Experimental and Computational Analysis of a Water Spray; Application to Molten Metal Atomization

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ABSTRACT

In the process of water atomization of molten metal, a number of water jets impinge on a liquid metal stream. By the time each water jet reaches the molten metal, it has formed a spray that interacts with the molten metal to produce molten metal droplets that ultimately become powder. The characteristics of the water sprays, such as droplet size distribution, have a significant influence on the particle size distribution and morphology of the metal powder. To control the metal powder features effectively, it is crucial to understand the spray behavior and characteristics. However, the visualization of the water sprays at the impingement zone is a challenge in a full-scale industrial water atomizer. Therefore, a transparent lab-scale water atomizer has been built. The combined approach of high speed imaging and computational modelling of the high pressure water spray has revealed interesting information about spray pattern, droplet size distributions, and droplet trajectories. The numerical model has been tuned up based on the lab-scale experimental results and can be used to predict the spray features in a full-scale water atomizer.

INTRODUCTION

With advances in powder metallurgy (PM), more manufacturers have adopted PM techniques including hot/cold isostatic pressing (HIP/CIP) and additive manufacturing (AM). They now use metal powders as the raw material to build high-strength parts. This is especially evident in automobile industry and rapidly growing into other sectors. Therefore, the demand for high quality metal powders has increased.

The quality of a powder (and the consequent built part) is a function of powder characteristics, namely particle size distribution (PSD), particle morphology, particle porosity, surface condition, and structure. For example, among AM processes, the PSD defines the minimum layer thickness and the resolution of the finest detail in the component [1]. Additionally, the mechanical strength of the PM product is a direct function of the product density [2]. The density, in turn, depends on powder morphology where the more spherical the particles the higher the product density. Therefore, understanding and controlling powder characteristics is a very important aspect of powder production.

There are many known routes for metal powder production; among all, water atomization has been widely accepted as a cost-effective approach for high-volume metal production. Metal powder production through water atomization starts with pouring molten metal into a tundish placed on top of an atomization chamber. Due to the hydrostatic pressure within the melt and low pressure in the chamber, the melt flows through an opening at the bottom of the tundish. Both the melt level in the tundish and the internal pressure of the chamber will be maintained during the process. Once the molten metal enters the atomization chamber, it free falls into the atomization zone. Typically, a number of water nozzles are symmetrically arranged around the stream of liquid metal and water jets are directed at the metal stream (see Figure 1). At high operating pressures, the jets of water almost immediately break up into sprays of droplets, which then interact with the molten metal and produce molten metal droplets. During and subsequent to the atomization, during falling and deposition, the metal droplets solidify and form powder. In the final step, the water-powder slurry is pumped out of the chamber. The process continues with dehydration, filtration, annealing, classification, and packaging of powder.

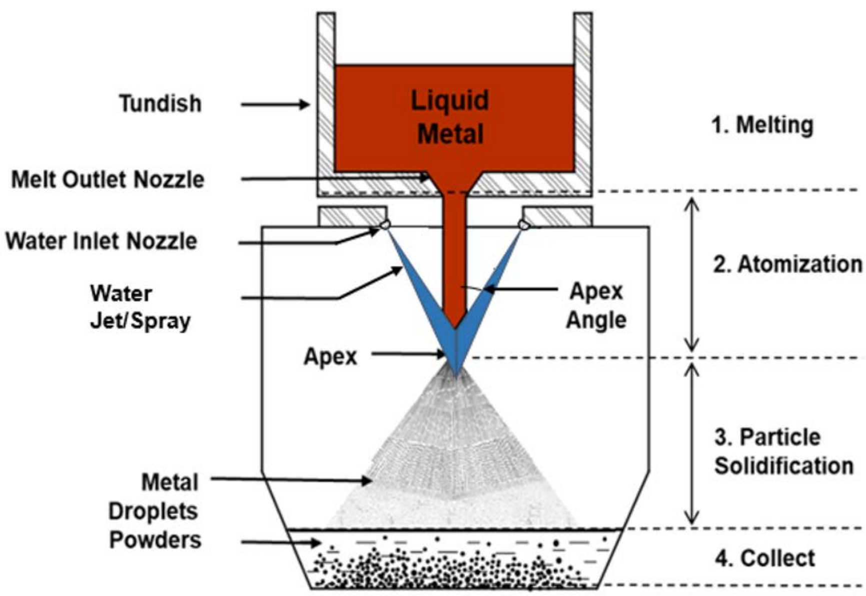


Figure 1. Schematic of water atomization process (modified from [3])

The history of research in this area goes back to the 1960's; during the decades since, the knowledge of how different operating and design parameters affect particle characteristics has matured to some extent. For example, owing to the scalability of the water atomization process, many empirical correlations have been developed linking the mass median particle size (d_{50}) to different operational parameters such as water pressure P_W, water velocity V_W, and nozzle apex angle α. Persson et al. [4] recently reviewed existing models for powder median size and concluded that the Bergquist model [5] best fits available experimental data for water atomized iron powder. Therefore, they proposed a modified version of that model to account for the diameter of liquid metal stream (D_M):

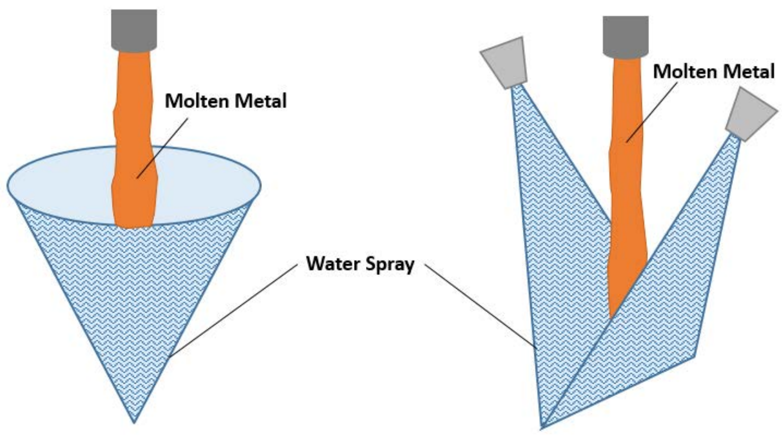
$$d_{50} = k \frac{\gamma_M^{0.80} \mu_M^{0.93} D_M^{0.21}}{P_W^{0.98} \sin\alpha} \left(\frac{m_W}{m_M}\right)^{-0.04} \quad \text{Eq. 1}$$

, where k is a constant and γ, μ, and m are surface tension, viscosity, and mass flowrate, respectively. Subscripts $_W$ and $_M$ refer to water and liquid metal. The review of Persson et al. was comprehensive; we would add just one more correlation to their list. Seki et al. [6] studied two types of nozzle configuration in an atomizer setup and obtained the following correlations for d_{50}:

Annular nozzle (Figure 2a): $d_{50} = 114\ P_W^{-0.58}$ Eq. 2

Open V-jet nozzle (Figure 2b): $d_{50} = 68\ P_W^{-0.56}$ Eq. 3

They concluded that at the same water pressure, the open V-jet nozzles yield finer particles than the annular nozzle.



(a) (b)

Figure 2. Water jet configurations (a) annular or cone, and (b) open V-jets

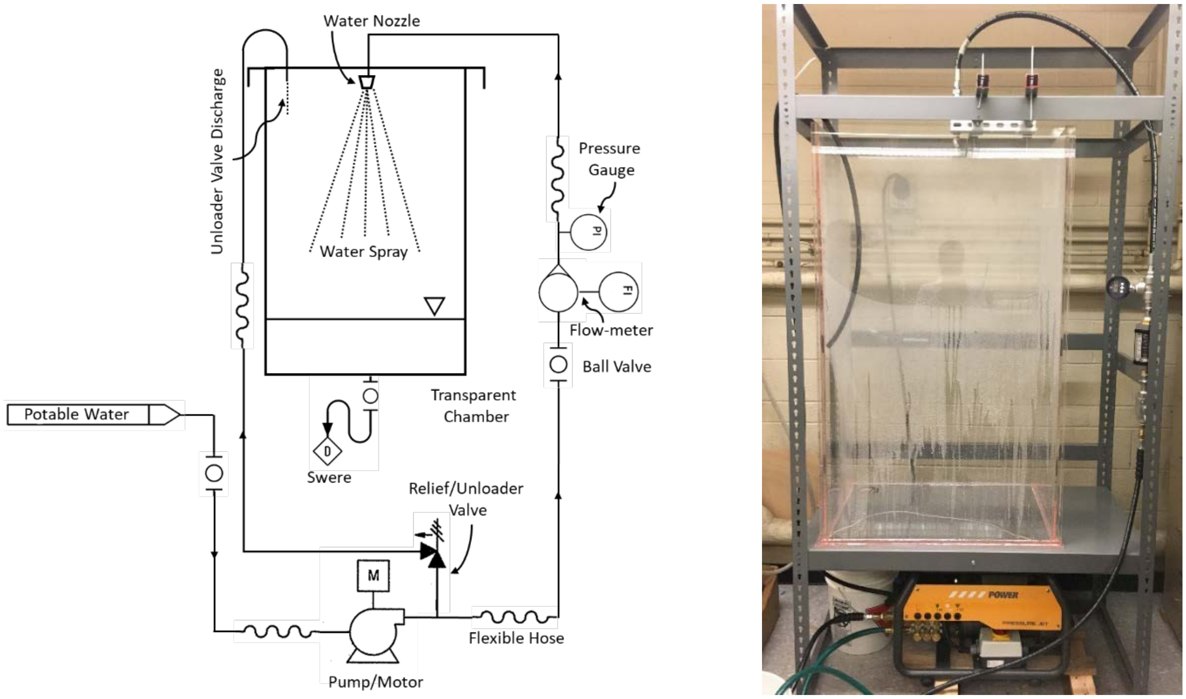
In summary, one can categorize the operating parameters of a water atomization facility in terms of the impact on the mass median particle size as (i) highly influential, such as water pressure, water velocity, and nozzle apex angle, (ii) mildly influential, such as melt viscosity, (iii) and slightly influential, such as melt flow rate and surface tension.

Finally, most previous investigations have focused on the mass median behavior of particle size distributions that says nothing about non-average behaviors such as the variance or standard deviation of a particle size distribution. To respond to the new challenges introduced by the latest methods of powder manufacturing, concurrent efforts must investigate and control the statistical distribution of particle size. In addition, as Persson et al. [4] point out in their final discussion, existing models in the literature are mainly empirical, lacking an understanding of the complex phenomena within the atomization chamber, that has been treated as a black box. Previous work has focused on finding relations between the inputs and output, with no concern for the intermediate thermofluidic and physicochemical phenomena. This is partly due to the nature of this topic, which requires knowledge of multiple disciplines.

In order to shed some light on the processes internal to the atomization chamber, we are conducting experimental and computational analyses of flat-fan sprays, commonly used in V-jets water atomization (Figure 2b).

EXPERIMENTS

The visualization of water sprays in a full-scale industrial water atomizer is a challenge. Even though an atomization chamber may be equipped with a sight window, it does not allow for high quality imaging. Therefore, a lab-scale setup including a high-pressure pump, a transparent chamber, a water nozzle, and associated piping and instrumentation has been designed and built (see Figure 3).



(a) (b)

Figure 3. Experimental setup: (a) Process flow diagram (b) As-built apparatus

This has enabled us to obtain important qualitative and quantitative data of the water spray involved in the water atomization process. The apparatus has also been used to calibrate and validate numerical results obtained from CFD (Computational Fluid Dynamics) modelling. In addition, in some cases the CFD model requires experimental inputs, such as spray spreading angle β and dispersion angle θ; the lab-scale setup can provide this data. The main parameters are illustrated in Figure 4(b). The other important parameter is the apex angle α; in this research the spray was studied in a vertical position, i.e. $\alpha = 0$.

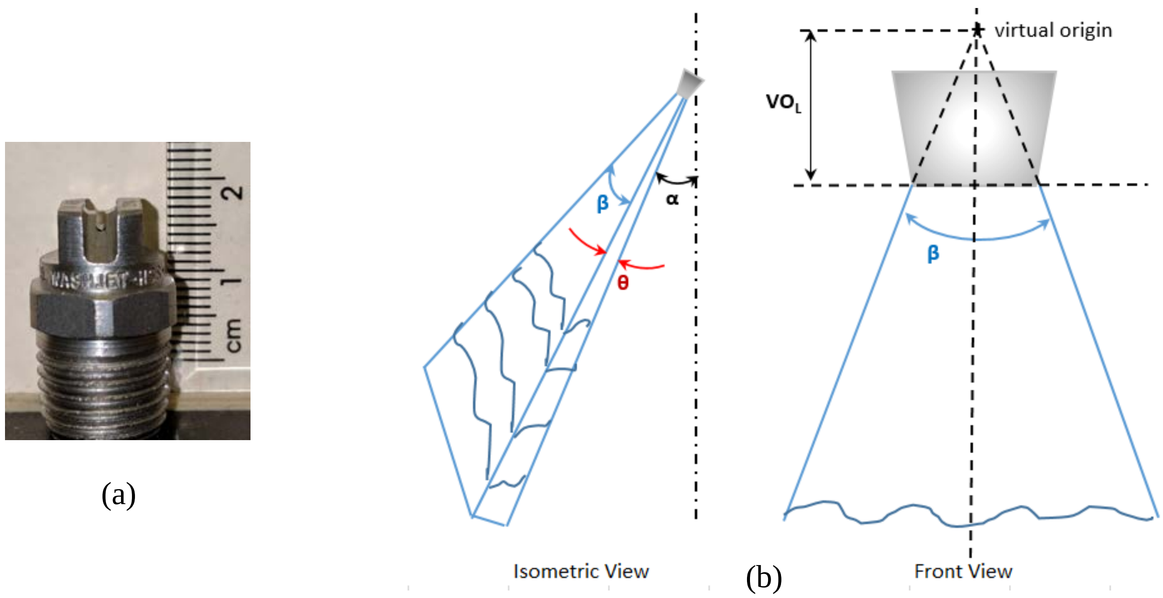
Table 1 lists the specifications of the water nozzle used in the experimental study, illustrated in Figure 4(a). The nozzle belongs to a family of flat fan atomizers with a wide range of applications including metal powder production, descaling, pressure washing, and agricultural pesticide and fertilizer spraying. As a first step to study the water atomization process, we collected information about the geometrical pattern of a single spray, as well as on droplet sizes and trajectories.

Table 1. Nozzle specifications

Nozzle general type	Hydraulic diameter, D_h (mm)	Flowrate at 300 kPa (Lit/min)	Flowrate at 10,000 kPa (lit/min)	Spreading angle (degree)
Flat Fan Spray	1.16	1.6	9.1	25*

* This is the vendor published value; however, the spreading angle varies with pressure.

Some background theory of spray formation will be presented in the next section. Here, the aim is to visualize a high-speed (up to 140 m/s) spray at different nozzle pressures. As a starting point, the velocity of droplets can be estimated based on the nozzle pressure, $V_w = 1.3\, P_W{}^{1/2}$[7].



(a) (b)

Figure 4. (a) Flat fan nozzle (b) Flat fan spray pattern and important parameters

High-speed shadowgraph imaging was used for this study. The water spray was imaged from two different angles, front and side, using a high-speed camera. The camera was triggered at 2000 frames per second (fps) and the minimum possible exposure time of 1 μs was used. The field of view roughly encompasses a 3 mm x 3 mm square on the centre-plane of the spray. The camera and the backlight were sequentially displaced along the vertical axis to capture images of the spray at different distances from the nozzle. The images were then post-processed using an open source image-processing tool, ImageJ, for quantitative analysis of the spray patterns and droplet sizes. This part of the experimental work has been computed and results will be discussed in subsequent sections.

CFD Modelling

Using a flat fan spray nozzle, the water first forms a thin liquid sheet. Within a very short distance from the nozzle, the liquid sheet experiences an aerodynamic instability and disintegrates into transverse ligaments. Shortly after, the ligaments also break down into small droplets (see Figure 5). Senecal et al. [*8*] proposed a model to estimate the median drop size and overall spray shape, which has been widely adopted by CFD platforms. This model, Linearized Instability Sheet Atomization - LISA, is based on instability theory for a 2D viscous liquid sheet subject to periodic disturbing waves. More information on this modelling approach can be found in the original article [*8*].

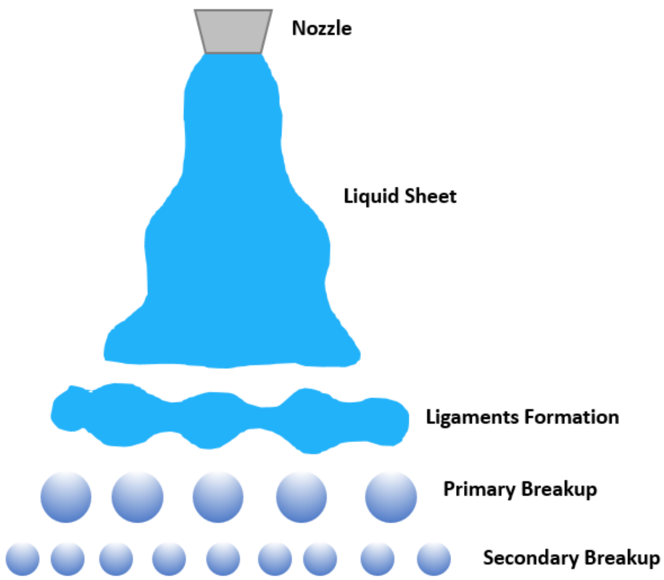
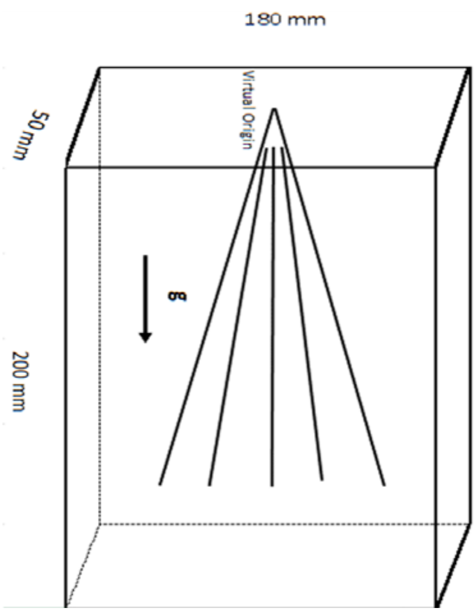


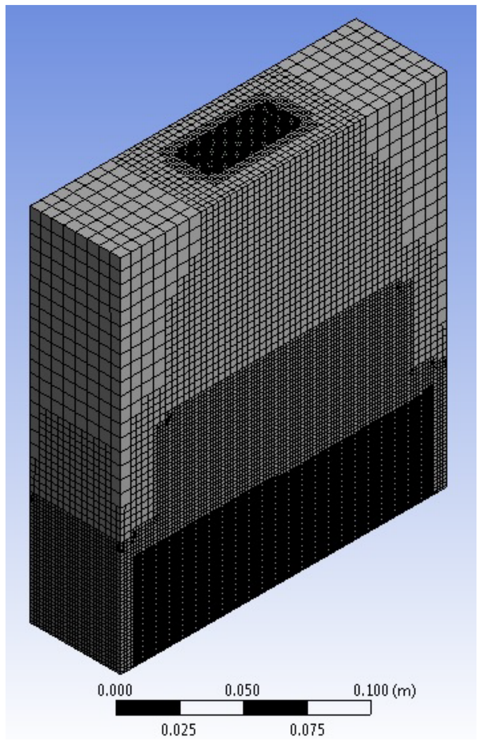
Figure 5. Instability and disintegration of a liquid sheet into a spray of droplets

ANSYS/FLUENT Ver. 18.2 was used for the computational modelling of the spray. A three-dimensional geometry was defined around the expected water spray, with the nozzle location defined at the top center of the domain, as shown in Figure 6(a). The domain was discretized into about one million hexahedral cells. To minimize the computational cost, the mesh size gradually increases from 1 mm at the central region to 5 mm outside of the spray domain, as shown in Figure 6(b). Except for the dark rectangle on the top face, the rest of the boundaries are pressure outlets. The rectangle represents the tip of the nozzle, and so a wall boundary condition is applied. The nozzle exit area corresponds to that of the nozzle used in the experiments, illustrated in Figure 4(a).

The calculation was done in transient mode with a time step of 10 microseconds. The main inputs to the model include water flow rate, geometrical parameters of the nozzle opening, and geometrical parameters of the spray pattern (the latter was obtained from the experiments). To model the two-phase air-droplet flow, the Euler-Lagrange approach was adopted. Air is treated as a continuum by solving the Navier-Stokes equations, while droplets are injected and tracked through the calculated flow field for air. The injection of droplets, including droplet size and velocity distribution, is controlled by a flat-fan atomizer model. This model ignores the initial sheet formation but incorporates the equations for primary breakup. The droplets are tracked within the domain, and droplet size and velocity are updated based on predicted interactions with air.



(a)



(b)

Figure 6. (a) Physical geometry and (b) CFD mesh

RESULTS & DISCUSSION

The single spray was visualized at different pressures. Figure 7 shows water sprays at two different pressures, 207 kPa and 2068 kPa, from two different angles, front and side. The liquid sheet is observed immediately at the outlet of the nozzle; however, shortly after it breaks up into transverse ligaments. The sheet break-up length, from the nozzle outlet to the breakup point, is at 5.5 cm for the 207 kPa spray and 1.5 cm for the 2068 kPa spray. The reduction of the breakup length with increasing pressure has been reported by others, [8]&[[9]. Since water atomizers normally operate at water pressures ranging from 5 to 20 MPa (~750 to 3000 psi), the sheet break up will be almost immediate as water exits the nozzle.

By further tracking the ligaments in Figure 7, one can see that they in turn disintegrate into water droplets. We can now conclude that in industrial scale water atomizers, it is a spray of water droplets that interacts with the molten metal stream. The spray atomizes the stream to molten metal droplets that ultimately become powder. Therefore, the study of water spray droplet size and velocity distributions can help better understand and control metal powder size distribution. This paper presents a combined approach to experimental and visual modelling of a flat fan water spray in order to obtain the droplet size and velocity distributions.

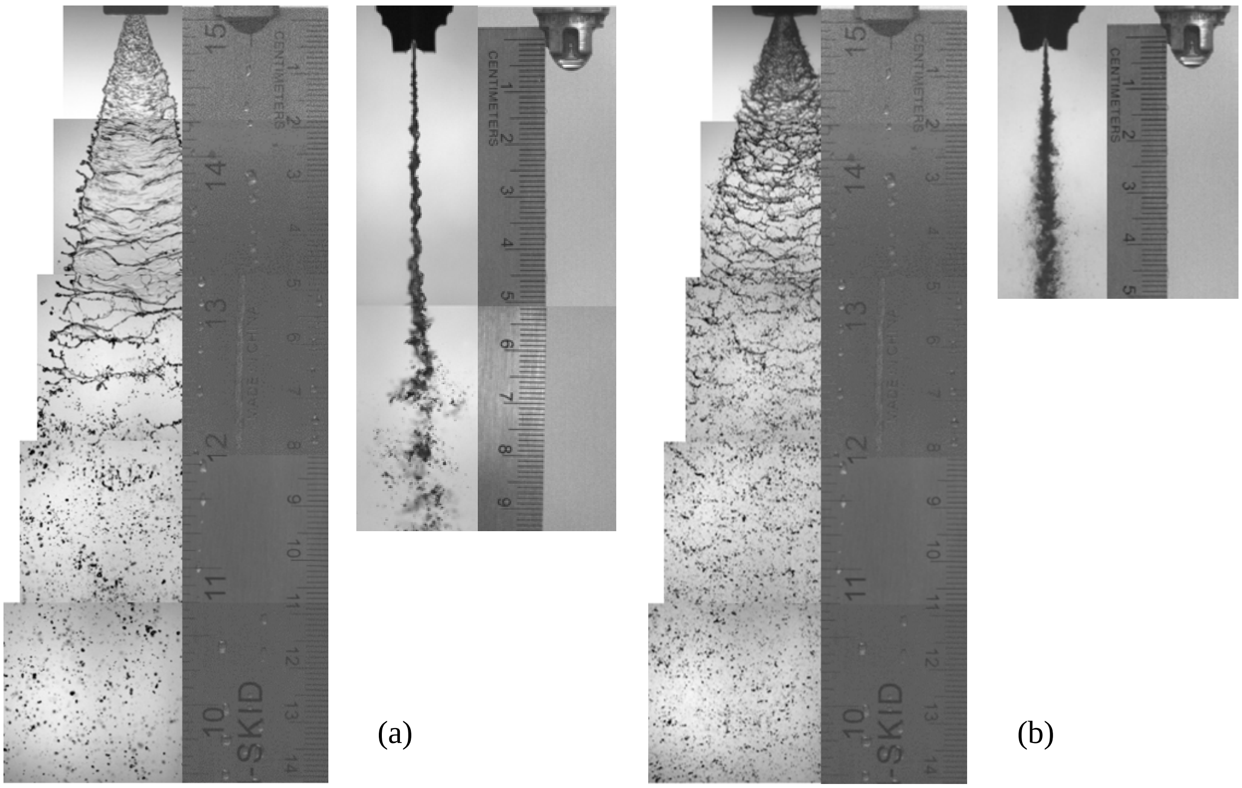


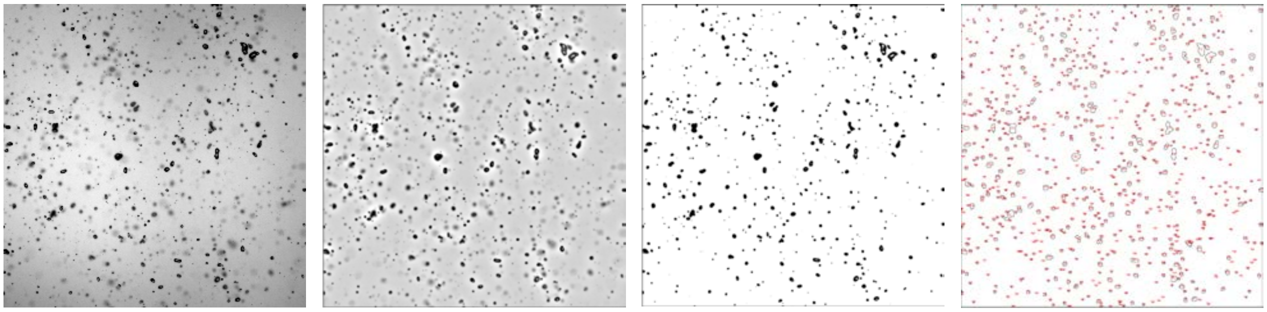
Figure 7. Shadowgraphs of water spray (front and side views) at (a) 207 kPa (30 psi) and (b) 2068 kPa (300 psi)

The spray spreading angle and dispersion angle were measured from two different images for each pressure. The measurements were then averaged to minimize errors and temporal effects. The values are tabulated in Table 2. Both angles increase with nozzle pressure. For input into the CFD model, we used the measured angles instead of the vendor published data in Table 1.

Table 2. Experimental measurements for the two water sprays in Figure 7

Nozzle Pressure, P_W kPa (psi)	Water Flowrate Lit/min (US gpm)	Spreading Angle β (degree)	Dispersion Angle θ (degree)
207 (30)	1.32 (0.3)	33.5	4.00
2,068 (300)	4.14 (1.1)	39.8	5.60

Image processing was used to measure the size distribution of droplets at different pressures and different distances from the nozzle. The process of preparing an image and measuring droplets is shown in Figure 8. The software returns the area occupied by each droplet in the image. The equivalent diameters are calculated, assuming droplets are spherical. A sample droplet size distribution is shown in Figure 9.



Original image FFT filter applied Threshold applied Droplets are measured

Figure 8. Steps of image processing to calculate droplet size distribution

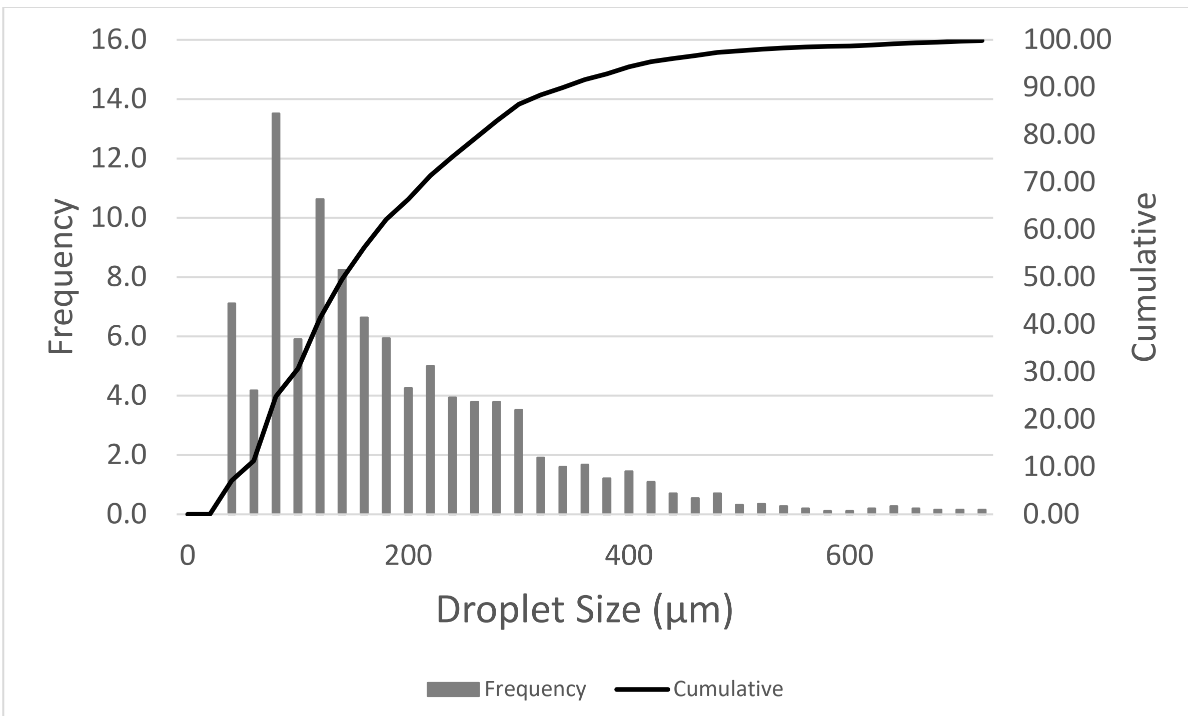


Figure 9. Droplet size distribution for spray at 2,068 kPa (300 psi), from 11 to 14 cm below the nozzle. Arithmetic Mean Diameter (d_{10}) = 170.9 µm.

Once the geometrical parameters of a spray, i.e. spread and dispersion angles, were measured, we setup the flat fan spray model in ANSYS/FLUENT. Figure 10 illustrates a CFD spray pattern compared to the experimental images. Processing of the numerical data confirms that both spreading angle and dispersion angle agree well with values reported in Table 2; this was expected as we specified these angles in the CFD model. Droplets are colored according to their velocity; it is seen that velocity decays with distance due to aerodynamic drag.

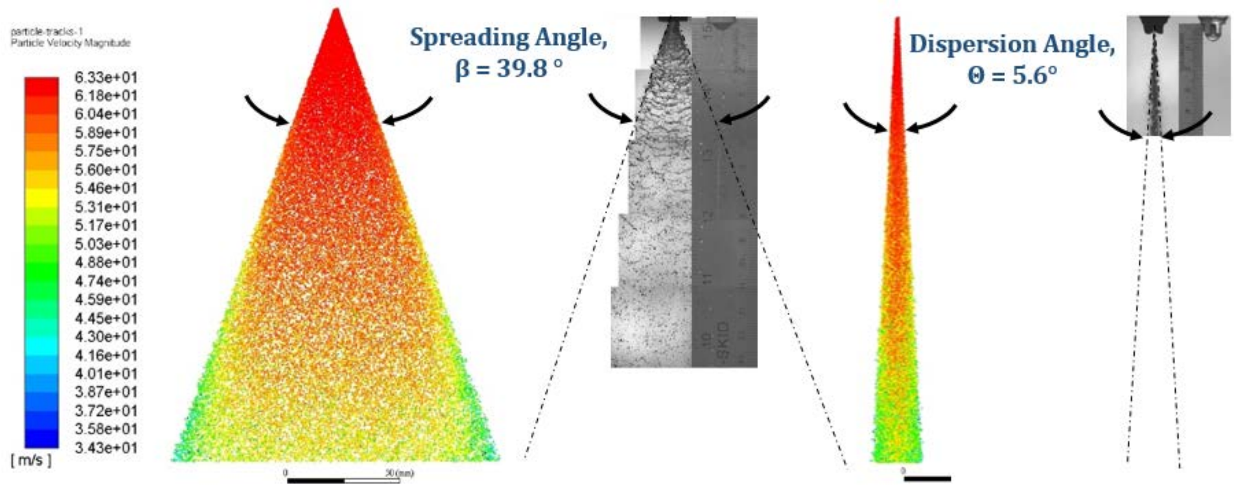


Figure 10. Comparison of CFD and experimental result at 2,068 kPa (300 psi)

In addition to the visual comparison, the droplet size distribution was calculated at different distances from the nozzle. An example is shown in Figure 11.

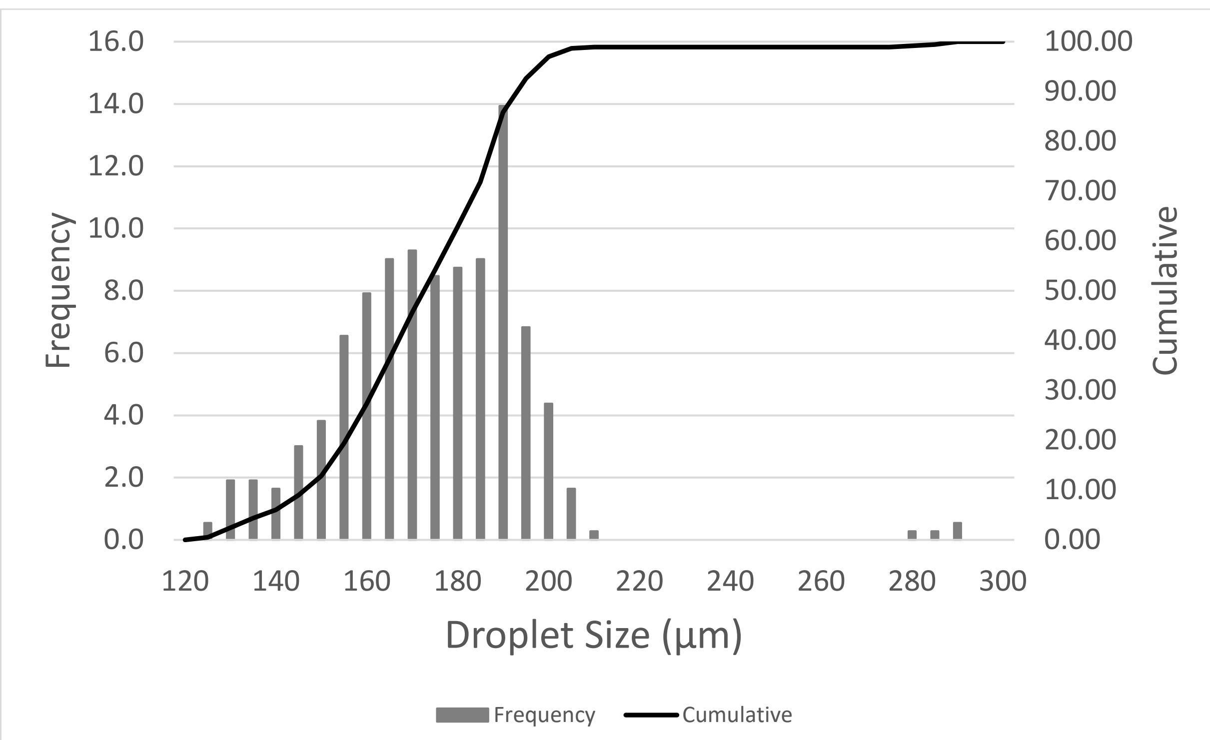


Figure 11. CFD results for droplet size distribution for the spray at 2,068 kPa (300 psi), from11 to 14 cm below the nozzle. Arithmetic Mean Diameter (d_{10}) = 176.7 µm.

The droplet size distribution can be compared to the experimental distribution, Figure 9. The comparison shows that the model predicts the droplet mean diameter satisfactorily. However, there is a difference between the spread of droplet size distributions. While the experimental result features a long-tail distribution, the CFD histogram does not spread as much. We suspect this is due to the secondary break up model which predicts the formation of child droplets from a parent droplet. In this study, the Taylor Analogy Breakup (TAB) model [10] was used; it is likely that the TAB model breaks up droplets faster than what happens in reality. As a result, the real spray contains larger droplets when compared with CFD predictions at the same distance from the nozzle. Further investigation on this topic is ongoing including use of other secondary breakup models.

CONCLUSION

This study clearly shows that in water atomization of molten metal, the water sprays actually impinge on the metal stream, not the water jets. If it were possible to control the water spray characteristics i.e. water droplet size distribution, it would be possible to better control the final powder particle size distribution. The water spray characteristics are a function of the process parameters and design parameters which include water pressure, water flow rate, nozzle design, and impingement angle. The water model in the lab-scale study yields interesting insights on spray characteristics and spray droplet size distribution for a variety of input conditions. A complementary mathematical model was developed to predict the spray characteristics as well; the CFD results are in good agreement with the experimental results. This validated mathematical model is now being extended to predict the metal droplet size distribution, and will be further validated with experiments of low melting point alloy atomization. Future research includes parametric studies on nozzle design, data analysis from an industrial plant for various process parameters, and an assessment of the impact of design changes on the atomization process.

ACKNOWLEDGEMENT

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