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STUDY OF THE INTERNAL FLOW CONDITIONS ON THE BEHAVIOR OF TWIN-FLUID NOZZLES WITH INTERNAL MIXING CHAMBER

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ABSTRACT This research is devoted to the understanding of the flow behavior inside a twin-fluid nozzle with an internal mixing chamber. In previous studies the influence on the resulting cloud of droplets of some operational and design parameters such as the air and liquid mass flow rates and pressures, the diameter of the air flow channel, and the liquid inlet slots, have been studied. It was concluded that the higher the ALR, the lower the spray SMD. It was also verified that nozzles with wider air central channel diameters yielded larger droplets. In the present paper, detailed measurements of the air flow discharge velocity at the mixing chamber and of the two-phase pressure at this point have been obtained. Experiments have been performed for different air central channel diameters and for various air and liquid volumetric flow rates. Simultaneously the flow patterns in the internal mixing chamber have been experimentally visualized using laser-induced fluorescence and a high-speed camera in a scaled-up device specifically designed for this set of experiments. Results obtained will help to optimize the design of this kind of nozzles.

Keywords: Twin-fluid Atomizers, Liquid Atomization, Flow Visualization, SMD

1. INTRODUCTION

Atomization is the key process in the performance of liquid fuel-fired combustion systems [1]. Nowadays the energy production in the world is mainly provided by combustion of fossil fuels, and a similar scenario is expected in the foreseeable future. Combustion of liquid hydrocarbon has to be optimized because it is responsible of the emission of large amounts of gas and solid particles, which cause air pollution, “greenhouse” effect, acid rain and other health hazards. A liquid fuel volume can be disintegrated by effects of its own kinetic energy or by interaction with a high-velocity air or steam co-flow. In practice, there are many ways to generate a spray using, for example, rotary cups [2], twin-fluid [3], pressure swirl [4], fan [5], ultrasonic [6] or effervescent atomizers [7], forming solid or hollow cones of droplets. However, for large-scale facilities (boilers and industrial furnaces), one of the nozzles most commonly used is the steam-assisted type with a “Y” configuration [8], which can be operated either keeping a constant steam-to-fuel flow rate ratio or a fixed fuel-to-steam pressure ratio.

The situation of the oil market has forced many power plants in Cuba to replace the lighter fuel oil previously used by native crude petroleum. In this kind of fuel oil the values of some of the parameters with major influence on the atomization and combustion processes exceeds the range recommended by the boiler manufacturer. Kinematic viscosity, for example, reaches values as high as 1.546x10⁻³ m²/s at 50°C and 0.255x10⁻³ m²/s at 80°C. In order to produce a fine spray this variable is recommended to be around 4.5x10⁻³ m²/s, which requires heating the fuel up to 130°C. Asphaltene contents are also high, roughly doubling the recommended value. All these features affect the behavior of the boiler, complicating the maintenance tasks and forcing necessary unplanned shutdowns.

Since 2001, our research team is working on the improvement of the atomization and combustion processes of crude petroleum, and has designed a new-concept nozzle with an internal mixing chamber. 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 very important because it avoids some of the well-known drawbacks of the “Y-jet” nozzles. In the industry the atomizing fluid typically used is steam exiting at a relative large velocity, which sometimes cools down excessively the reaction zone, contributing to local flame extinction. So, a very long, flicker, unstable and sooty flame is generated, with a reddish-yellow color, even reaching the boiler walls. This situation produces the emission of large quantities of pollutant gases and solid particles.

In the present research, detailed measurements of the air flow discharge Mach number at the mixing chamber and of the two-phase pressure at this position have been acquired. Experiments have been performed for different air central channel diameters and for various air and liquid volumetric flow rates. Simultaneously the flow patterns inside the internal mixing chamber have been visualized using both laser-induced fluorescence and a high-speed recording technique in a scaled-up device specifically designed for this set of experiments. Results will help in the design optimization of this kind of nozzles.

2. EXPERIMENTAL FACILITIES AND TECHNIQUES

In order to perform a complete analysis of the complex flow inside the nozzle, experimental measurements of some specific parameters are needed. For this reason, several devices have been used in this research.

2.1 Twin-fluid nozzle and test rig

Measurements have been performed in the new-concept nozzle, which has been initially designed to
replace original “Y-jet” atomizers in a Cuban power plant. It is formed by two different pieces, an inner and an outer part [10], requiring a nominal flow of 1 t/h to generate the specified electric power using native crude petroleum. A sketch of this nozzle is depicted in Fig. 1.

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

The outer part is a conical hollow piece designed to receive the inner part forming a body when assembled. It has 8 cylindrical exit holes with a diameter of 3.5 mm. 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. The liquid ports are slanted $\theta=20^\circ$ respect to axis of the nozzle, and the diameter of the air discharge orifice to the mixing chamber ($d_d$) has been varied from $4 \text{ mm} < d_d < 8 \text{ mm}$. For all the experiments the same external piece has been used.

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

The nozzles have been tested in the test rig shown in Fig. 3, with controlled volumetric flow rate and inlet gauge pressure for both air and liquid flows. Air is supplied with a multistage compressor capable of circulating a maximum flow rate of 100 Nm$^3$/h at 8 bar, and a centrifugal pump is used to supply the water. The experimental conditions have covered the range of the actual conditions at the power plant where a maximum fuel oil (liquid fluid) pressure of 6 bar is achieved, with a 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 pressure have been simultaneously measured. Air flow has been measured with a flowmeter 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 is 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 are collected in an extraction container. Water is re-circulated with a centrifugal pump to the main tank, and an air extraction fan is connected in order to guarantee stable flow conditions.

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.

2.2 Characterization of the flow conditions at the mixing chamber

Two different experiments have been performed to characterize the flow conditions at the internal mixing chamber. They have been mainly motivated by some results previously obtained [11,12], in which the spray SMD seemed to be directly dependent on the two-phase flow interaction at the internal chamber. On the one hand, the air flow compressibility at the entrance of the mixing chamber has been measured. To this end, a specific device has been devised, as depicted in Fig. 4.

Fig. 4. Set-up used for air flow measurements
In the real situation, liquid air is discharged to the internal chamber that is, in fact, a large reservoir compared to the duct diameter. So, to facilitate the measurements, experiments have been performed directly discharging the air flow to the room environment. One of the external pieces was cut allowing both the location of a static pressure intake in the inner piece wall and the proper assembly of the setup. A stagnation pressure probe was also placed just at the exit of the orifice. Both static and stagnation pressure probes were connected to individual U-tube manometers, which used either mercury or manometric oil, depending on the pressure range in order to maintain a suitable precision in the reading. Assuming one-dimensional flow and isentropic flow expansion, the Mach number at the exit (the entrance of the internal mixing chamber) can be calculated by the expression [13],

\[
M = \sqrt{\frac{2}{\gamma - 1} \left( \frac{p_{a_o}}{p_{a_{stat}}} \right)^{(\gamma - 1)/\gamma}}
\]

(1)

where \( p_{a_o} \) and \( p_{a_{stat}} \) are the air stagnation and static pressures, respectively, and \( \gamma \) is the air specific heat ratio.

From these experiments one can exactly know the pressure difference across the air duct of the nozzle at which the flow becomes sonic, corresponding, in this particular case, with the direct reading of the inlet air gauge pressure. It can also be expected that the choked condition for the actual nozzle operation, when air and liquid interact inside the mixing chamber, will be achieved for the same pressure difference between the air at the nozzle entrance and that established at the mixing chamber. On the contrary, as the inlet air pressure to the nozzle when discharged to room conditions is different to that established when interacting with the liquid phase at the internal mixing chamber, the obtained air mass flow rates for the single-phase experiments will also be different to those corresponding to the two-phase flow.

**2.2 Flow pattern visualization**

Experiments performed in previous studies have highlighted the importance of the interaction of air and liquid at the internal chamber. In order to determine the flow patterns as a function of both the flow conditions and geometrical parameters, laser-induced fluorescence (LIF) and a high-speed camera have been employed. To ease the analysis of the recorded images, a scaled-up device has been machined in transparent plastic. It consists of a half-nozzle, as depicted in Fig. 6. During the scaling-up process, geometric distances and air and liquid flow area ratio have been kept constant to achieve similar experimental conditions as the actual nozzles.

![Fig. 6. Scaled-up device used to visualize the two-phase flow patterns at the internal mixing chamber](image)

During the experiments, different geometries have been tested. On the one hand, two different inner pieces have been chosen, with a total height of 26 mm and 31 mm, respectively. In both of them, the flow area and the slant of the liquid ports, as well as the diameter of the air central channel have been kept fixed. However, these two pieces also allow the formation of internal chambers with different height as can be observed in Fig. 7. On the other hand, the geometry of the base of the internal chamber has also been varied, forming both conical and flat surfaces. In the case of the conical configuration, three different cones have been used with angles (\( \beta \)) of 150°, 120°, and 90°, as defined in Fig. 7a).

![Fig. 7. Two of the geometries tested in the device: a) small internal chamber with conical base surface (\( \beta=120^\circ \)); b) large internal chamber with flat base surface.](image)
For the LIF experiments, flow patterns have been visualized using Sulforhodamine B (Kiton Red) dissolved in water as the luminescent tracer. To excite the dye, a double cavity Quantel YG781C-10 pulsed Nd:YAG laser has been used, doubling the frequency of its emission to obtain an energy of 100 mJ per pulse at 532 nm, with a pulse duration of 6 ns. This excitation scheme is very efficient for this dye because the absorption spectrum of Sulforhodamine B has a maximum at 556 nm [14]. The emitted fluorescence light is in the orange range, with the peak at 620 nm. To further decrease the background light, a Schott OG 550 filter has been placed in front of the camera lens, blocking any 532 nm reflection from the incident laser beam. The dye is seeded with a I&J Fisnar JBE 1113 liquid seeder, which is pneumatically driven with a maximum air pressure of 6 bar.

The fluorescence emission has been imaged with an interlined Hamamatsu ORCA-ER 1024x1024 pixels CCD camera, placed perpendicular to the device. A spherical lens with a focal distance of –25 mm has been placed at 1 m of the device to expand the laser beam obtaining a divergent cylinder of light, which illuminates the mixing chamber at an angle of 60º with respect to the axis of the camera. This arrangement does not introduce any perspective distortion in the images and eliminates any possible direct reflection of the laser light that might damage the CCD camera. Data sets have been recorded with a 70-210 mm f/4 Tamron macro-lens, giving a field of view of 35x35 mm with a spatial resolution of 34 µm/pixel. To study the evolution of the flow streamlines, several image sequences have been acquired for both different flow conditions and different device geometries to track the dye trace, setting the time interval between successive images at 0.5 s. The camera is synchronized to the laser pulses with a Stanford Research System Delay Generator DG-535, which is externally triggered by the laser lamp trigger signal.

Simultaneously, a high-speed camera has been used to study the fast processes that take place inside the internal mixing chamber. Based on visual observation of the flow, it was decided to use the air bubbles in structures formed by the strong two-phase flow interaction as tracers. Sequences have been acquired with a RedLake HS-4 high-speed camera with a 512x512 CMOS sensor at a frame rate of 28.500 img./s. Data sets have been recorded with a 50 mm f/1.4 Nikon lens. The acquisition frame rate and the lens used in the experiments allowed a maximum field of view of 45x25 mm. After several tests, a front illumination with two halogen 500 W spotlights has been used, placed at 45º respect to the illuminated plane.

3. RESULTS AND DISCUSSION

An example of the results obtained using Eq. (1) for the characterization of the compressibility of the air flow discharged to the mixing chamber for an inlet diameter of 4 mm is shown in Fig. 8. The flow is almost linearly accelerated until it reaches the sonic condition ($M=1$) for an air mass flow rate of 43.4 kg/h. For air mass flow rates higher than this value, the Mach number remains roughly constant. This behavior is also verified for the rest of the air discharge diameters. As previously commented, this measured air mass flow rate does not exactly agree with that at which the air flow is choked for the actual nozzle operation, due to the difference in the air pressure at the nozzle inlet caused by the interaction with liquid at the internal chamber.

![Fig. 8. Mach number obtained for different air mass flow rates for $d=4$ mm: a) single-phase; b) two-phase flow](image)

To calculate the actual air mass flow, a relationship between the air mass flow rate and the pressure difference between the air inlet and that at the internal mixing chamber has been fitted. With the measured pressuredifference for the air flow corresponding to the sonic condition for the single phase experiments (see Fig. 8a), one can easily find the air mass flow rate for the two-phase flow, as depicted in Fig. 8b). A summary of the results obtained for both single- and two-phase flow can be observed in Table 1.

<table>
<thead>
<tr>
<th>$d_a$ (mm)</th>
<th>$\Delta P$ (bar)</th>
<th>$m_{am}^{SP}$ (kg/h)</th>
<th>$m_{am}^{TP}$ (kg/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.1</td>
<td>43.4</td>
<td>47.6</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
<td>61.9</td>
<td>89.9</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>91.6</td>
<td>112.7</td>
</tr>
<tr>
<td>7</td>
<td>1.7</td>
<td>105.6</td>
<td>155.4</td>
</tr>
<tr>
<td>8</td>
<td>2.3</td>
<td>156.1</td>
<td>188.1</td>
</tr>
</tbody>
</table>

Plotting these measurements, it is verified that a quadratic dependence is obtained between the air mass flow rates at which the air is choked and the air channel discharge diameter, in the form
\[ m_{a}^{TP} = k \cdot d_{d}^2 \]  

as represented in Fig. 9. As expected, in the case of the single-phase flow the best fitting is achieved for \( k = 2.4 \), while it reaches \( k = 3.081 \) for the two-phase one, expressing \( d_{d} \) in mm.

Fig. 9. Air mass flow rate vs. air discharge diameter for both single- (a) and two-phase flow (b)

This is a very important and novel result. It is evident that the derived equation is a powerful tool in hands of researchers and engineers for the optimum design of this kind of nozzles. Once the nominal liquid mass flow rate (or fuel oil in case of industrial boilers) is known, the optimal mass atomizing flow rate (e.g. steam) can be obtained from the suitable ALR that reports the best SMD of the spray. After that, the central channel diameter can then be estimated using Eq. (2).

These measurements can also be used to explain some results previously obtained. It has been verified that the SMD of the spray increases for higher values of the air discharge channel diameter [11]. In order to gain clarity in the discussion, a brief summary is presented in Fig. 10 for two nozzles for the nominal liquid flow rate (1000 kg/h) and air central channels with 4 mm and 8 mm diameter. It should be reminded that for \( d_{p} = 4 \) mm the air flow rate for choked condition is around 40 kg/h, and this value is above 185 kg/h for \( d_{p} = 8 \) mm, which is out of the range for the air mass flow measured. This result indicates that the occurrence of choked conditions for the air flow improves the performance of these nozzles. It is possible that the sudden expansion of the compressed air that takes place at the internal mixing chamber can induce the production of small air bubbles that will be included into the bulk liquid, in a similar way as in effervescent atomizers.

Some pictures obtained from the flow visualization experiments using LIF are depicted in the sequences shown in Figs. 11 to 14. The images depicted in Fig. 11 correspond to an experimental condition with the inner piece of 26 mm, and a flat base surface, forming the largest internal mixing chamber. Besides, a liquid mass flow rate of 200 kg/h, and an air mass flow rate of 12.6 kg/h have been selected, given an ALR of 0.063.

Fig. 11. Flow visualization using LIF for an inner piece of 26 mm, and a flat base surface. ALR = 0.063.

As indicated by the arrows in the first image, the dye enters the internal chamber through the slanted liquid ports. Due to the asymmetry of the device respect to the liquid ports, the interaction of both streams with the central air flow is different, as observed in the second image. In this case, liquid exiting the right port directly strikes against the wall and the base of the chamber, respectively. On the contrary, the velocity component of the liquid stream that exits the left port hits the vertical air jet, bending and forming a vortical structure, as clearly depicted in the third picture.

Fig. 12. Flow visualization using LIF for an inner piece of 31 mm, and 120° conical base surface. Experimental conditions are the same as in Fig. 11.
The same trends and features discussed in Fig. 11 are also observed in Fig. 12. Again the vortex in the left part of the internal chamber is visible. Besides, even for this low air-to-liquid mass flow ratio, too low to be used in the previous atomization studies, the appearance of air bubbles into the bulk of the liquid can be observed. It should also be noted that for this experimental conditions the dye pulse is contained only in three of the 10 images included in each sequence. Then, the residence time of the liquid into the chamber can be estimated around 1.5 s. It is also evident that this characteristic time is a function of the flow conditions, implying that for higher ALR is has to be shorter. This conclusion has also been verified for large water/air flows where only two illuminated images were included in the complete sequence.

Fig. 13. Sequence of images using LIF visualization detailing the exiting jets, for the same setup as that in Fig. 12. Experimental conditions are also the same as in Fig. 11.

The sequence depicted in Fig. 13 corresponds to both the same experimental setup and flow conditions as those selected in Fig. 12. In this front-view the exiting liquid jets are detailed. The apparent discontinuity observed in the images is due to the angular configuration of this section at the external surface of the transparent nozzle device (see Fig. 6). The existence of ligaments and big droplets detaching from it can be easily observed, in accordance with the low value of the ALR used in these experiments. The initial idea during the design of this kind of nozzles was to combine the advantages of both pressure-swirl and twin-fluid nozzles. However it seems that its actual operational principle is closer to that of the effervescent atomizers.

Fig. 14. Influence of the air mass flow rate on the flow patterns at the internal chamber. Water flow is fixed to 500 kg/h: air mass flows of a) 35.6 kg/h, and b) 114.1 kg/h, respectively.

A comparison showing the different flow patterns produced inside the mixing chamber for two different ALR is presented in Fig. 14. In this case, the same experimental setup as in Figs. 12 and 13 has been selected (inner piece length of 31 mm, and a 120° conical base surface, yielding a smaller internal chamber). In case a) the liquid mass flow rate is 500 kg/h and an air one of 35.6 kg/h, giving an ALR ratio of 0.071; while in b) the selected air mass flow is 114.1 kg/h, resulting in an ALR of 0.228. On the one hand, the overall trends are very similar for the two ALR conditions. Nevertheless, the structures are much smaller for the higher ALR, which corresponds to image b). At the same time, for the higher ALR, the number of air bubbles formed is increased, and their size is reduced. Another feature should also be highlighted. The increase in air mass flow rate also introduces another difference in the internal chamber flow characteristics. A careful analysis of these two images reveals that when the ALR is high enough, as for example in Fig. 14 b), the large air jet energy causes the formation of an air cylinder in the center of the chamber, its boundaries acting like a shield. This situation can be observed in this figure looking at the two gray lines less intense in the chamber that match the air central channel walls if extended downwards, identified with the letter “a”. Moreover, when the air jet impacts on the conical base it is deflected, causing a detachment of the liquid from this surface, as indicated with letter “b”.

For the high-speed camera recording experiments, six different water mass flows have been tested (100, 200, 300, 400, 500, and 700 kg/h), combined with four air mass flow rates (10, 20, 30, and 40 kg/h), covering an ALR range from 0.063 to 0.626, representing one order of magnitude. Careful analysis of the evolution of the two-phase flow structures in the recorded sequences reveals some trends not detected in the still images. In some cases the detection of a typical behavior can only be determined with a frame-by-frame analysis of the recorded high-speed video. Some of the main results obtained are summarized in the following figures.

Fig. 15. Images acquired for a water mass flow rate of 500 kg/h and different air mass flows: a) 13.45 kg/h; b) 68.9 kg/h. Same experimental setup as in Fig. 12.

In Fig. 15 the above-discussed effect of the air-water interaction is clearly observed. In both of the depicted images the liquid flow is the same (500 kg/h), but in image a) the ALR is 0.026, whereas in b) its value is more than 5 times higher, reaching 0.138. It is evident that when the air mass flow rate is increased (Fig. 15 b) the air stream cylinder is perfectly visible, as well as its impact with the chamber floor. This condition is also responsible for the formation of another vortex at the right-part of the chamber that appears for some experimental conditions, and for the liquid detachment.

As the illumination used in these experiments has always been the same for all the experimental conditions, these results are suitable to compare the intensity of the two-phase flow interaction using the scattered light intensity. Two different water mass flow rates are presented in Fig. 16, 600 kg/h (upper row), and 700 kg/h in the lower
one. Besides, air mass flow rates have also been changed, increasing from left to right, as indicated by the ALRs values labeled below each image.

Fig. 16. Flow visualization for different air and water mass flow rates. Water mass flow rate are 600 kg/h and 700 kg/h for the upper and lower rows, respectively.

As can be observed, the intensity of the scattered light increases both for increasing liquid and air mass flow rates. However, it is likely that the resulting increase in the emitted light will have a different cause depending on what is being increased, the liquid or the air flow rates. In our opinion, for higher values of the liquid mass flow rate bubbles with a large size are formed, while, on the other hand, when the air mass flow is higher both the number of bubbles is increased, and its size is reduced. This assumption is supported by the results of the SMD measurements performed in previous studies. It has been demonstrated that the spray SMD is reduced for increasing air mass flow and, on the contrary, increases for higher liquid flow rates. Furthermore, this assumption also explains why this kind of nozzles produces a spray with smaller SMD than that produced with a “Y-jet” type at similar operational conditions. The breakup of the liquid volume in “Y-jet” nozzles is achieved by the shear of the liquid flow by the atomizing fluid just at the exit holes. On the contrary, in these nozzles atomizing fluid bubbles are inserted into the bulk liquid.

Another important parameter to be analyzed is the influence of the size of the internal chamber on the structures formed by the two-phase flow interaction. This analysis is performed in Fig. 17 in which the two images correspond to the same liquid mass flow rate (500 kg/h) and also similar air volumetric flow rate (40 Nm³/h). In this case, the conical base surface with 150° angle has been selected for the comparison. In the left image a smaller internal chamber has been formed using the 31 mm length internal piece, whereas in the right one a bigger chamber has been obtained mounting the 26 mm inner piece. It is important to remind that the experiments have been performed fixing a constant water flow and then scanning the whole range of air volumetric flows. It has been verified that the inlet pressure needed to supply the same air volumetric flow is different for the two sizes of the internal mixing chamber, this effect being more notorious for higher values of ALR. So, the bigger the internal chamber, the higher the inlet air gauge pressure measured. It is for this reason that the resulting air mass flow rates are different, as labeled below each image.

In general, the same behavior discussed before has been observed, with the vortex in the left part of the chamber and the liquid flow detached at the right surface of the base for this experimental condition. However, as can be observed, the size of the vortical structure is bigger for the larger mixing chamber. This result has also been reproduced for other experimental setups, as well as for other liquid and air mass flow conditions.

Fig. 17. Influence of the internal chamber size on the flow interaction for constant water mass flow rate (500 kg/h) and air volumetric flow rate. Left image corresponds to the smaller chamber, and the right one to the bigger.

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Fig. 18. Sketch of the formation of a toroid by the two-phase flow interaction at the internal chamber.

With all these results we can indicate that the interaction of the liquid and air at the internal mixing chamber generates a toroidal structure that rotates around the axis of the nozzle, as sketched in Fig. 18. The liquid flow is represented by arrows bounded by solid lines, whereas the atomizing fluid (air in the present research) by light-gray arrows. Both, the atomizing fluid central jet and the slant of the liquid ports help in the formation of this structure. Only one of the two symmetric vortices that conforms the 3-D toroid at the illuminated plane has been detected due to the asymmetry of the half-nozzle used in the device. This toroidal structure enhances the two-phase flow interaction, and also helps in the formation and ingestion of bubbles into the liquid.

4. CONCLUSIONS

This experimental research has been devoted to the analysis of the flow conditions inside the internal mixing chamber of a twin-fluid atomizer. It has been demonstrated that under certain experimental conditions the atomizing fluid is choked. Sonic condition is achieved for different air mass flow rates as a function of the air central channel diameter. This is a very important and novel result, and the derived equation can be a powerful tool in hands of researchers and engineers to calculate the optimum size of
the diameter of the atomizing fluid central channel, as a function of the nominal fuel mass flow rate.

These results can be used to explain why the SMD of the spray is increased for larger diameters of the air discharge channel as previously obtained. Probably, the sudden expansion of the compressed air that takes place at the internal mixing chamber can induce the production of small air bubbles that will be included into the bulk liquid, in a similar way as in effervescent atomizers. This strong interaction of the two fluids inside the internal chamber has been clearly demonstrated in the flow visualization experiments using LIF and a high-speed camera. The intensity of the light scattered in the recorded images is associated with the number and size of the air bubbles produced. To the authors’ point of view, the verified reduction of the droplets size produced by these nozzles when compared to the “Y-jet” types at similar conditions could be due to the sudden expansion of the atomizing fluid bubbles when exiting the nozzle.

Finally, pending for experimental evidences in a real size nozzle made in transparent plastic, the formation of a toroidal structure is postulated. The asymmetry of the scaled-up device used in the experiments has prevented us from visualizing the complete structure. The design of the nozzle, i.e. the central air jet, the slant of the liquid ports, and the conical shape of the mixing chamber floor, helps in the toroidal formation. This toroidal structure enhances the two-phase flow interaction, as well as the formation and inclusion of small atomizing fluid bubbles into the bulk of the liquid.

NOMENCLATURE

\[
egin{align*}
ALR & \quad \text{air-to-liquid mass flow rate ratio} \\
d_d & \quad \text{diameter of the discharge orifice [mm]} \\
k & \quad \text{constant in Eq. (2) [kg/(h-mm\textsuperscript{2})]} \\
M & \quad \text{Mach number} \\
m_{\text{am}}^\text{SP} & \quad \text{air mass flow rate for single-phase flow [kg/h]} \\
m_{\text{am}}^\text{TP} & \quad \text{air mass flow rate for two-phase flow [kg/h]} \\
m_l & \quad \text{water mass flow rate [kg/h]} \\
P_{\text{st}} & \quad \text{stagnation pressure [bar]} \\
P_{\text{stat}} & \quad \text{static pressure [bar]} \\
\Delta P & \quad \text{pressure difference [bar]} \\
SMD & \quad \text{Sauter mean diameter of the spray [µm]} \\
\beta & \quad \text{angle of the conical base surface [°]} \\
\gamma & \quad \text{air specific heat ratio} \\
\theta & \quad \text{slant angle of the liquid ports [°]}
\end{align*}
\]

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