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Design optimization of twin-fluid atomizers with an internal mixing chamber for heavy fuel oils

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ABSTRACT

The present work is devoted to determine the magnitude of the main parameters that yield the optimum results for twin-fluid nozzles with an internal mixing chamber. The focus is placed on the study of the interaction of both air and liquid flows at the internal chamber and its effects on the resulting spray. To this end, some experiments have been performed for different air central channel diameters and liquid ports, as well as for several experimental conditions (air and liquid mass flow rates), in order to understand the influence of the flow conditions at the mixing chamber on the size of the droplets produced. It has been demonstrated that under certain experimental conditions the atomizing fluid discharged to the internal chamber is choked. The sonic condition is achieved for different air and liquid mass flow rates as a function of the air central channel diameter. It has also been obtained that to achieve the best results with moderate atomizing fluid flow rates, it is convenient to operate in choked conditions. This is an important result that will help in the optimum design of this type of nozzles.

1. Introduction

A spray is formed when a liquid volume is fragmented into a cloud of droplets with different sizes, usually either by effects of its own kinetic energy or by interaction with a high-velocity air or steam co-flow. Basic studies on atomization processes initiated in the XIX century [1,2], partly because it is indubitable that they are determinant in the performance of liquid fuel-fired combustion systems [3]. Nowadays the energy production all over the world is provided above 90% by combustion of fossil fuels, and a similar scenario is expected in the foreseeable future [4]. Oil reserves are decreasing alarmingly, and prices are rising in accordance. These facts combined with the existence of a world natural reserve of bituminous petroleum three times higher than that of regular fuel oils, have motivated the change to heavy fuel oil in most boilers at electric power plants. Unfortunately, combustion of lower quality fuels has a negative impact on the global environment with higher contributions to greenhouse gas emissions, air pollution, acid rain and other health hazards.

As an example, in Cuban power plants the light fuel oils previously used in their boilers have been replaced by crude native petroleum. In this type of fuel the values of some of the parameters with major influence on the atomization and combustion processes are out of the ranges recommended by the nozzle and boiler manufacturers. Kinematic viscosity, for example, reaches values as high as 1.546×10^{-3} m^2/s at 50 °C and 0.255×10^{-3} m^2/s at 80 °C. In order to produce a fine spray this variable is recommended to be around 4.5×10^{-5} m^2/s, which requires heating the fuel up to 130 °C. Asphaltene

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Nomenclature

a	Numerical constant in Eq. (9)
A_a	Air central channel sectional area [m^2]
A_l	Total area of the liquid ports [m^2]
ALR	Air-to-liquid mass flow rate ratio
d_d	Diameter of the discharge orifice [mm]
D	Droplets diameter [mm]
$F(D)$	Droplet size distribution function in Eq. (7)
k	Constant in Eq. (8) [kg/(h-mm^2)]
k^{SP}	Single-phase flow constant in Eq. (9) [kg/(s-m^2)]
M	Mach number
M_a	Air molecular weight [kg/mol]
$\dot{m}_a$	Air mass flow rate [kg/h]
$\dot{m}_l$	Water mass flow rate [kg/h]
p_{a_o}	Stagnation pressure [bar]
p_{a_i}	Absolute air flow pressure [bar]
$p_{a_{stat}}$	Static pressure [bar]
P^{SP}	Air pressure at standard conditions [bar]
Q'_a	Measured inlet volumetric air flow rate [Nm^3/h]
Q_{a_i}	Corrected inlet volumetric air flow rate [m^3/h]
Q_l	Volumetric flow rate for the water fluid [m^3/h]
R	Universal gas constant [J/(mol K)]
SMD	Sauter mean diameter of the spray [μm]
T_{a_i}	Absolute air flow temperature [K]
T^{SP}	Air temperature at standard conditions [K]
ρ_a	Air density [kg/m^3]
ρ_l	Liquid density [kg/m^3]
γ	Air specific heat ratio

contents are also high, roughly doubling the recommended limits. Atomizing adequately this native petroleum is very difficult, and has become a challenge. In practice, there are many ways to generate a spray using, for example, spinning cups [5], twin-fluid [6], pressure swirl [7], fan [8], ultrasonic [9] or effervescent atomizers [10], forming solid or hollow cones of droplets. However, for large-scale facilities such as boilers and industrial furnaces, the atomizers most commonly used are the steam-assisted nozzles with a "Y" configuration [11,12], which can be operated either keeping a constant steam-to-fuel flow rate ratio or a fixed fuel-to-steam pressure ratio.

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 [13]. In a previous study [14], it has been demonstrated that, for the same liquid mass flow, this nozzle requires a lower atomizing fluid mass flow rate than an equivalent "Y" type one, 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 high 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, that could reach the boiler walls. This situation produces the emission of large quantities of pollutant gases and solid particles.

The present work concentrates in the study of the behavior of the flow of both air and water in a twin-fluid nozzle with an internal mixing chamber, pointing the attention on the optimization of some geometrical parameters that have a considerable influence on its correct performance. So, 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 liquid ports geometries, as well as for various air and liquid volumetric flow rates. Results obtained will help in the optimal design of this kind of nozzles.

2. Experimental facilities and measurements techniques

In order to carry out a complete analysis of the two fluid flows inside the nozzle, experimental measurements of some specific parameters are needed. For this reason, several devices and techniques 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, requiring a nominal flow of 1 t/h to generate the specified electric power using