PERFORMANCE OF INTERNAL MIXING AIR-ASSISTED NOZZLES FOR HEAVY FUEL OIL BURNERS

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Abstract

An experimental research has been developed in order to study the influence of the atomizer geometry and injection pressure on spray quality, analyzing some internal mixing air-assisted nozzles used for heavy fuel oil burners. Four nozzles of different geometries have been tested in a laboratory scale facility, determining the best performance relative to the air or steam consumption. Considering the results of the atomization tests, a commercial model and the best new designed prototypes have also been tested in an industrial boiler. The performance of the last one of them has been simulated on a computer code in a high capacity boiler. All the results have demonstrated the advantages of the newly designed nozzle which consists of two different elements for twin-fluid atomizer.

Introduction

Twin fluid atomizers are typically used in steam boilers in which heavy fuel oils have to be atomized. Having in mind the constant reduction in the fuel oil quality, which is becoming heavier and much more viscous, an improvement in the design of this type of nozzles is required in order to obtain similar efficiencies in the atomization process; reducing at the same time the steam consumption.

In the last years the influence of several parameters on liquid atomization has been analyzed, and many statistical correlations have been obtained [1]. The influence of a group of parameters on spray angle was studied by Ruiz and Chigier [2]. The principal results showed a strong influence of the geometric characteristics such as orifice diameter and nozzle length. Ballester and coworkers [3] studied the influence of the nozzle geometry and exit orifice diameter on the discharge coefficient and spray angle using a high-speed photographic technique. In this research a wide range of the atomizer dimensions was covered, and some statistical correlations were obtained for the main parameters under study.

Numerical modeling of twin fluid atomizers has also been attempted. Tapia and coworkers [4] studied the flow behavior of a Y-type nozzle both experimentally and numerically. An experimental facility was designed in order to visualize the internal flow structure in the mixing chamber of the nozzle. An oil with the same properties as the heavy fuel and compressed air were used as both the atomized and the auxiliary fluid respectively. The numerical modeling of the mixing chamber, using the FLUENT code was achieved as well. The results obtained have shown the importance of the flow direction of the different fluids in the internal mixing process on the atomization quality. The visualization results showed that only a part of the fuel is atomized by the air flow while the rest of the liquid flow moves close to the wall forming a thin film which breaks into big droplets downstream of the nozzle exit. Both, experiments and simulation demonstrated that the mixing process is improved when increasing the fuel angle. The main results point out the necessity to design new nozzles in order to improve the efficiency of the atomization process.

In spite of that, the knowledge of the behavior of twin fluid atomizers is quite limited because of the complexity of the involved processes. It is for this reason that an experimental study has been performed in order to investigate the influence of both geometrical characteristics and fluid parameters on the performance of an internal-mixing air-assisted nozzle. For this study, the test has been performed using a laboratory scale facility, analyzing the influence of water and air pressures on the mass water flow, the spray angle and the quality of the spray, for different nozzle geometries. Finally, two of the nozzles have also been tested on a real situation in a power plant, burning a heavy fuel oil.

Experimental facilities

In the present experimental research, several Y-type nozzles have been tested, using both a laboratory scale facility (LSF) and an industrial boiler. The LSF is a horizontal test rig specifically designed to test air-assisted nozzles. In this case, the fluids (water as the atomized fluid and air as the atomizing one) are supplied to the atomizer by two different pipes; one for air with an internal diameter of 35 mm and another, with an internal diameter of 52 mm, for water. A compressor, with a maximum gauge pressure of 0.7 MPa, provides the air. The water is supplied by a pump with discharge pressure around 2 MPa. Taking into account the maximum fuel oil atomization pressure and the flow conditions for the real practical application in the boiler, the experimental requirements for the water flow were limited to a maximum pressure of 1.55 MPa, and a flow rate of 7 m^3/h. The pressures are measured with two manometers and the water flow with a flow meter. The set is also equipped with a digital photographic camera SONY MAVICA 92 for the spray visualizations. The reported angle corresponds to the tangent of the spray at an axial distance of 260 mm from the nozzle exit. Finally, the air flow was measured with a Pitot tube previously calibrated.

In the first stage of the research, a total of 189 experimental tests have been performed analyzing the influence of the water (p_w) and air (p_a) pressures on the water mass flow rate (G), spray angle (2θ) and spray quality (SQ), for different nozzle geometries. The air flow and the air-water ratio were measured only for the better performance nozzles (**1** and **4**) in some other auxiliary experiments. Spray angle and spray quality have been analyzed through video images and photographs. The three evaluated pressures for the air flow were selected to be close to those used in the real situation for the steam in the industrial boiler.

The study has been completed testing the commercial nozzle in an industrial boiler at the “Antonio Guiteras” Power Plant, burning a heavy fuel oil. The main fuel characteristics were evaluated during the tests. In this case, the value of the kinematic viscosity fluctuated between 0.0017 and 0.0012 m^2/s, at a constant temperature of 50 ^oC, and the density, at 30 ^oC, gave a roughly constant value of 995 kg/m^3. The tests were performed in the normal operational conditions of the Plant along three days. The behavior of nozzle **4** could not be tested in these boiler conditions because of the strict security rules in the Power Plant. Therefore its performance was simulated with a computer code. As an alternative, using the dimensional analysis, as well as the results obtained from the LSF tests, nozzles **1** and **4** were re-scaled and built to be used in a boiler with a capacity ten times lower than those used for the atomization tests. Their performance was first also analyzed in LSF, obtaining similar result relative to those obtained for the same nozzles in their original dimensions. At this moment they have been tested in an industrial boiler at the “José Martí” Power Plant.

Four different types of nozzles have been studied, divided into two main configurations. The first one, which includes the first two nozzles, is a commercial-type nozzle with eight exit slits as depicted in Fig. 1. The second group (two other nozzles) presents a similar configuration but the number of inlet fuel slits to the swirling chamber was reduced from 8 to 6, keeping a constant volumetric flow. The structure of the last two nozzles consists of two separated elements, making the maintenance task easier. As a peculiarity, the cross-section of the fuel holes has been changed from cylindrical to rectangular (see Fig. 2). The external piece is formed by a conical cavity (1) with the exit holes (3) in its upper part. The internal part fits in the cavity and includes six rectangular slits of variable section for fuel (4) with their respective bottom holes for steam (5) and an additional central hole for the remaining steam flow (6). The combination of both internal and external elements forms a swirling chamber (2), which further improves the spray quality. It should also be noted that, in all cases, the total flow area for fuel and steam at the inlet and exit slits has been preserved.

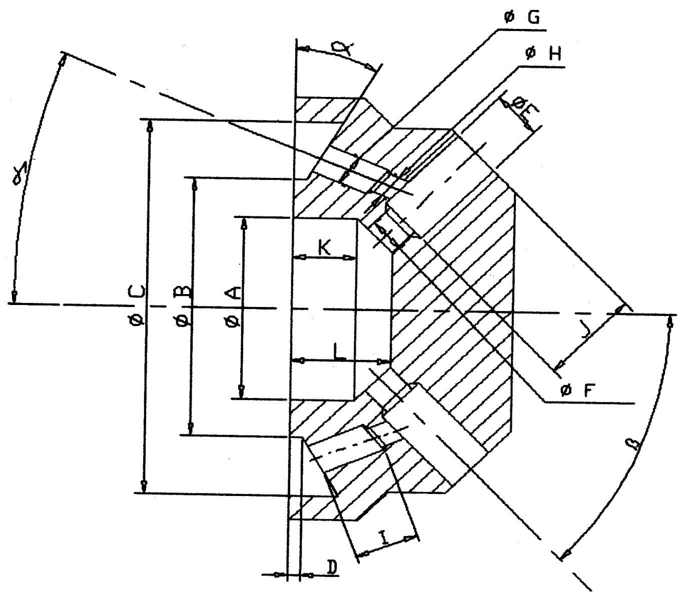


Figure 1: Commercial nozzle “Y”-type

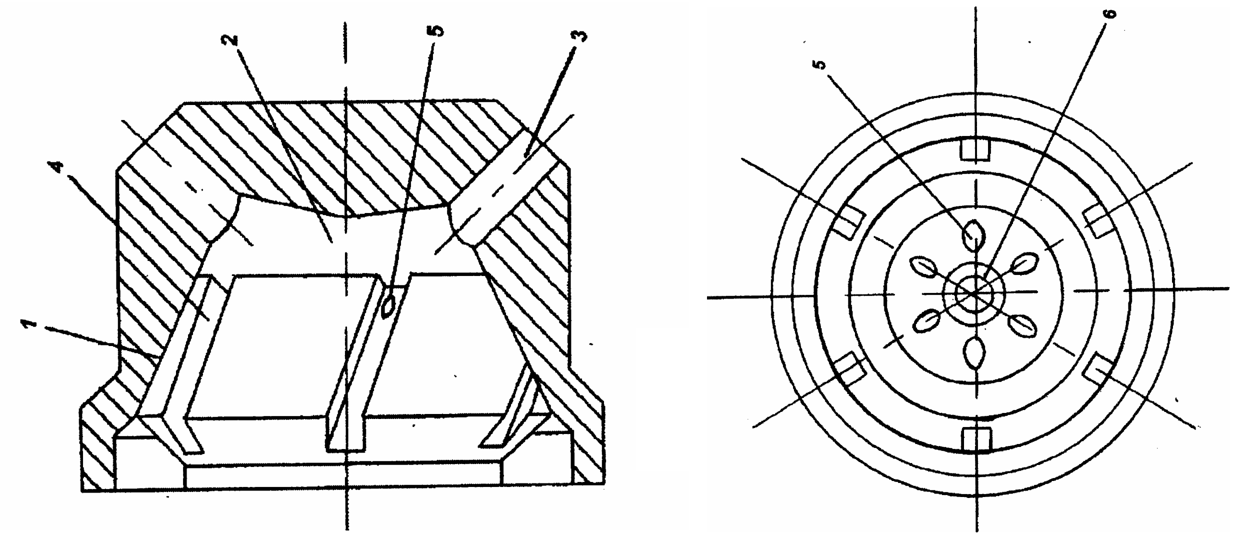


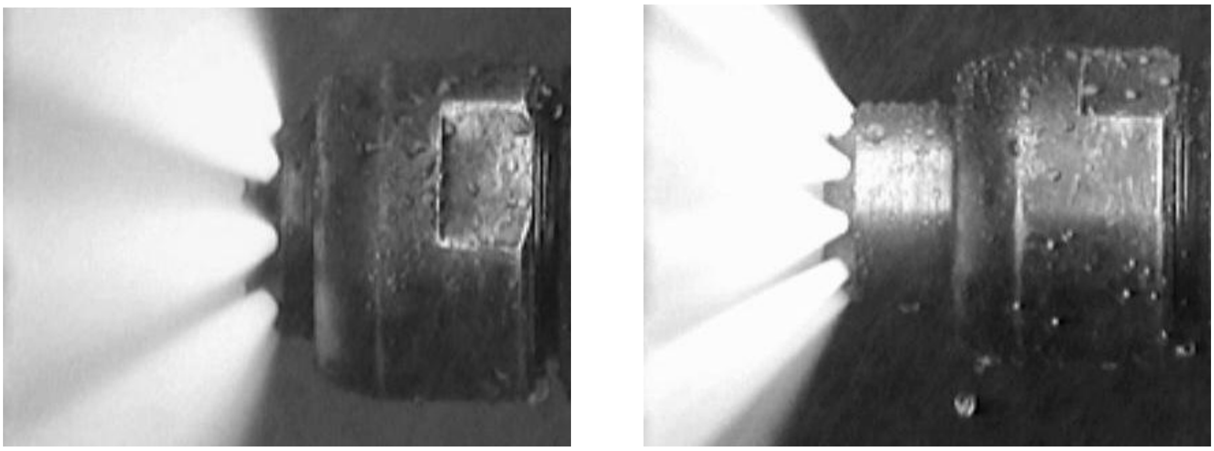
Figure 2: Sketch of new nozzle design divided into two elements

Test results

The average values for each experimental test in LSF are presented in Table 1. As expected, the water flow rate (*G*) increases with water pressure. A different behavior is observed for the spray angle respect to the air and water pressure for the two groups. In the commercial nozzles (**1** and **2**), the spray angle increases with water pressure and decreases when the air pressure is reduced. However, in the newly designed nozzles (numbers **3** and **4**) it can be noted that for low air pressure the spray angle rises with water pressure, but for high air pressures a slight reduction or insensitivity to these parameters is observed. On the other hand, a better visual spray quality (*SQ*) is reached for higher air pressure, even for the higher water flow conditions for the new nozzles. In this entry, *VG* means a "very good" spray quality, *G* "good" and *P* "poor", depending on the visual characteristics of the spray. As a rule, the lower the air pressures the worse the atomization quality.

		p_a (MPa)											
		0,1				0,3				0,5			
Nozzle 1	p_w (MPa)	2θ	*G* (kg/s)	*Air-water ratio*	*SQ*	2θ	*G* (kg/s)	*Air-water ratio*	*SQ*	2θ	*G* (kg/s)	*Air-water ratio*	*SQ*
	1,15	121,0	1,444	0,028	G	117,5	1,334	0,033	G	113,2	1,317	0,034	VG
	1,35	120,5	1,558	0,028	P	117,5	1,483	0,032	G	114,6	1,444	0,033	VG
	1,55	129,0	1,667	0,029	P	121,0	1,616	0,030	P	114,6	1,522	0,034	G
Nozzle 2		0,2				0,4				0,6			
	1,15	114,6	1,460	-	P	112,6	1,419	-	P	109,0	1,281	-	G
	1,35	114,6	1,580	-	P	119,4	1,566	-	P	119,4	1,460	-	G
	1,55	121,0	1,667	-	P	121,0	1,667	-	G	120,5	1,631	-	G
Nozzle 3		0,3				0,5				0,7			
	1,15	97,5	1,403	-	G	92,3	1,386	-	VG	97,5	1,343	-	VG
	1,35	106,9	1,522	-	G	95,6	1,499	-	G	95,6	1,476	-	VG
	1,55	102,7	1,623	-	R	98,8	1,602	-	G	92,3	1,579	-	VG
Nozzle 4		0,3				0,5				0,7			
	1,15	106,1	1,483	-	G	115,4	1,411	0,015	VG	111,1	1,308	0,017	VG
	1,35	114,0	1,573	-	P	111,1	1,550	0,014	VG	111,1	1,460	0,016	VG
	1,55	-	-	-	-	111,1	1,667	0,014	G	111,1	1,616	0,015	VG

Table 1. Tests results for LSF experiments



a) **b)**

Figure 3: Photographs of the atomization test for **a) Nozzle 1** (commercial type) and **b) Nozzle 4** (new design) for the same experimental conditions (see text)

The results displayed in this table, together with those obtained from the spray photos and videos have shown that the best performance is attained for nozzle number **4**, corresponding to one of the new designs. In Figure 3 two photographs of the atomization tests obtained for nozzles **1** and **4** are depicted. In this case, the same experimental conditions have been established, corresponding to a constant water pressure of 1.35 MPa and an air pressure of 0.5 MPa, giving an air/water ratio of 0.033 and 0.014, respectively. It was observed that for the case of nozzle **4**, the new design, the same atomizing condition are obtained with less than half of the air flow compared to the commercial nozzle **1**. This is an important result because it implies a reduction in the steam consumption in the case of the fuel atomization in the boiler.

Figure 4 summarizes the results of the influence of water pressure on air-water ratio for both the commercial and the new design nozzles (**1** and **4**), respectively, for different values of the air pressure. The reduction of the air flow needed to achieve the same quality in the atomization process is the most important aspect to be highlighted, which corroborates the conclusion previously obtained in the atomization experiments. The behavior of the spray angle versus water pressure is showed in Figure 5. The results indicate that this parameter was always above the recommended limits for all the experimental conditions tested, even in the case of the new designed nozzles. This result contributes to the selection of the nozzle **4** for the final industrial studies.

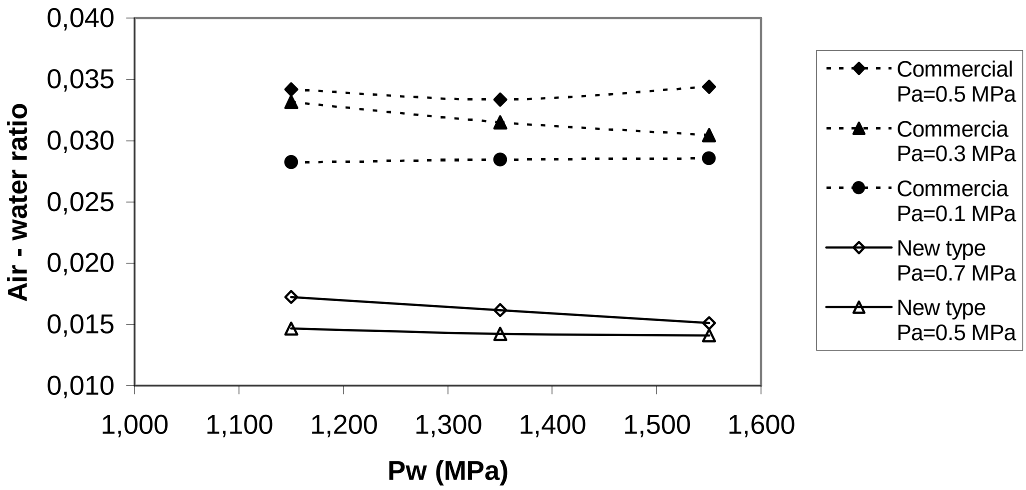


Figure 4. Relation between water atomizing pressure and air-water ratio

The full set of 16 commercial nozzles installed in the steam boiler at the “Antonio Guiteras” Power Plant was previously tested in the LSF. As commented before, the industrial tests were performed fixing in the boiler the nominal operational conditions. Measurements of the different parameters were collected every 15 minutes during 8 hours from the computer control unit in each test. Two additional measurements were also carried out, the determination of the exhaust gas composition using a TESTO 360 gas analyzer and the fixed carbon loss evaluation, using the Bacharach method. In Table 2 only the average values of the main parameters in the tests are displayed. The efficiency (η) was calculated with the mean values, using the AUDIT computer code [5].

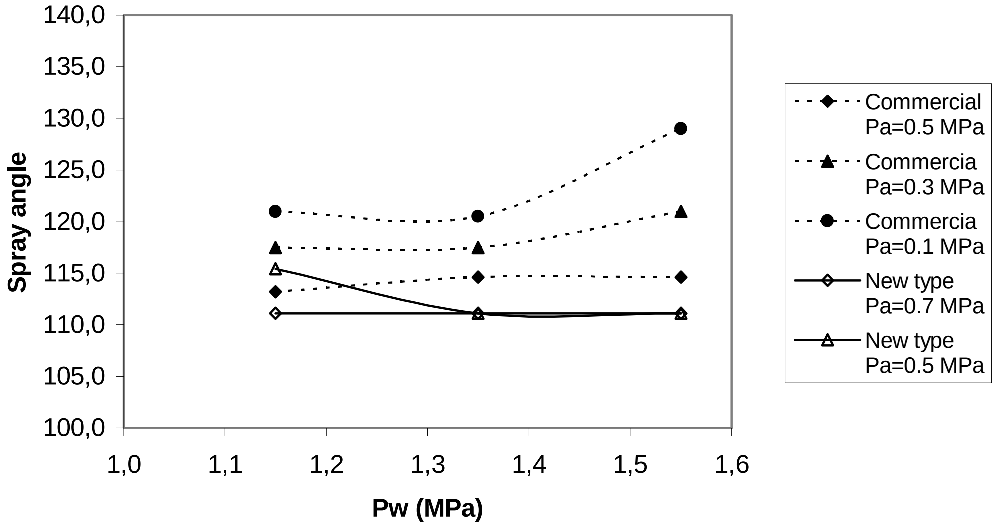


Figure 5. Behavior of the spray angle (2θ) versus water atomizing pressure

In Table 2 numerical simulations of the boiler behavior when nozzle number **4** is considered in the atomization process are also included. The simulation of the heat transfer process for all heat transfer surfaces in the boiler was carried out with a custom-made computer code, BOILER [6] based on the TKSOLVER software [7]. As a first stage in the study, the combustion conditions measured in tests performed when the commercial nozzles were installed in the boiler was taken into account, considering a similar spray quality for both nozzles. However, the real steam-fuel oil ratio (air-water ratio) obtained in the laboratory scale experiments for nozzle number **4** has been modified in the simulation process.

Name	Test	Simulation	Unit	Comment
Nozzle	Commercial **(1)**	New design **(4)**		
G_{ato}	0,03	0,016	kgs/kgf	Atomization steam flow
D_{sc}	270,56	270,56	kg/s	Super heater steam flow
D_{ri}	243,44	243,44	kg/s	Reheater steam flow
P_{sc}	16,67	16,67	MPa	Superheated steam pressure
t_{aa}	245,00	245,00	C	Water fitting temperature
t_{fuel}	140,00	140,00	C	Fuel temperature
t_{gexit}	155,14	155,47	C	Exhaust gas temperature
r	0,18	0,18	-	Recirculated gas ratio
α_{exit}	1,13	1,13	-	Stoichiometric ratio
Q_d	41116,85	41116,90	kJ/kg	Total heating value
q_2	5,59	5,59	%	Exhaust gas loss
q_3	0,17	0,17	%	Chemical carbon loss
q_4	0,10	0,10	%	Fixed carbon loss
q_5	0,20	0,20	%	Conduction heat loss
η	93,94	93,94	%	Overall efficiency
B	69,25	69,21	t/h	Fuel consumption
D_{By}		333,44	t/year	Fuel saved due to efficiency
dBy		379,23	t/year	Fuel saved (steam reduction)
B_{saving}		712,67	t/year	Total fuel saved
USD_{saving}		106900,33	USD/year	Money saved

Table 2 Commercial nozzle tests in an industrial boiler and computing simulation for nozzle 4.

If one compares the results displayed in Table 2 it is clear that the reduction of the steam-fuel ratio in the atomization process to half of the ratio needed for the commercial nozzle (**1**) does not affect either the exhaust gas temperature or the boiler efficiency. However the fuel consumption is reduced due to the increase in the total heating value caused by the lower steam fraction in the exhaust gases according to the atomization heat inlet calculation.

The yearly fuel and money saved have also been displayed in the last rows of Table 2, considering a fuel cost of 150 USD/t. The difference in fuel consumption between the two nozzles is reported in the variables named “Fuel saved due to efficiency” and “Fuel saved (steam reduction)” which takes into account the savings due to the reduction in steam consumption in the atomization process. A total saving of 106 900 USD per year is estimated, but this value could be increased if the reduction in the maintenance costs for the new designed nozzle is taken into account.

In the different tests performed it was noticed a slightly better behavior of nozzle **4**, but some other industrial test are required for more reliable results. It is for this reason that this nozzle was scaled down around ten times in order to be tested in a boiler with a lower capacity, yielding excellent results when a heavy fuel was used. At this time they have been installed in 6 burners of one of the steam boilers at the “José Martí” Power Plant. The even preliminary industrial tests performed shown that indeed the new atomizer compares favorably respect to the commercial “Y-type” used previously in the power plant, decreasing the boiler fuel consumption for the same boiler efficiency. Tests at the power plant are still ongoing in order to obtain final conclusions regarding the overall boiler efficiency.

Conclusions

Some experiments have been performed in order to study the behavior of different types of internal mixing air-assisted nozzles for heavy fuel oil burners. The relation of fuel and steam pressures with spray cone angle and steam-fuel ratio has been analyzed. Two different geometry nozzles have been compared with the commercial ones.

The capabilities of the new nozzle design consisting of two different elements for twin-fluid atomizer have been demonstrated. At the same time, experiments and simulations have confirmed several advantages of one of the new designs (nozzle number **4**) when burning heavy fuel oil, resulting not only in fuel economy, but also in a reduction in the operational and maintenance costs of the boiler. More tests with this new nozzle are still ongoing in some industrial boilers.

As a future issue, measurement of droplet diameters with a Malvern MASTERSIZER diffractometer will be carried out in cooperation with researchers of the Laboratory for Research in Combustion Technology (LITEC/CSIC) in the next months.

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