Effect of Primary Spray Characteristics on the Spray Generated by an Airblast Atomizer under High-Pressure Conditions

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Abstract
In this paper the spray generated by an airblast swirl atomizer is studied experimentally. This atomizer consists on the pressure swirl nozzle generating a primary spray. This spray impacts
The parameters of the spray are characterized using the Phase Doppler instrument. The data are used also to estimate the air velocity of the atomization air. Additionally,
Next, a customized empirical correlation is formulated to estimate the Sauter Mean Diameter of the air-blast spray produced by a MTU atomizer. The model is based on the primary spray measurable parameters and the estimated air velocity. The effect of different parameters; air flow rate, water flow rate and chamber pressure on both of the hollow cone spray produced by pressure swirl atomizer and the air-blast spray is investigated.

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Nomenclature

\( D_{32} \)  Sauter Mean Diameter  
\( m_A \)  Airflow rate  
\( m_L \)  Water flow rate  
\( N \)  number of samples  
\( U \)  Air velocity  
\( t \)  Film thickness

Greek letters

\( \mu \)  Dynamic viscosity  
\( \sigma \)  Surface tension  
\( \rho_L \)  Liquid density

Abbreviations

PDA  Phase Doppler Technique  
Oh  Ohnesorge Number  
SCMH  Standard Cubic Meter per Hour  
SMD  Sauter Mean Diameter  
We  Weber Number

Introduction

Producing fine drops in a well-mixed spray that has relatively high volume-mass ratio is required to ensure good combustion in gas turbines and diesel engines. In general, some parameters distinguish one spray from another [1]. In a swirl pressure spray, the cone angle, the droplet distribution and the velocity profile of the droplets determine the finger print of it, whereas the determined parameters in an air-blast spray are the ALR, Sauter mean diameter, radial liquid distribution, three velocity components of the droplets and the gas phase velocity profile. Detailed experiments have been done to investigate almost each of the parameters. For example, the effect of ambient pressure and injection pressure on the spray angle of different pressure atomizers has been investigated by [2]. Pressure conditions strongly affect the parameters of both the pressure swirl spray and the air-blast spray [3] and [4]. Increasing the ambient pressure, for example, leads to an increase in droplet diameter and a decrease in its velocity components.

Improving the performance of atomizers in general is an important process to achieve well controlled and described atomization process. Also studying the effect of liquid and gas phases properties is an important action to fit the right atomizer for the right application [5].

One of the important parameters characterizing the performance of the atomizer is the average diameter of the liquid drops in the spray. A weighted average Sauter Mean Diameter of the drops is defined through

\[
SMD = \frac{\sum N_i D_{32}}{\sum N_i}
\]

Various empirical correlations for the drop size of the spray generated by airlift atomizers

\[
D_{32} = 0.95 \left( \frac{\sigma \bar{m}_L}{\rho_L U_A} \right)^{0.31} \left( 1 + \frac{\bar{m}_L}{m_L} \right)^{0.7} + 0.13 \left( \frac{\mu d_{32}^{0.3}}{\sigma \rho_L} \right) \left( 1 + \frac{\bar{m}_L}{m_L} \right)^{0.7}
\]

\[
D_{10} = 0.48d_L \left( \frac{\sigma}{d_L \rho \bar{U}_L} \right)^{0.6} \left( 1 + \frac{\bar{m}_L}{m_L} \right)^{0.4} + 0.18 \left( \frac{\mu \bar{d}_L^{0.5}}{\sigma \rho_L} \right) \left( 1 + \frac{\bar{m}_L}{m_L} \right)^{0.8}
\]

\[
D_{90} = 3.33 \times 10^{-4} \left( \frac{\sigma \bar{m}_L}{\rho_L U_A} \right)^{0.5} \left( 1 + \frac{\bar{m}_L}{m_L} \right) + 1.3 \times 10^{-4} \left( \frac{\mu \bar{d}_L^{0.5}}{\sigma \rho_L} \right) \left( 1 + \frac{\bar{m}_L}{m_L} \right)^{0.5}
\]

\[
D_{50} = 0.33d_L \left( \frac{\sigma}{d_L \rho \bar{U}_L} \right)^{0.6} \left( \frac{\rho_L}{\bar{p}_L} \right)^{0.5} \left( 1 + \frac{\bar{m}_L}{m_L} \right) + 0.068 \left( \frac{\mu \bar{d}_L^{0.5}}{\sigma \rho_L} \right) \left( 1 + \frac{\bar{m}_L}{m_L} \right)
\]

\[
D_{30} = (2.67 \times 10^4 U_A P_{inj}^{0.5})^{-1}
\]

can be found in [6]-[10], respectively. Generally, the study of the spray generated by airlift atomizers remains empirical since the flow inside the atomizer is extremely complicated and all the mechanisms of splash, breakup and atomization are not completely understood.

The main subject of the present work is the experimental investigation of the airlift atomizer. The primary spray and the final spray generated by the atomizer are characterized using the phase Doppler instrument. Additionally, the airflow velocity at the nozzle exit is estimated by averaging the velocity of the small drops of the diameter smaller than 10 \( \mu m \).

Finally a semi-empirical model for the drop size is proposed using the hypothesis that the main reason responsible for the atomization is the deformation of the film created on the prefilmer inside the atomizer. The obtained length scale for the drop diameter agrees well with the experimental data.

Atomization mechanisms in an air-blast atomizer

Different types and models of air-blast atomizers have been developed to match different applications. Plain-jet and pre-filming types are reported by [11]. In this work an air-blast atomizer
with pre-filmer is used to perform the experiments. This type is known as the MTU air-blast atomizer. In this atomizer, a pressure swirl atomizer produces the primary spray that impacts onto the pre-filmer where a thin, fluctuating, unstable liquid film is generated. The instability of this thin-liquid film is due to relatively high-velocity air stream that passes on the upper surface of the film. Due to the high shear forces, the liquid film breaks up to ligaments and then to droplets as shown in figure 1.

The air has swirl motion due to the geometry of the air-blast atomizer, which produces three velocity components for the droplets; axial, radial and tangential (azimuthal) velocity components.

Performing direct measurements inside the air-blast atomizer is rather a complicated process due to different reasons; the small room where the processes take place and the lack of measurement techniques that can deliver useful information. Therefore, different efforts have been paid to perform experiments using super position principle in sense of separating the mechanisms that take place inside the air-blast atomizer; spray impact onto a solid target [11] and breakup of annular and plane liquid sheets in the presence of shear forces [12]. Other works were devoted to developing of models that can predict the droplet size based on the understanding of the atomization mechanisms. Based on this understanding and using statistical analysis, [13],[14] have used the maximum entropy principles to predict the droplet size and velocity distribution.

Neither the super position based description of the atomization mechanisms nor the maximum entropy based models are global. All of them are valid for predefined parameters and atomizer’s geometry. Different is the work done by [15], in which huge number of experiments have been performed at different conditions and different types of atomizers, which lead to empirical formulas that describe the dependency of the resulted droplet size on the operating conditions.

In this work, the air-blast atomizer is treated as black box. The parameters of the primary spray (droplet size and velocity) and the atomization air (flow rate) are measured. Then the parameters (droplet size, droplet radial distribution and three velocity components) of the resulted air-blast spray (end spray) are measured at different operating pressure. Then the results are discussed based on the available knowledge of atomization principles.

### Experimental setup

A MTU atomizer is used to produce the end air-blast spray. A pressure swirl atomizer produces the primary spray that impacts onto the pre-filmer where the atomization mechanisms take place as shown in figure 2. The air-blast atomizer is mounted in the atomization cup inside the pressure chamber.

The pressure chamber has three optical accesses to facilitate the measurements using PDA technique and
for other purposes the time resolved imaging and the particle image velocimetry technique as in the sketch in figure 3. The pressure chamber can withstand up to 50 bars. The pressure is produced by regulating compressed air into and out of the pressure chamber. The airflow is controlled by means of valves system. A pressure reducing valve and the valves system help controlling the pressure difference through the system.

A DantecDynamics dual-mode, two-velocity components laser Doppler/phase Doppler system is used in the experiment. The blue (488 nm) and green (514.5 nm) lines of a 20 W Argon-Krypton laser (Spectraphysics) are used. The beam spacing is 60 mm and the beam diameter before the front lens is 1.35 mm. A 600 mm focal length lens is used for the transmitting optic and 400 mm for the receiving optic. The effective slit width at this optical configuration is 0.32 mm.

**Primary spray**

The spray that impacts onto the pre-filmer in an air-blast atomizer is the primary spray. A pressure swirl atomizers is used to produce hollow-cone primary sprays. The effect of chamber pressure, water flow rate and coaxial air flow on spray parameters (droplet size and two velocity components) is investigated. The PDA measurements are done at 5 mm distance down stream in a radius of 15 mm, since exactly at this distance the primary spray impacts onto the pre-filmer in the MTU air-blast atomizer.

The penetration distance of the primary spray has almost no effect on the droplet size distribution as shown in figure 4a, which indicates that no secondary atomization happens. Slightly different is the effect of subjecting the primary spray to a coaxial air flow field. In figure 4b, that droplet size distribution of the primary spray at 5 mm down stream is presented. The

![Figure 4](image-url)
The volumetric flow rate of the coaxial air flow is changed between 20, 35 and 50 SCMH, which are the same values used for the air flow rate to produce the air-blast spray. One expects an increase in the droplet size when increasing the water flow rate through the pressure swirl atomizer, if the droplet size is independent of the water pressure and the droplet velocity distribution. The droplet size distribution shows a decrease when increasing the water flow rate as displayed in figure 4c. This can be explained by the large increase in the water pressure when increasing the water flow rate. It is also understandable the effect of the chamber pressure on the droplet size. In figure 4d, one can notice that the droplet size is not influenced by the chamber pressure. This is due to the fact that the pressure difference between water and the chamber remains constant when increasing the chamber pressure, since the pump regulates the pumping pressure to maintain a constant flow rate.

Two different pressure swirl atomizers are used to produce two primary sprays with different parameters. Figure 5 shows the radial SMD distribution of the two pressure swirl atomizers.

Different is the effect of the studied parameters on the droplet velocity of the primary spray. In figure 6a for example, one can notice that the penetration distance strongly influences both the axial and the radial velocities. Also subjecting the primary spray to a coaxial air stream affects the two velocity components as displayed in figure 6b. The water flow rate has also a noticeable effect on the droplet velocity components as in figure 6c.

### Air-blast spray

An experimental study concerning the effect of different parameters: air flow rate, water flow rate and chamber pressure is presented in [3] and [4]. Here, the effect of the primary spray characteristics (flow rate, SMD and velocity components) on the air-blast spray is discussed.

Figure 7a shows the change of droplet size as a function of the distance downstream. In general, with air at room temperature, the droplet size doesn’t change during the penetration of the spray in the pressure chamber. The effect of the chamber pressure is shown in figure 7b. As the air volumetric flow rate is constant (20 SCMH) and at the same time, the air density increases as increasing the chamber pressure, then the air velocity decreases which explain the increase in the droplet size. The water flow rate is constant and equal to 2.66 l/hr.

Keeping a constant chamber pressure of 1 bar and a constant water flow rate of 2.66 l/hr and increasing the air volumetric flow rate leads to a decrease in the droplet size as shown in figure 7c. The last discussed parameter is the water flow rate, which is also discussed later in the drop size relationships part. Never the less, figure 7d shows that changing the water flow rate in this case and keeping the air flow rate and the chamber pressure constant doesn’t change the droplet size dramatically.

### Estimation of air velocity

Injection of seeding particles in the air bath to measure the air velocity is somehow complicated in the available setup. Therefore, the PDA data for liquid phase measurements are used to estimate the air velocity distribution of the gas phase. The validated liquid particles that have diameter size equal or smaller than 10 µm are considered to be representative of the gas-phase velocity. The data presented in figure 8 is the estimated velocity at 5 mm downstream. Another method to estimate the maximum air velocity at the exit of the air-blast atomizer can be done by simply averaging the air volumetric flow rate to the exit area of the air-blast atomizer. Doing so results in 52, 91 and 130 m/s for 20, 35 and 50 SCMH flow rates respectively.

Comparing the maximum estimated velocity at 5 mm downstream with the calculated velocities at the exit of the air-blast atomizer shows good matching taking into consideration the depreciation of the air velocity through the mentioned 5 mm distance. Based on this, the values of the air velocity at the exit of the air-blast atomizer to be considered are listed in table 1.
Figure 6. Velocity of water droplets in a pressure swirl spray at 1 bar chamber pressure.
Table 1. Estimated air velocity.

<table>
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<tr>
<th>Chamber pressure Bar</th>
<th>Airflow rate SCMH</th>
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<th>Calculated velocity m/s</th>
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</tr>
<tr>
<td>10</td>
<td>50</td>
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</tr>
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</table>

Figure 7. Sauter Mean Diameter of droplets in spray produced by an air-blast atomizer
Scaling analysis for the atomization

The spray generated by the airblast atomizer is influenced by number of the operating parameters, like the volumetric rates of the airflow and of the liquid flow, parameters of the primary spray, pressure in the chamber, material properties of the fluids, etc. Since the mechanism of atomization is extremely complicated the main problem is not in the luck in the formulas relating the operating parameters with the spray parameters. The problem is actually that since the large number of the operating conditions allows one to consider various types of the empirical relations, like those listed in the Introduction section of this paper. Such formulations, however, do not add much to the understanding of the processes occurring inside the nozzle. There is also not confidence that such relations are universal.

In this situation the scaling analysis of the problem, relating even one of the parameters with the drop size of the spray, can be valuable.

The details of the mechanism of atomization are not considered in the present model. The size of the drop is estimated from the energy balance. The primary spray creates on the prefilmer a liquid film of the thickness $h$. The flow in the film is accelerated by the

Figure 8. Estimated air velocity at 5 mm distance downstream
fast airflow. At some instant the film breaks up and creates drops. The initial drops velocity is comparable with the film velocity, therefore, the total kinetic energy cannot be used in the energy balance of the atomization. Our main assumption is that the reason for the atomization is the liquid film deformation. The kinetic energy of the film deformation goes to the creation of the surface of the drops [16].

Consider an element in the liquid film of the typical size \(a\). The volume of this element is proportional to \(a^3\). Denote \(\dot{\gamma}\) the rate of its deformation. Therefore, the kinetic energy of deformation of the element is approximately

\[
K \sim \rho_s a^3 \left(\dot{\gamma} a\right)^2
\]

(2)

During the breakup this energy goes to the creation of the new surface. The corresponding surface energy is estimated as

\[
S \sim \sigma a^2
\]

(3)

The smallest possible drop corresponds to the case when all the energy of deformation transforms to the surface energy. Therefore, the typical size of the drops, \(a\), can be estimated equating \(K\) and \(S\). The resulting expression is

\[
a \sim \left[\frac{\sigma}{\rho_s \dot{\gamma}}\right]^{1/3}
\]

(4)

We assume that the main deformation of the liquid and of the gas take place in a thin turbulent boundary layer. The shear stress at the interface between the liquid and the air can be estimated from the Blasius-law in the boundary layer in the air

\[
\tau_* \sim \rho_a U_a^2 \left(\frac{V_a}{U_a \delta_a}\right)^{1/4}
\]

(5a)

Now the rate of deformation of the fluid element in the film at the edge of the prefilmer \((x = L)\) can be estimated in the form

\[
\dot{\gamma} = \frac{\tau_*}{\rho_s V_a^2} = \frac{V_a \rho_s L^{1/5} U_a^{1/5}}{V_a L^{1/5}}
\]

(6)

Now, the typical size of the drops in the spray can be estimated using (4)

\[
a \sim \frac{V_a^{1/5} \sigma U_a^{2/5} L^{1/5}}{V_a \rho_s L^{1/5}}
\]

(7)

It should be noted that in all the existing empirical relations, listed in the Introduction section of this paper, the Sauter mean diameter is scaled as \(U_\alpha^n\), where \(n\) is in the range -1.2 to -0.8. Our analysis predicts \(n = 1.2\), which is in agreement with the previous observations.

However, in all the empirical relations the influence of the material properties in different studies is expressed differently. It is the result of the difficulty of the representation of the experimental data in the condition when the number of the influencing parameters is rather high while the collecting of the experimental data is sufficiently laborious.

In figure 9 the dependence of the Sauter mean diameter is shown as a function of the typical size \(a\) determined in (7). It is shown that SMD is proportional to \(a^2.6\) at \(a < 20 \mu m\)

\[
SMD = 6.2a\quad at\quad a < 20\ \mu m
\]

(8)

The deviation from the linear dependence at larger diameters can be explained by the secondary, aerodynamic drop breakup, which is not considered in the present study. Accounting for the secondary breakup required more accurate analysis which is the topics of the future research.

Conclusions

Droplet size and velocity obtained by phase Doppler measurements of spray generated by an air-blast atomizer are used to estimate the velocity of the gas phase. Then the effect of water flow rate, air flow rate and chamber pressure on the parameters of the air-blast spray and hollow-cone spray generated by a pressure swirl atomizer is investigated.

A typical length scale of the atomized drops inside the nozzle is obtained from the analysis of the breakup of the film created on the prefilmer. This scaling is confirmed by the experimental data for relatively small drop diameters. Additional analysis of secondary, aerodynamic breakup is required in
order to predict the drop diameter of the spray in a wide range of the operating parameters.

References