Evaluation of Orifice Shape Design on Flat Fan Atomization

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Abstract. The atomizer is a crucial component in spray columns used in mass transfer applications. Proper function of the atomizer can enhance mass transfer and reduce sorbent evaporation and droplet drift (physical loss). Commonly used atomizers for spray column application suffer from excessive droplet drift and high spray polydispersity. Flat fan sprays were beneficially used to reduce droplet drift in agricultural applications and in studies dealing with CO₂ capture. Six 3D printed flat fan atomizers with different internal channel geometry (elliptical, cone-shaped) were tested at four inlet pressures in this study. The liquid sheet breakup length and spray cone angle derived from high-speed visualization are compared for each atomizer design. No systematic difference was found between the elliptical and cone-shaped channels. The spray cone angle and breakup length were correlated only with experimental regimes (Reynolds number and Weber number). Perforations were responsible for the breakup of the liquid sheet at lower injection pressures, whereas the combined effect of perforations and waves dominated the liquid sheet breakup at higher injection pressures.

1 Introduction

Several different atomizers were tested in spray columns to assess suitability for scrubbing processes. The atomizer should yield a suitable droplet size to provide a sufficient mass transfer area, a suitable spray cone angle (SCA) to cover a large area without hitting the walls of the spray column, and a high spray monodispersity, which plays an important role in these processes. Full cone or hollow cone pressure atomizers have been widely studied under spray column conditions [1]. Twin-fluid atomizers were also tested as potential atomizers [2] [3]. Rapid liquid breakup is characteristic for the aforementioned atomizers, and a dense spray of small droplets is created close to the atomizer, which causes increased droplet drift. Many papers investigated the suitability of liquid sheets for spray columns conditions [4] to reduce the droplet drift. The liquid sheet can be created by impinging of two jets [5], impinging of a jet on a flat surface [6] or wire and by discharge of a liquid through a specially shaped exit orifice, e.g. flat fan atomizers [7]. Flat fan atomizers are widely used in agriculture applications, where the character of breakup influences the droplet drift [8]. The thin, almost one-dimensional, liquid sheet has a small frontal area and exerts less drag. Flat fan atomizers can create an undistorted thin liquid sheet resistant to ambient flow. In this study the effect of flat fan exit orifice shape on liquid sheet characteristics as SCA and liquid sheet breakup length (lₘ) is investigated.

Liquid sheet breakup and subsequently created droplets were thoroughly investigated in the past. Bourmand et al. [9] investigated the liquid sheet breakup over a wide pressure range and applied Proper orthogonal decomposition (POD) analysis to extract the underlying flow phenomenon. The bag breakup regime was identified. Xianguo et al. [10] identified two modes of liquid sheet instabilities, namely aerodynamics and viscosity enhanced mode. For the small Weber number (We), the main controlling mechanism of instabilities was asymmetrical disturbances. Antisymmetric disturbances dominated for high We. Asgarian et al. [11] combined experiments and CFD simulations to investigate the breakup mechanism of the liquid sheet for industrial conditions (high pressure and turbulent liquid flow). The breakup of the outer part of the liquid sheet differs from the central region because of different velocity. The studies were mainly devoted to industrial conditions with high pressure and short breakup length (lₘ). In the application of spray columns, long undisturbed liquid sheet is preferred, therefore a liquid sheet was tested on inlet pressures (pᵢ) from 0.05 MPa to 0.4 MPa.

2 Experimental setup

The High-speed visualization setup is provided along with a detailed description of the tested atomizers in this chapter. The water from the storage tank was pumped by the centrifugal pump and the flow rate was measured using a Coriolis mass flow meter (Siemens AG., GE), the pᵢ was measured close to the atomizer using a piezo-resistive sensor DMP 331i (BDsensors s.r.o., CZ).

2.1 High-speed Visualization

A high-speed camera FASTCAM SA-Z (Photron, Japan) was used along with a Sigma 180 mm f/2.8 (SIGMA Corporation, Japan) to capture the
instantaneous propagation of a liquid sheet. The high-speed camera frame rate was 20,000 fps with a shutter speed of 1 µs. The frame resolution was set to 1024 × 1024 px. The LED light model HPL3-36DD18B (Lightspeed Technologies, USA) was used to illuminate the spray with a pulse duration of 400 ns. A total of 2000 images were captured. The Matlab code was developed to derive the SCA and \( l_b \). Edge detection was applied to each image to find the boundaries of the liquid film. The liquid film boundaries were then fitted with a robust fit with linear function and SCA was determined. The standard mean deviation of the SCA was ± 2°. Along with the SCA, \( l_b \) was also derived with a standard deviation of ±1.5 mm.

2.2 Flat Fan Atomizers

Several different flat fan atomizers were designed and 3D printed on the SLA printer with a resolution of 35 µm/px. All atomizers were designed to obtain the same exit orifice area. Some deviations occurred due to the resolution of the 3D printer. The average exit orifice area was 0.132 mm\(^2\) with a standard mean deviation of ±0.114 mm\(^2\). The dimensions of the exit orifices were probed using a microscope. The exit orifice of the flat fan atomizer was created by intersection of the V groove and the conical (CI, CII, CIII) or elliptical channel (EI, EII, EIII) shown in Figure 1. The V groove dimensions were kept constant. The shape and dimensions of an inner channel varied.

![Fig. 1. Dimensions of the the intersection of conical (CI, CII, CIII) and elliptical (EI, EII, EIII) channel with V groove.](image)

3 Results and Discussion

This chapter provides a discussion about \( C_{du} \), SCA and \( l_b \) of liquid sheets created by different atomizer designs.

3.1 Liquid sheet breakup

We can observe that two jets are present at the outer periphery, which are connected via a thin liquid sheet for \( p_{in} = 0.1, 0.2 \) and 0.4 MPa (Figure 2). The liquid sheet created on the \( p_{in} = 0.05 \) MPa is wrapped by the surface tension forces and forms a jet stream that disintegrates into the droplets at a relatively small distance from the atomizer. A wider liquid sheet is created on the higher \( p_{in} \). The liquid sheet breakup due to perforations for \( p_{in} = 0.1 \) and 0.2 MPa. The perforations are also present for \( p_{in} = 0.4 \) MPa (observed from the front high-speed images). Waves (bag breakup) were observed from the side images. The combined effect of perforation and waves is responsible for the breakup of the liquid sheet for the \( p_{in} = 0.4 \) MPa. Breakup regime map can be found in Figure 3 for different Reynolds (\( Re \)) and Ohnesorge numbers (\( Oh \)). We can see that all experimental regimes (red dots in Figure 3) lie in the first and second wind-induced regimes.

![Fig. 2. Liquid sheet breakup for \( p_{in} = 0.05, 0.1, 0.2 \) and 0.4 MPa (from left to right) front (top) and side (bottom) view.](image)
3.2 Discharge Coefficient

The discharge coefficient ($C_d$) as a function of $We$ is illustrated in Figure 4. $C_d$ is slightly decreasing with increasing $We$. There was no link between $C_d$ and the geometry. The $C_d$ values are within the range measured in other studies [13].

3.3 Spray cone angle

The $SCA$ is very important spray characteristics as it determines the interaction with ambient flow. With the right selection of $SCA$, the desired area can be covered in the spray columns, and liquid amount sprayed on the walls can be minimized. The $SCA$ is determined only from the front view (since the side $SCA$ is very small). The $SCA$ is shown in Figure 5 for different atomizer designs and $Re$. $SCA$ almost linearly increases with $Re$. There is no difference between elliptical atomizers for small $Re$, but a large difference is obtained for higher $Re$. This is caused by the dependence of $SCA$ on the atomizer geometry (Figure 6) for higher pressures (higher $Re$). No dependency of $SCA$ on geometry was found for small pressures (small $Re$). Note here that there is a notable difference between the $Re$ regime for EI and other atomizers. This increases the $SCA$ for 0.4 MPa in Figure 6. No link between the geometry of conical atomizers and $SCA$ was found.

Chen et al. [14] found the link between the $SCA$ and the internal geometry for the intersection of the ellipse with the V groove. It was found that with an increase in the dimension of the ellipse major axis ($a$) the $SCA$ increased. Authors in [14] also found out that the diameter of the ellipse had no effect on the $SCA$ and that the angle of the V groove had the most prominent effect on the $SCA$. The opposite trend of $SCA$ with increasing $a$ was obtained in this study. The relationship between $a$ and $SCA$ is outlined in Figure 6.

The $SCA$ was corelated with $Re$, $We$ or exit orifice diameter ($d$) in [6] as $SCA \sim Re^{0.022}$, $SCA \sim We^{0.18}$ or as $SCA \sim d^{0.5}$. No correlation was found between the atomizer geometry and $SCA$, therefore $SCA$ was corelated with $Re$ as $SCA \sim Re^{0.95}$ with $R^2 = 0.81$ in this study (Equation 1). The correlation is shown in Figure 7.

$$SCA = 0.007Re^{0.95}$$ (1)

3.4 Liquid breakup length

When the disruptive forces overcome the cohesive forces the liquid sheet disintegrates into the ligaments
and subsequently into droplets. The liquid sheet is thinning with increasing distance from the atomizer, therefore atomizers with larger \( l_b \) create smaller droplets. The main requirement for the atomizers is to create a long and compact liquid sheet. The \( l_b \) of different atomizer designs is shown in Figure 8. Note here that the \( p_{in} \) ranged from 0.05 to 0.4 MPa, and \( l_b \) is increasing in this \( p_{in} \) region. With a further \( p_{in} \) increase, the \( l_b \) would shorten.

**Fig. 8.** \( l_b \) for different atomizer design.

\( We \) and \( Re \) were used to correlate \( l_b \) with \( R^2 = 0.73 \). The correlation for \( l_b \) is outlined by Equation 2 and Figure 9.

\[
l_b = 0.75 Re^{0.15} We^{0.25}
\]

(2)

**Fig. 9.** Comparison of measured and computed \( l_b \).

**4 Conclusion**

The effect of different flat fan atomizer designs on \( SCA \) and \( l_b \) was investigated in this study. The flat fan atomizers created by the intersection of the ellipse or the cone shaped channel with a V groove were investigated for \( p_{in} = 0.05, 0.1, 0.2 \) and 0.4 MPa. High-speed imaging was used to capture the instantaneous behavior of the liquid sheet. \( SCA \) and \( l_b \) were derived from images with a standard mean deviation of \( SCA \pm 2^\circ \) and \( l_b \pm 2 \text{ mm} \). All experimental regimes lie within the first and second wind-induced breakup regimes. The sheet perforations were responsible for the breakup in the lower \( p_{in} \) regimes, whereas the combined effect of perforation and waves (bag breakup) was responsible for liquid sheet break up for \( p_{in} = 0.4 \text{ MPa} \). The \( C_d \) was found to be comparable with other published studies investigating flat fan atomizers. A decreasing trend of \( SCA \) with \( a \) was found for the atomizer created by the intersection of the ellipse and the V groove. No systematic trend was found for cone intersection with V groove. The \( SCA \) was correlated with \( Re \) as \( SCA \sim Re^{0.05} \) with \( R^2 = 0.81 \). \( l_b \) increased for all measured regimes and was correlated as \( l_b \sim We^{0.25} \) and \( l_b \sim R^{0.15} \) with \( R^2 = 0.73 \). No systematic difference was found between the flat fan atomizer created by the intersection of the cone and V groove and the atomizer created by the intersection of the ellipse and V groove.

**Nomenclature**

| \( a \) | Ellipse main axis length [mm] |
| \( C_d \) | Discharge coefficient [-] |
| \( d \) | Exit orifice diameter [mm] |
| \( l_b \) | Liquid sheet breakup length [mm] |
| \( Oh \) | Ohnesorge number [-] |
| \( p_{in} \) | Injection pressure [MPa] |
| \( R^2 \) | Correlation coefficient [-] |
| \( Re \) | Reynolds number [-] |
| \( SCA \) | Spray cone angle [°] |
| \( We \) | Weber number [-] |

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