PERFORMANCE OF TWIN-FLUID NOZZLES WITH AN INTERNAL SWIRL CHAMBER

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ABSTRACT

The aim of this work is focused on the characterization of the behavior of large capacity multi-hole industrial twin-fluid atomizers. Sauter mean diameter, discharge coefficient and air-to-liquid mass flow ratio are the parameters that have been selected for the experimental study. Two kinds of nozzles have been tested: a commercial "Y"-jet type and a new-concept twin-fluid nozzle with an internal swirl chamber. This new-concept nozzle, which is specifically designed to atomize crude petroleum in power plants, is formed by two different pieces, which ease cleaning and maintenance tasks. The best performance has been obtained for the new-concept nozzle without "Y"-ports in the internal part, yielding smaller droplets with a lower air mass flow rate. A non-dimensional relationship between the *SMD*-to-air core diameter at the exit holes (d_{ao}) *versus* the air Reynolds number, also defined with d_{ao}, has been found. This non-dimensional relationship reproduces very well the experimental measurements for the whole range of atomizing conditions, which includes the actual power plant operating conditions.

1. INTRODUCTION

Atomization is the key process of the behavior of liquid fuel-fired combustion systems. Nowadays the total energy production in the world is mainly provided by combustion of fossil fuels. Despite the enormous effort that researchers have performed in many fields in order to find other alternatives for energy production such as windmills, solar energy, tidal power, etc., the strong dominance of fossil fuel combustion will continue in the foreseeable future, as the world energy production is expected to be raised. As it is known, hydrocarbon combustion has a major impact on global environment due to the emission of gas and solid particles, which cause air pollution, "greenhouse" effect, acid rain and other health hazards. The production of a cloud of droplets with smaller sizes improves the fuel oil evaporation rate, yielding higher combustion efficiency, very stable flames and reducing the emission of pollutants.

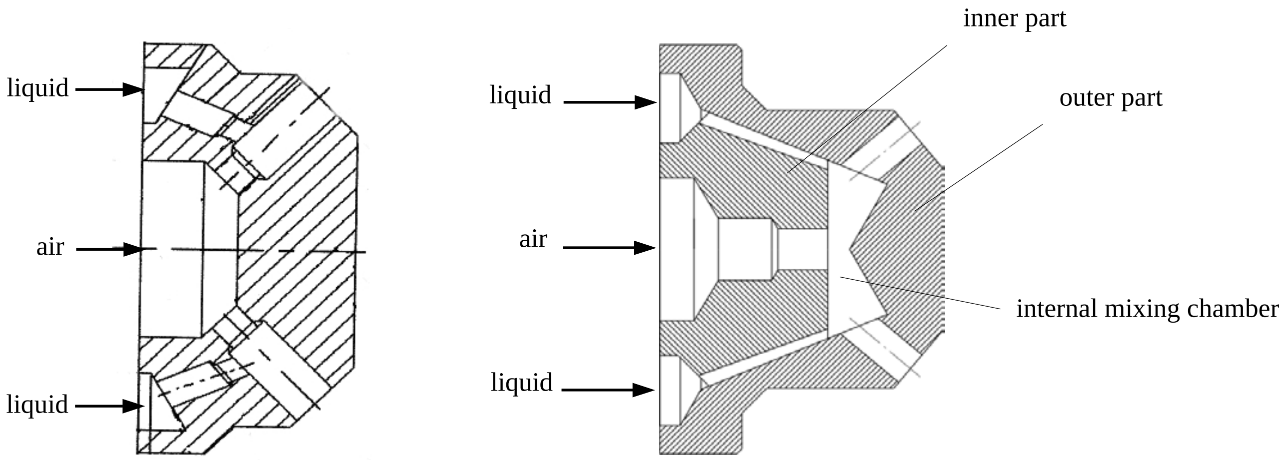
In most cases, liquid fuel volume can be disintegrated by effects of its own kinetic energy or by interacting with a high-velocity air or steam co-flow. In practice, there are many ways to generate a spray using, for example, rotary cups [1], twin-fluid [2], pressure swirl [3], fan [4], ultrasonic [5] or effervescent atomizers [6], forming solid or hollow cones of droplets. However, for large-scale facilities such as boilers and industrial furnaces, where large amounts of very viscous fuel oil have to be handled, the numbers of methods capable of giving a reasonable efficiency are dramatically reduced. In these practical situations, one of the nozzles most commonly used is the steam-assisted type with a "Y" configuration [7,8]. It generally consists of some jets (from 2 to 20) arranged in a ring-shaped layout to generate a hollow conical spray. In each individual "Y", fuel oil is injected at an angle into the exit port, where it mixes with the atomizing fluid (steam). These atomizers are operated either keeping a constant steam-to-fuel flow rate ratio or a fixed fuel-to-steam pressure ratio. A well-known drawback of these nozzles is that, in order to produce a fine spray, a relative large amount of steam is needed, resulting in a lower flame temperature and a reduction in the ignition temperature. So, a very long, flicker, unstable and sooty flame is generated, with a reddish-yellow color, which interacts with the boiler walls. This situation produces the emission of large quantities of pollutant gases and solid particles.

The increasing consumption of petroleum-derived liquids as fuel has resulted in a reduction in the quality of the residual oils that are becoming heavier, as well as an increase in price of regular fuel oil. 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 boilers at power plants. Cuba is a clear example of such countries. The deep economic crisis in which the country is immersed has motivated the change of commercial fuel oil by native crude petroleum in all the power plants. Combustion of heavier fuel oils with higher levels of viscosity, asphaltenes and Conradson carbon, cause an undesirable increase in the spray average droplet size if no other actions are taken to improve the atomization process. Under these conditions, to produce a spray for heavy fuel oil or crude petroleum with the same quality as that generated with lighter oils has became in a challenge for engineers and researchers all over the world.

The present work is focused on the analysis of the behavior of large-capacity industrial twin-fluid atomizers. Sauter mean diameter, discharge coefficient (*CD*) and air-to-liquid mass flow ratio (*A.L.R*) are the main parameters that have been selected in the experimental characterization of the atomizers performed in this study.

2. DESCRIPTION OF THE EXPERIMENTS

Two different nozzle types have been characterized in this study, both intended to be used in a power plant burning heavy crude petroleum: a commercial “Y”-jet nozzle and a newly-designed one with an internal mixing chamber. The commercial “Y”-jet nozzle is similar to that recommended by the boiler manufacturer when a lighter fuel oil was used. A sketch of this nozzle is depicted in Fig. 1 a). Atomizing fluid is supplied through the central channel and is divided into six jets, one for each individual “Y” branch. In each “Y”, liquid and atomizing fluids strongly interact to generate instabilities in the liquid flow that further cause the breakup into droplets forming the spray. The 6 exit ports are uniformly spaced around the atomizing body with an exit diameter of 4 mm, yielding a nominal fuel oil flow rate of 1 t/h. In all the experiments water and air have been used as the liquid and atomizing fluid, respectively.



a) b)

Figure 1. Sketch of the two nozzles used in the experiments: a) original “Y”-jet atomizer, and b) new-concept nozzle

The new-concept nozzle has been specifically designed to replace the “Y”-jet atomizer. It is formed by separated elements, an inner and an outer part, that form an internal mixing chamber when assembled [9]. A sketch of the assembly of the two parts of this nozzle is shown in Fig. 1 b). The inner piece has a truncated-cone shape with 6 swirl slots with rectangular cross section slanted 20° with respect to the axial direction. The inner diameter of the air central channel is 10 mm, which is reduced to 4mm when the air flow is discharged to the mixing chamber. The outer part is a hollow conical piece designed to receive the inner part. It has 8 cylindrical exit holes with a diameter of 3.5 mm. Two different internal pieces have been used, as depicted in Fig. 2. In the first one, Fig. 2 a), all the air flow is supplied to the internal swirl chamber through the air central channel, while in the other, Fig. 2 b), a part of the air flow is diverted and pre-mixed with the liquid flow in the swirl slots. In this case a similar configuration to the “Y”-jet nozzles is formed inside the nozzle. As these new nozzles have been manufactured to replace the original “Y”-type in the boiler, a similar liquid flow rate of 1 t/h has been considered during their design and construction.

a) b)

Figure 2. Two different internal pieces used in the experiments: a) without “Y” ports, b) with “Y” ports

The nozzles have been tested in a test rig with controlled volumetric flow rates and inlet gauge pressures for both air and liquid flows. Air is injected with a multistage compressor capable of delivering a maximum flow rate of 100 m^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 and a steam pressure (atomizing fluid) of 7 bar are achieved. The resulting two-phase flow of droplets and atomizing air is collected in an extraction container. Water is re-circulated with a centrifugal pump to the main tank, and an extraction fan is connected to the container to ensure stable flow conditions, avoiding droplet re-circulation to the measurement volume.

In the present experiments, for a constant water flow different air flows have been established. For each experimental condition, water and air gauge pressures, as well as inlet air temperature, have been simultaneously measured. Volumetric air flow rate has been varied from 30 to 60 Nm^3/h in increments of 10 Nm^3/h, while the corresponding water flow has ranged from 500 to 1 000 l/h in 100 l/h steps. Discharge coefficient (C_D), air-to-liquid ratio ($A.L.R$) and Sauter mean diameter (*SMD*) of the droplet size distribution have been analyzed. Droplet size distributions have been measured using a Malvern 2600 laser difractometer. The measurement volume has been located 15 cm downstream from the nozzle exit to minimize the effects of secondary break-up and droplet coalescence. To determine the average diameter, 1 000 samples have been collected for each flow conditions. From the size distributions, the Sauter mean diameter has been obtained. This instrument is designed on the assumption that a laser beam is scattered only once by the cloud of droplets. In the case of dense sprays, where the particle number density is high, the occurrence of multiple scattering can cause systematic error in the *SMD* measurement. In order to keep the obscuration coefficient inside the recommended values, a spray selector has been used in the experiments. This is an especially designed device that selects only one jet exiting from the multiple nozzle holes (8 for the new-designed nozzle or 6 for the commercial “Y”-jet one) allowing its interaction with the laser beam without blocking the flow from the rest of the atomizer head, as shown in Fig. 3. The nozzle is inserted in the upper part of the selector hollow cylinder and the rest of the individual sprays are re-routed and collected into the body of the draining through the lower open face where a flexible hose is connected.

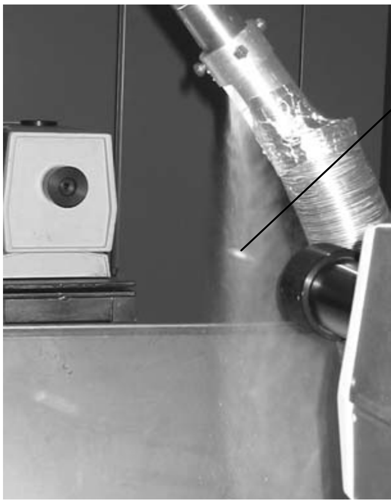


Figure 3. Photo of a running experiment using the spray selector

3. RESULTS AND DISCUSSION

To ease the analysis, in the rest of the paper, the following name convention has been adopted: “Commercial” refers to the original “Y”-jet nozzle, and “New with Y” and “New without Y” are used to indicate the two configurations for the new-design nozzle, depending on which one of the two different inner parts has been assembled.

3.1. Behavior of the nozzles as a function of the operating conditions

Strictly speaking, the discharge coefficient of a nozzle relates the real mass flow to the theoretical one, and can be written as the ratio yielding the well-known equation

$$C_D = \frac{\dot{m}_l}{A_o \sqrt{2 \rho_l P_l}} \tag{1}$$

where A_o is the total cross sectional area of the discharge orifices, P_l is the pressure difference of the liquid flow across the nozzle and ρ_l its density. As liquid flow can be considered to be incompressible, ρ_l is assumed constant for all the calculations. The mass flow $\dot{m}_l$ is defined as $\dot{m}_l = Q_l \rho_l$, where Q_l is the measured volumetric flow rate for the water fluid.

Air-to-liquid mass flow ratio, on the other hand, is calculated by

$$A.L.R = \frac{\dot{m}_a}{\dot{m}_l} = \frac{Q_a \rho_{a_i}}{Q_l \rho_l} \tag{2}$$

Here Q_a is the measured volumetric flow rate for the air fluid and ρ_{ai} is the air density corresponding to the inlet pressure and temperature conditions. As the air volumetric flow is measured with a rotameter calibrated to standard condition, this value has to be corrected by the actual values of pressure and temperature. So, Eq. (2) can be expressed only as a function of measured parameters by

$$A.L.R = \frac{Q'_a \, P_{a_i}}{R \, T_{a_i} \, Q_l \, \rho_l} \tag{3}$$

with $$Q'_a = Q_a \sqrt{\frac{P^{Std}}{P_{a_i}} \frac{T_{a_i}}{T^{Std}}} \tag{4}$$

where R is de ideal gas constant and T_{ai} and P_{ai} are the absolute air flow temperature and pressure, respectively.

As new-concept nozzle has been designed to replace the commercial "Y"-jet one, calculated values of C_D and *A.L.R* for the actual air mass flow rates and water volumetric flow rates shown the expected behavior. Slightly higher values of discharge coefficients have been obtained for the original "Y"-jet nozzle, while the *A.L.R* are almost the same for the three nozzles. However, a careful analysis of these figures shows that for the new-design nozzle without "Y"-ports the maximum actual air mass flow rate that is reached is lower than those for the other two nozzles for the different volumetric water flows rates. This behavior is clearly depicted in Fig. 4 a) and b), where the three nozzles are plotted simultaneously for a constant volumetric water flow of 500 l/h and 1 000 l/h, respectively. For the lower volumetric water flow rate of 500 l/h (Fig. 4 a) while the original "Y"-jet nozzle and the newly-designed with "Y"-channels yield 204 and 208 kg/h of maximum air mass flow rate, the new-concept nozzle without "Y"-ports only passes 189 kg/h. A marked difference is attained for the highest water volumetric flow rate (Fig. 4 b). In this case the air mass flow rates for the original "Y"-jet nozzle and the newly-designed with "Y" reach 181 and 185 kg/h, respectively, while for the new-concept nozzle without "Y" this parameter drops until 158 kg/h, yielding a reduction grater than 13%. This is a very important result if it is analyzed from the combustion viewpoint.

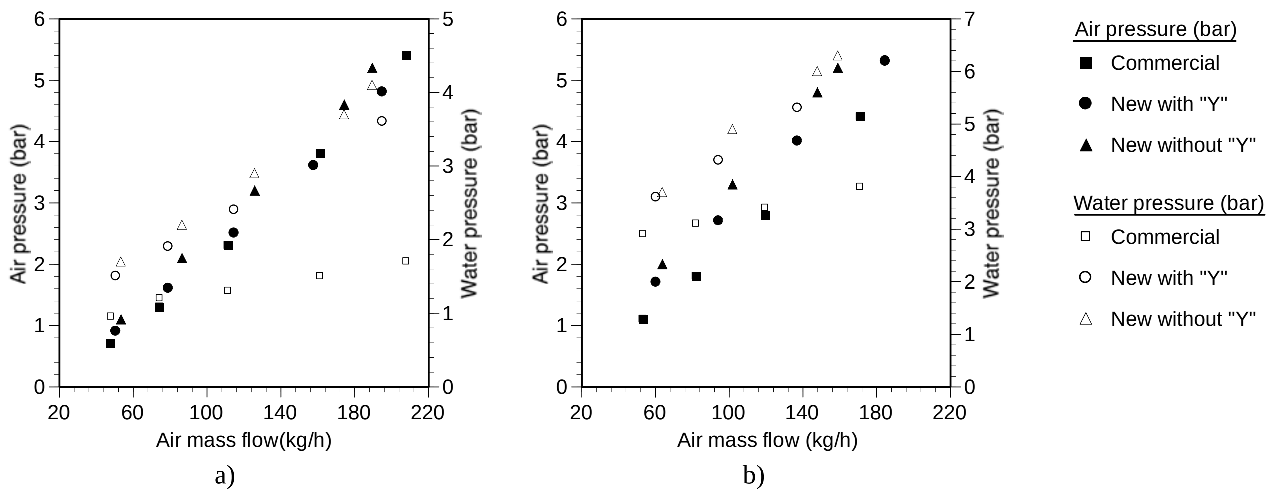


Figure 4. Liquid and air pressures for the three nozzles as a function of the actual air mass flow rate for two constant water volumetric flow rates: a) 500 l/h, b) 1 000 l/h

It is also recommended by the manufacturer of the twin fluid "Y"-jet atomizer to maintain the pressure of the atomizing fluid between 1 and 2 bar above the fuel oil pressure. Figure 4 b), which corresponds to the nominal liquid flow rate of these nozzles, shows that only the original "Y"-jet nozzle fulfills this requirement for the maximum volumetric air flow rate, that should produce the finest spray. In the case of the new-concept nozzle without Y-channels, air gauge pressures allowed for the different *A.L.R* tested were always lower than those of the liquid for the nominal liquid flow rate. However a higher absolute value of air gauge pressure is needed to fix the different operating conditions selected. These particular behaviors of the newly-designed nozzle without "Y" configuration in the internal piece might suggest that the reduction in the effective air flow cross sectional area, together with the dynamic interaction of the two fluids in the internal chamber, cause that air flow is choked due to compressibility effects. It should also be expected that combustion efficiency must increase if a spray with, at least, similar characteristics (*SMD*) is obtained with a lower air-to-liquid mass flow rate. Nevertheless as it will be discussed immediately below, Sauter mean diameters of the drop size distributions produced with the new-concept nozzle are always lower than those obtained with the "Y"-jet nozzle.

3.2.- Sauter mean diameter

The measurements of the *SMD* obtained for all the experimental conditions for the three nozzles are depicted in Fig. 5 as a function of the air mass flow (Fig. 5 a), and the air-to-liquid mass flow ratio (Fig. 5 b). It is observed that for the same operational conditions the new-concept nozzle produces smaller droplets that the original "Y"-jet one. The difference decreases when increasing the air mass flow rate, but even for the highest value of air mass flow rate a difference of about 15 μm is achieved. A clear dependence of the Sauter mean diameter on the air mass flow is depicted in Fig. 5 a). On the contrary Fig. 5 b) indicates a dependence of the *SMD* with liquid flow lower than expected, which agrees with the week dependence of the *SMD* with the calculated liquid sheet thickness. This result suggests that atomizing (air) flow is the key parameter on the behavior of the *SMD* in this type of nozzles.

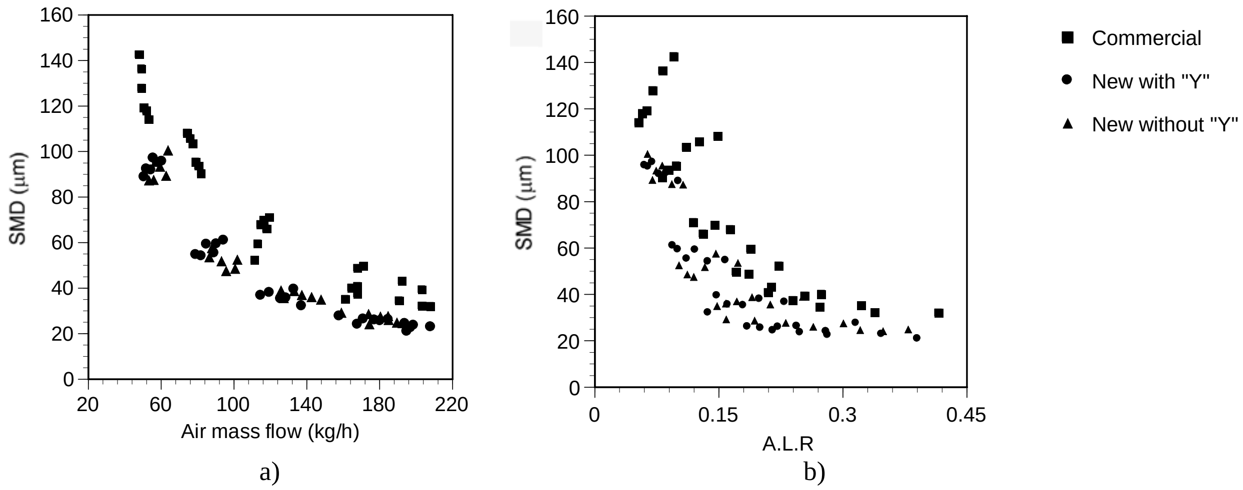


Figure 5. *SMD* of the three nozzles as a function of the air mass flow rate a), and air-to-liquid mass flow ratio b)

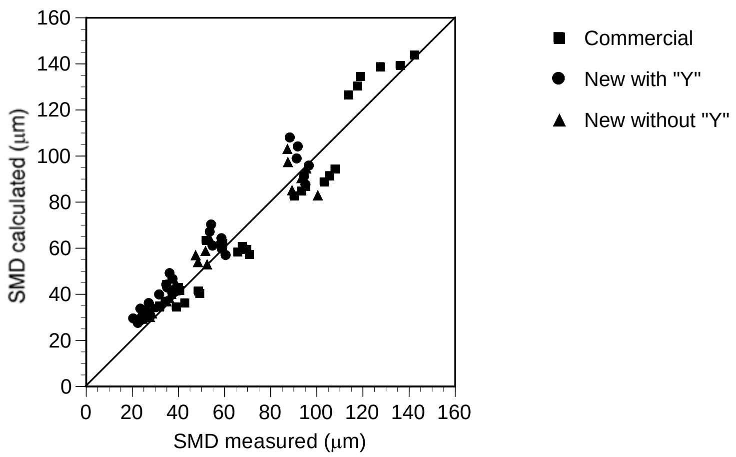


Figure 6. Comparison of measured and calculated *SMD* using Eq. (5)

To ease the analysis of engineers in industries and to predict the spray characteristic it is sometimes useful to look for empirical or physical equations relating the *SMD* with the operational parameters. Based on energy considerations, in 1992 Lefebvre [10] derived a theoretical equation to calculate the *SMD*, in which the effect of the kinetic energy of the liquid flow was neglected. It has been verified that this methodology cannot be used to accurately predict the value of the *SMD*, even if the kinetic energy of the liquid flow is taken into account. However, if a non-dimensional analysis of the problem is performed pointing the attention on the role of the atomizing flow, a suitable relationship can be obtained. In Fig. 6 the measured and calculated SMD are plotted. To perform the calculation, two dimensionless groups are formed, the by the air flow Reynolds number with the air core at the exit holes (d_{ao}) as the characteristic length and the *SMD* divided by the d_{ao}. The best fit to the experimental data including all the measurements for each nozzle is achieved for the equation

$$\frac{SMD}{d_{a_o}} = \frac{3.83 \cdot 10^7}{Re_a} \tag{5}$$

with an acceptable confidence level. As can be expected, if the analysis is performed for each individual nozzle, a better fit can be achieved with differences between the measured and calculated *SMD* lower than 5 μm.

4. CONCLUSIONS

An experimental study has been performed on three industrial large capacity multi-hole twin-fluid nozzles, a commercial one and two with a new design. It has been shown that the values of the air-to-liquid mass flow ratio obtained are almost the same for the three nozzles, while higher values of the discharge coefficient have been obtained for the original "Y"-jet nozzle. Nevertheless, the best overall performance corresponds to the new-concept nozzle without "Y"-ports at the internal piece. On one hand a lower maximum air mass flow rate is reached for the different water flow rates tested. The difference is marked for the highest water flow rate (1 000 l/h), which agrees with the nominal of the original design, yielding a reduction over 13% when compared to the other two nozzles. On the other hand, a higher absolute value of air pressure gauge is needed to reach the different operational conditions, resulting in an increase of the air velocity at the exit holes. These conditions contribute to the formation of a cloud of droplets with lower average size than that generated with the "Y"-jet commercial nozzle. For all these reasons, an increase in the combustion efficiency of the very viscous fuel oils should be expected.

From the results obtained in *SMD* measurements, it can be concluded that the atomizing flow rate is the key parameter determining the spray characteristics of this type of nozzles. Based on non-dimensional analysis, an equation has been derived that accurately relates the droplet size as a function of the air flow Reynolds number. It has been demonstrated that the suitable characteristic length of the problem is the diameter of the air core at the exit of the nozzle, proving that the air flow has larger influence on the twin-fluid atomization process than that of the liquid one.

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5. NOMENCLATURE

Latin alphabet

A	area [m^2]
$A.L.R$	air-to-liquid mass flow rate
C_D	discharge coefficient
d	diameter [m]
$\dot{m}$	mass flow [kg/s]
P	pressure [bar, Pa]
Q	volumetric flow [m^3/h, l/h]
R	ideal gas constant [m^2 s^{-2} K^{-1}]
Re	Reynolds number
SMD	Sauter mean diameter [μm]
T	absolute temperature [K]

Greek symbol

ρ	density [kg/m^3]

Subscripts

a	air
i	inlet
l	liquid
o	outlet section

Superscript

Std	standard flow conditions

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