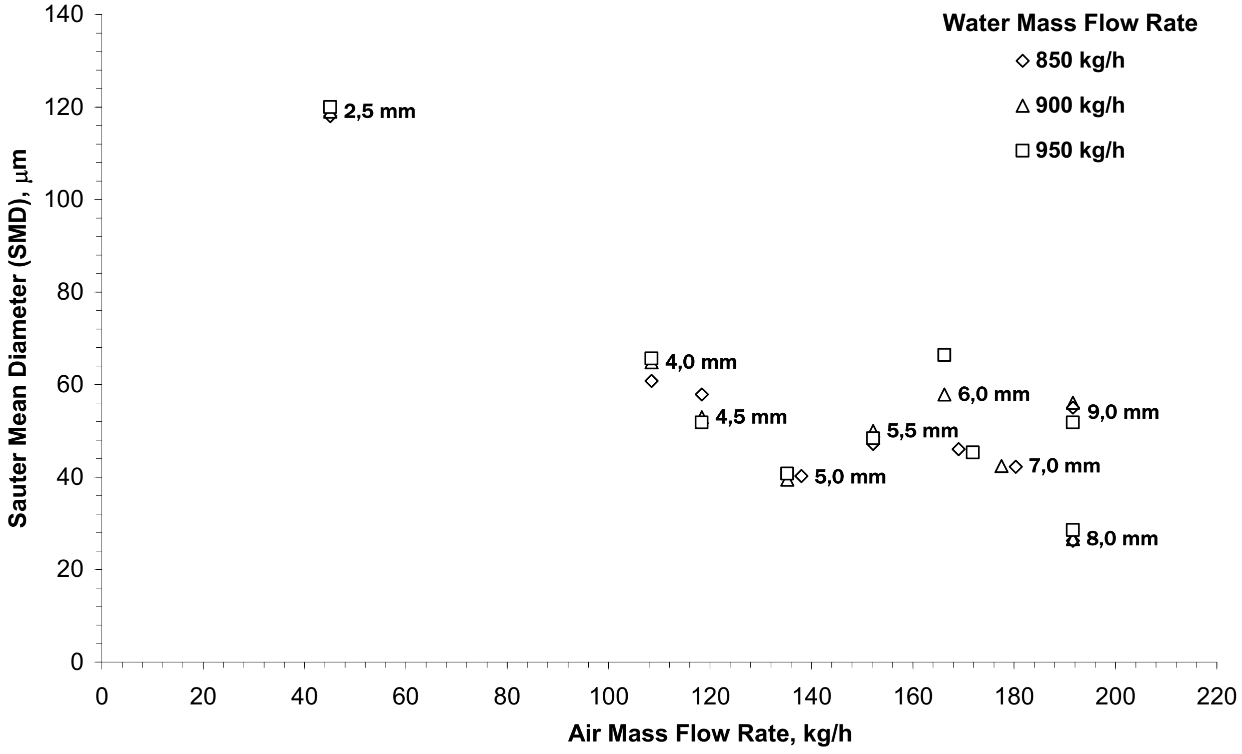

Fig. 10. *SMD* as a function of air mass flow rate for different air inlet channel diameters (marked on the symbols) and a fixed air pressure of 5 bar.

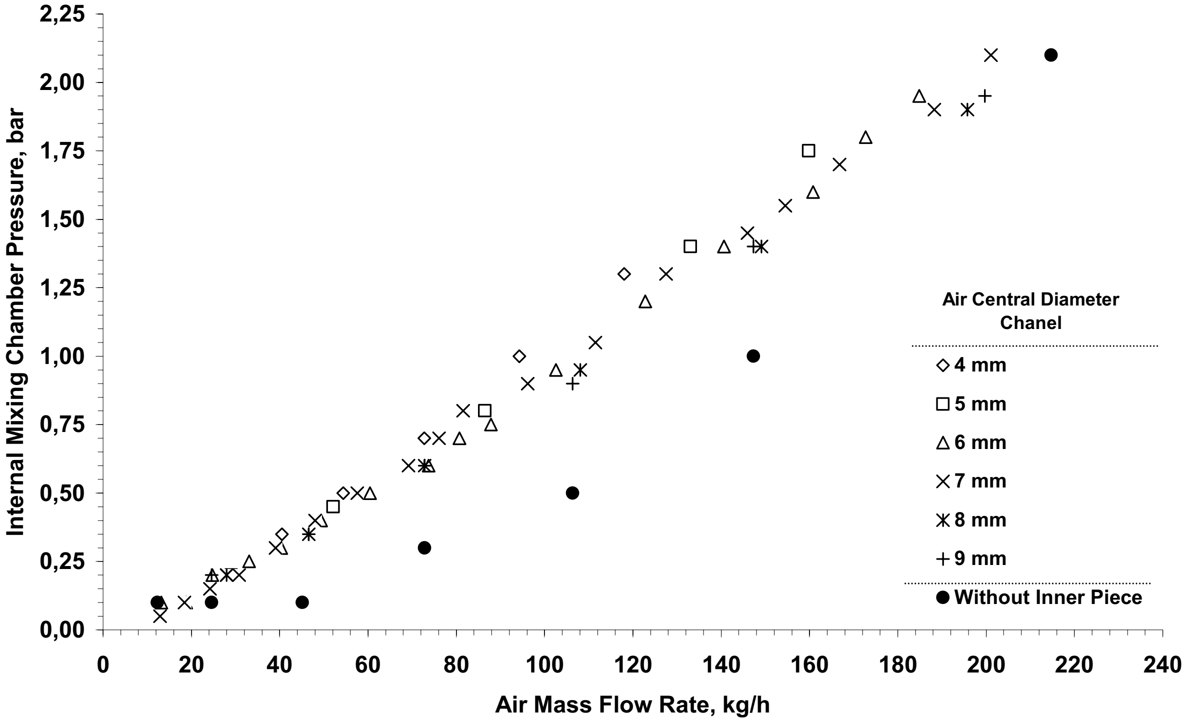

Fig. 11. Chamber pressure as a function of the air mass flow rate for varying air inlet channel diameters and a water mass flow rate of 500 kg/h

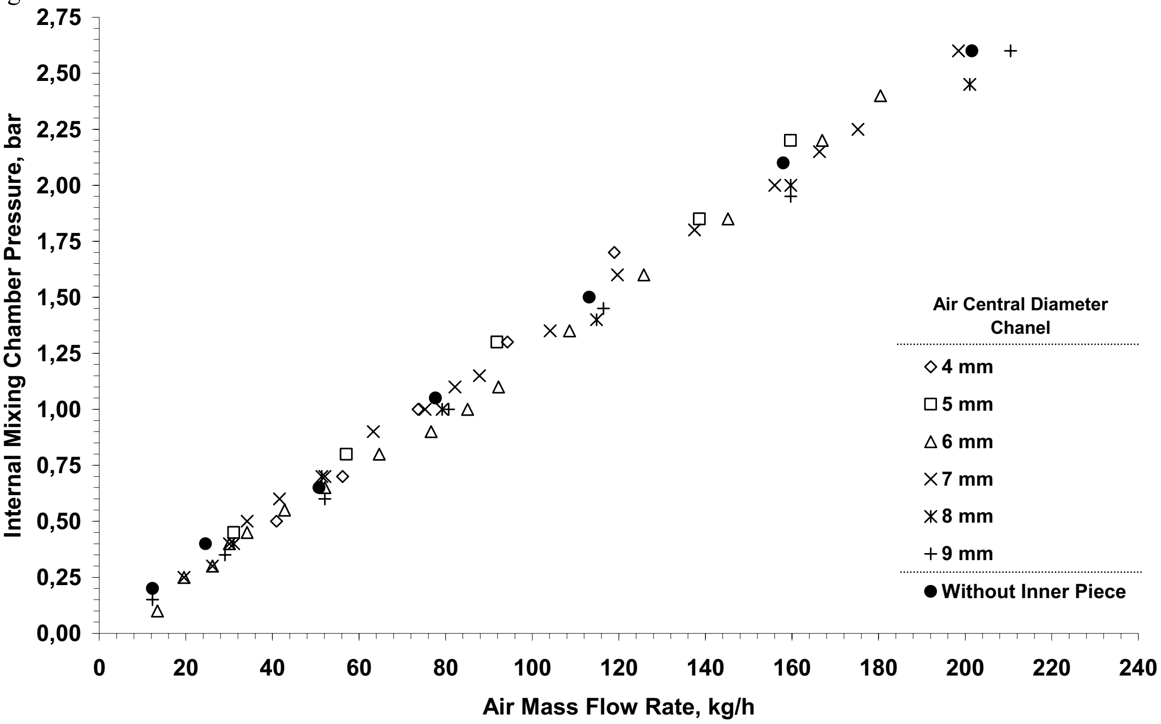

Fig. 12. Chamber pressure as a function of the air mass flow rate for varying air inlet channel diameters and a water mass flow rate of 800 kg/h

CONCLUSIONS

This paper has presented a sequential study on successive modifications trying to optimize a nozzle designed to atomize heavy crude oil in a power plant. The nozzle is composed by two pieces that fit together forming an internal mixing. The results presented have been based on droplet size distribution and spray *SMD* measurements. The main conclusions that have been obtained indicate that even though it seems that the flow forms a toroidal structure inside the mixing chamber, in this particular nozzle liquid swirl is not a fundamental parameter altering the spray characteristics. In the same way, some details related to the mixing chamber geometry are also minor regarding the *SMD* of the generated spray. Special attention has been devoted to analyzing the influence of the air inlet channel diameter. An initial hypothesis pointing to the convenience of having air choked flow at the chamber entrance to improve the atomization has not been consistently supported by all the measurements. As a conclusion, if the channel that supplies gas to the mixing chamber is too narrow, the mass flow rates required for an efficient atomization cannot be achieved without exceeding the maximum allowable pressures. On the other hand, for a very wide channel, small droplets can be generated, but with excessive gas flow rates. For the analyzed geometry, the optimum value is located around 5 mm. As a final and surprising result, adequately small *SMD* values have been measured operating the nozzle without the inner piece. This fact will have to be re-checked because, if confirmed, it will suggest reconsidering the design criteria followed to produce the nozzle under study, simplifying the two-piece concept.

ACKNOWLEDGEMENTS

This work has been partially supported by the Spanish Ministry of Education and Science under project ENE2004-05118/CON.

REFERENCES

1 Lefebvre, A. H., Atomization and Sprays, Hemisphere Publishing Corp., 1989.

2 Mullingen, P.J., Chigier, N.A., The Design and Performance of Internal Mixing Multijet Twin Fluid Atomizers, J: Inst. Fuel, vol. 47, pp. 251-261, 1974.

3 Barroso, J., Lincheta, E., Barreras, F., Lozano, A., Influence of Geometrical and Operational Parameters on the Behavior of Twin-fluid Nozzles with an Internal Mixing Chamber, Proc. of the 20th Int. Conference on Liquid Atomization and Spray Systems (ILASS- Europe '05), Orléans, 2005.

4 Barreras, F., Lozano, A., Ferreira, G., Lincheta, E., Study of the internal flow conditions on the behavior of twin-fluid nozzles with internal mixing chamber, Porc. of the 10th. Intl. Conference on Liquid Atomization and Spray Systems (ICLASS 2006), Kyoto, Japan, 2006.

5 Barreras, F., Lozano, A., Barroso, J., Lincheta, E., Experimental Characterization of Industrial Twin-Fluid Atomizers, Atomization & Sprays, vol. 16, pp. 127-145, 2006.

6 Lincheta, E., Suarez, J., Barroso, J., Lozano, A., Barreras, F., High Efficiency Nozzle for Viscous Liquids and Its Use, International Patent PCT/ES03/00643 (in Spanish).

7 Bar-Kohany, T., Sher, E., Effervescent atomization under sub-sonic and choked conditions – a theoretical approach. Chem. Eng. Science, vol. 59 pp. 5987-5995, 2004.

8 Graziadio, M., Andreussi, P., Tognotti, L., Zanelli, S., Atomization of coal – water fuels by a pneumatic internal mixing nozzle. Part I – Two-phase flow inside the nozzle, Atomisation and Spray Technology, vol. 3, pp. 187-208, 1987.

9 Andreussi, P., Tognotti, L., Graziadio, M., De Michele, G., Atomization of coal – water fuels by a pneumatic nozzle: characteristics of the spray, Aerosol Science and Technology, vol. 13 pp. 35-46, 1990.