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Analysis and prediction of the spray produced by an internal mixing chamber twin-fluid nozzle

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ABSTRACT

Internal mixing chamber twin-fluid nozzles can advantageously replace traditional Y type nozzles to atomize high viscosity fluids. This is the case of power plants consuming heavy crude oils, where the use of this type of nozzles allows to obtain the smallest possible droplets with reduced gas flow rates. This work, based on previous experiments and new additional results, analyzes the flow in a specific twin-fluid nozzle of our own design and finally proposes some correlations to describe the flow conditions inside the mixing chamber, and subsequently, the characteristics of the final spray, represented by its Sauter mean diameter (SMD). These correlations include all the relevant variables, and the influence of each of them is discussed for different values of the inlet variables. Particular attention is focused on the situation in which the gas entrance to the mixing chamber is choked. The analysis and procedures here described could be easily applied to any twin-fluid nozzle with an internal mixing chamber.

1. Introduction

Atomization is essential to improve combustion efficiency and so, to reduce pollutant emissions, especially in power plants [1–3], and consists in the breakup and disintegration of a liquid mass into small droplets [4,5]. Atomization processes can be classified according to the way in which the liquid kinetic energy is increased to produce the instabilities that end up causing the drop formation. This energy increase can be associated to pressure in pressure atomizers, shearing forces in twin fluid atomization, centripetal forces in rotary cups, electrostatic forces, or ultrasonic waves, among others. Although studies on atomization and its applications are not new, the interest in the design and performance of atomizers, airblast atomization in particular, did not arise until mid-1960s, when their potential for achieving significant reductions in soot formation and exhaust gases became very important [4].

For the last years, our research group has worked on the design of a new internal mixing twin-fluid nozzle to atomize high viscosity fluids [6–11], replacing the standard Y type model [12–14]. In typical Y nozzles each one of the multiple independent exit orifices is connected to a liquid and a gas conduct that join together prior to the discharge. On the contrary, in the alternative design gas and liquid mix in a common chamber that communicates with all the discharge orifices. When a homogeneous mixing between the two fluids is achieved, the resulting spray is formed by droplets with smaller Sauter mean diameters (SMD) than those obtained with Y type nozzles for the same liquid flow rate. Additionally, the required gas flow rate to obtain the desired results is also lower. As a further advantage, the design concept notoriously reduces the nozzle cleaning and maintenance tasks. All these characteristics make the new nozzle ideal to be installed in combustion chambers of fuel oil power plants, application that was the origin of the initial project. In previous studies, the nozzle was experimentally analyzed, first measuring gas and liquid inlet pressures and flow rates, relating them to droplet size distributions, characterized by the SMD as is customary in combustion applications. To understand the operation principles, the internal flow was also visualized. These data were used to optimize several geometrical parameters such as the gas inlet area and the chamber dimensions [11].

Among the many characteristics that define a spray, such as droplet velocity, gas entrainment rate, spray unsteadiness, cone angle, or spray penetration, engineers working at industrial power plants are mainly interested on how the resulting SMD is affected by the operating conditions for a given fuel oil. This is why researchers have developed a wide range of correlations that can help to predict this parameter with more or less accuracy. Focusing the analysis on twin-fluid nozzles with internal mixing chamber that behave as effervescent atomizers, SMD models usually include operating conditions (differential pressure, air-to-liquid mass flow rate), fluid properties (surface tension, density, viscosity), and atomizer geometry (mainly the diameter of the discharge orifices). In most models, SMD mainly depends inversely on ALR and operating

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Nomenclature

Latin symbols

A	flow area, m^2
ALR	air–liquid mass flow ratio
c	speed of sound, m/s
C_d	discharge coefficient
d	diameter, m
g	gravity acceleration, m/s^2
h	mixing chamber height, m
H	height between inlet and exit, m
k	loss coefficient
K	steam specific heat ratio
$\dot{m}$	mass flow rate, kg/s
Ma	Mach number
p	pressure, bar
Q	volumetric flow rate, m^3/s
R	universal gas constant, J/(mol K)
Re	Reynolds number
SMD	Sauter mean diameter, μm
SFR	steam-to-fuel oil mass flow ratio
T	temperature, °C
V	velocity, m/s

Greek symbols

γ	air specific heat ratio
μ	viscosity, Pa-s
ρ	density, kg/m^3

Subscripts

0	stagnation
a	air
atm	atmospheric
cal	calibration
cham	chamber
cr	critical
e	exit
f	fuel
facility	from the experimental facility
in	inlet
max	maximum
meas	measured
nozzle	relative to the nozzle
s	steam
stat	static
w	water

pressure [15–18], as in standard twin fluid atomization. With respect to fluid properties, most models claim that SMD is nearly independent of viscosity [16,19,20] and surface tension [16,20]. The role of density is not so clear. In general SMD is assumed to approximately depend on $1/\rho$ [21–23], although other models propose a very weak dependence [24] or even a total independence [16].

In the present work, previous measurements have been compiled and joined to some new additional results to develop a correlation that can be used to predict, first, the conditions of the flow inside the mixing chamber, and as a final objective, the mean diameter of the resulting spray. The model includes all the relevant variables, and the influence of each of them is discussed for different operating conditions. Particular attention has been focused on the situation in which the gas entrance to the mixing chamber is choked, as this has been reported to be the determinant for the nozzle efficient performance [10]. The analysis should be valid for different internal mixing nozzles operating under similar initial conditions.

2. Experimental set-up

To understand the results on which this study is based, a brief comment on the experimental facility, the atomizing nozzle and the measurement techniques is required. The facility has already been described in detail in previous papers [9–11], and only a summary will be included here.

2.1. Test rig

All the measurements were obtained in the test rig shown in Fig. 1, using air and water as the atomizing and atomized fluids respectively. Air was supplied by an Ingersoll-Rand SSR-ML 22 compressor capable of circulating a maximum flow rate of 100 Nm^3/h at a maximum exit gauge pressure of 8 bar(g). A Deloule GE105/900 piston pump was used to feed the water, with a maximum gauge pressure of 100 bar(g), and a maximum flow rate of 1500 l/h. The experimental conditions covered those at a Cuban power plant. In the experiments, for a constant water flow, different air flows were established. For each experimental condition, inlet water and air gauge pressures were simultaneously measured. Airflow was measured with a rotameter ranging from 9 to 90 Nm^3/h, with a precision of 2 Nm^3/h. The gauge used to measure its inlet pressure was capable of detecting variations from 0 to 10 bar with a precision of 0.1 bar, although for low values, a more precise 0–4 bar manometer was used. On the other hand, water flow was measured with a flow meter with a range extending from 100 to 1000 l/h and a precision of 50 l/h. The corresponding Bourdon manometer used to measure the inlet water pressure had a range from 0 to 10 bar, and a precision of 0.1 bar.

It is important to note that water and air had to be used in the laboratory tests as atomized and atomizing fluids, respectively, due to some restrictions imposed by safety regulations. Substitution of the working fluids is very common in this type of analysis as it has been extensively discussed [21], but to extrapolate the absolute droplet diameter values obtained for water and air to other gas/liquid combinations a suitable dimensional analysis has to be previously performed, considering the influence of the physical properties of the fluids, as well as the operating conditions.

2.2. Atomizer

The new nozzle is formed by two pieces that fit one inside the other forming an internal mixing chamber, as depicted in Fig. 2. The outer part is a conical hollow piece with 8 cylindrical exit holes with a diameter of 3.5 mm. The inner part has a truncated-cone shape with 6 swirl slots with a rectangular cross section and a central orifice that supplies the air to the internal mixing chamber, with a diameter (d_a) initially established at 4 mm. The piece height is 16 mm, enabling a mixing chamber height (h) of 6 mm. The liquid ports are slanted 20° with respect to the axis of the nozzle. Although some of these geometrical parameters were modified in different previous studies, the dimensions here described constitute the base case, and are the ones that will be considered in the present analysis.

2.3. SMD determination

As in most combustion applications, the spray has been primarily characterized analyzing the SMD derived from droplet size distribution measurements. They were obtained with a Malvern Spraytec diffractometer coupled to the experimental rig. The cylindrical measurement volume, which has a diameter of 9 mm, was located at 14.7 cm (42 d_e) downstream from the nozzle exit, crossing a single jet exiting from