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# Usability of a low-end 3D printer for prototyping of pressure-swirl atomizers

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**Abstract.** With recent advance in print resolution of stereo lithography (SLA) 3D printers, a cheap and fast prototyping method of many industrial components is available. This paper examines the limits of the low-end SLA printer with a pixel resolution of 35 μm for the prototyping of pressure-swirl atomizers. Several differently sized atomizers with exit orifice diameter in range from 0.3 to 1.2 mm were produced with all dimensions evenly scaled. The circularity of the exit orifices was inspected by an optical microscope. Atomizers were operated under the same Reynolds numbers, which were selected to cover a pressure range between 4 and 10 bar for the smallest atomizer. The generated spray was observed with a high-speed camera. The discharge coefficient, spray cone angle (SCA) and circumferential liquid distribution were compared. Even the atomizer with 0.46 mm exit orifice produced a decent spray, almost comparable to the machined version. The discharge coefficient was slightly dependent on the size of the atomizer up to the exit orifice of 0.6 mm with the indices to print inaccuracies.

## 1 Introduction

Pressure-swirl (PS) atomizers are widely used to deliver fuel to various combustion chambers, for spray coating, or in agricultural applications. Each application requires different spray properties; in combustion, the small droplets are favourable, but in agriculture, these droplets will be carried away by an ambient air flow. To validate the atomizer design for a specific application, a rapid prototyping method is very convenient. The challenging part of atomizer manufacturing is the size of the smallest feature, which is the diameter of the exit orifice or an inlet port width. These dimensions are typically in the range from 0.2 to 2 mm.

Additive manufacturing is one of fast ways to create the atomizer prototype. The 3D printer adds layers of material and can create almost any design shape. To properly 3D prints the small PS atomizer, the printer resolution must be much higher than the size of the printed feature. This eliminates most Fused Deposition Modelling (FDM) printers, which add layers of melted thermoplastics in predetermined path. The width of this path is usually greater than 0.2 mm, which is too large for the majority of real-sized atomizers.

Another widely used method is stereo lithography (SLA) 3D print which relies on photopolymerization. These machines use a light source (laser or LCD screen) to cure a liquid resin into hardened plastic. They can achieve higher resolution compared to FDM types as the resolution depends only on pixel size of the LCD screen or laser beam diameter. In recent years, the LCD screen-based 3D printer gains popularity as screen resolution improves and the printers drops in price.

This study omits expensive methods as photolithography or two-photon polymerization, which might be suitable for atomizer prototyping [1]. But their investment costs are several orders of magnitude higher compared to low-end SLA printers, which starts from 250 EUR as in 2022.

Several papers investigated the suitability of 3D printing of PS atomizers. Dhivyaraja et al. [2] examined the scaling properties of the PS atomizer using the etching and FDM printing method. The exit orifice diameter of the 3D printed atomizer was 1.1 mm, while the etched atomizer used three-time smaller scale of 0.37 mm. They found that the flow rate varies with pressure with a power law exponent slightly lower than 0.5. Other authors used selective laser melting for atomizer production [3], however, large surface roughness limits its usability for small-scale atomizers.

This paper aims to determine the suitability of a low-end SLA 3D printer with an initial investment cost < 400 EUR for prototyping of PS atomizers with exit orifice < 1 mm.

## 2 Experimental setup

Experiments were performed at specially designed test bench for atomizer cold testing at Brno University of Technology. This chapter describes atomizer design, liquid supply system, and measurement apparatus (high-speed camera and mechanical patternator).

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### 2.1 Tested atomizer

Simplex PS atomizers, originally developed for fuel delivery into the combustion chamber, were investigated. Its design is identical to the atomizer used in [4], see Fig. 1, but with different scale. Six differently sized versions, see dimensions in Table 1, were produced with identical Swirl number and atomizer constant. The atomizers were printed in a single piece, which was connected directly to the water inlet line by a union nut. The printing plane was tilted by 30° for the smallest atomizer (atomizer I). Only in this setup, the atomizer was printed unclogged.

The atomizers were operated at three regimes characterised by a constant Reynolds number inside the inlet port, $Re_p$ = 1000, 1320 and 1650.

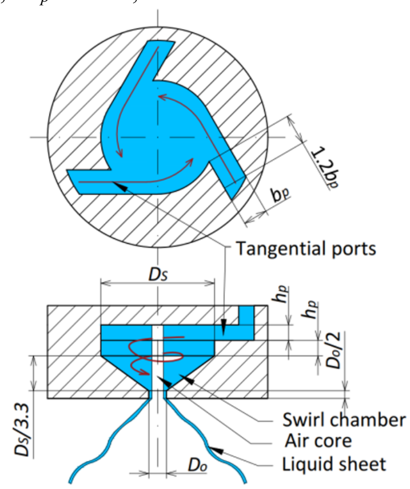


**Fig. 1**. Schematic drawing of the atomizer with main dimensions listed in Table 1.

**Table 1**. Dimensions of tested atomizers in mm, where $D_s$ is diameter of the swirl chamber, $D_o$ is diameter of the exit orifice, $h_p$ is height of the inlet port and $b_p$ is width of the inlet port.

| | I | II | III | IV | V | VI |
|---|---|---|---|---|---|---|
| $D_S$ | 1.9 | 2.9 | 4.0 | 5.0 | 6.0 | 7.7 |
| $D_O$ | 0.30 | 0.46 | 0.62 | 0.78 | 0.94 | 1.20 |
| $h_P$ | 0.26 | 0.40 | 0.54 | 0.68 | 0.82 | 1.04 |
| $b_P$ | 0.41 | 0.63 | 0.85 | 1.07 | 1.29 | 1.64 |

### 2.2 Liquid supply

Water was pumped by frequency-driven centrifugal pump to the atomizer. The water flow rate was metered by Siemens Mass 2100 Di3 Coriolis mass flow meter fitted with a Mass 6000 transmitter. The uncertainty of the flow rate is 0.2 % of its actual value. The liquid overpressure, $p_l$, was measured using a piezo-resistive sensor DMP 331i (BDsensors s.r.o., CZ) with an error of less than 3 kPa.

### 2.3 High-speed imaging

A high-speed camera FASTCAM SA-Z (Photron, Japan) was used along with a long-distance microscope 12X Zoom lens (NAVITAR, New York, USA) which consists of 2X F-mount adapter (type 1-62922), a 12 mm F.F zoom lens (1-50486) and 0.25X lens (type 1-50011) 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. For each spray, the field of view was changed to accommodate the same relative distance.

### 2.4 Patternator

The circumferential spray distribution was rated by a simple circular sectional vessel with 16 pie-shaped sectors, called a mechanical patternator; see [5] for details. The patternator was placed 50 mm downstream from the exit orifice of the measured atomizer. The duration of each test was determined by the time required for one of the sectors to become nearly full. The coefficient of variation ($Cv$) was used as a single parameter that describes the circumferential uniformity of the liquid. $Cv$ = 0 represents a uniform distribution.

## 3 Results and discussion

The results are divided into three main sections. The first one discusses atomizer's flow conditions, the second one deals with spray parameter as means of liquid distribution and spray cone angle (SCA) and the last discusses exit orifice print quality.

### 3.1 Atomizer flow conditions

Differently sized atomizers yield very different liquid flow rates when operated at constant $Re_p$. The flow rate scales almost linearly with atomizer size when $Re_p$ is constant. However, to accurately compare the flow in the atomizer, the discharge coefficient ($C_D$) should be used. The $C_D$ is a ratio between the actual and the theoretical mass flow rate through the exit orifice, defined as:

$$C_D = \frac{\dot{m}_l}{A_o\sqrt{2\rho_l p_l}} \quad (1)$$

where $\dot{m}_l$ is liquid flow rate, $A_o$ is area of exit orifice, $\rho_l$ is liquid density and $p_l$ is liquid overpressure. Because the atomizers operate at constant Re, no change in $C_D$ is assumed. This is supported by a simple, but widely used correlation of $C_D$ as a function of atomizer size only [6]:

$$C_D = 0.35\left(\frac{A_p}{D_s D_o}\right)^{0.5}\left(\frac{D_s}{D_o}\right)^{0.25} \quad (2)$$

Note that eq. 2 results in a constant value of $C_D$ = 0.42 for all tested atomizers. The measured values of $C_D$ are shown in Fig. 2. It is evident that the smallest atomizer size with $D_o$ = 0.3 mm exhibits much higher values of $C_D$ than the rest of the atomizers. This behaviour indicates an undeveloped internal air-core, which typically blocks off a significant portion of the exit orifice. A similar pattern was observed in the past for spill-return atomizers [7]. The reason for this behaviour might be linked with no properly printed swirl chamber or inlet ports, see the following sub-chapter with spray parameters. The slightly increased $C_D$ was also observed for the 0.46 mm exit orifice, but its effect on spray quality was not significant. The larger atomizer converged to the theoretically predicted $C_D$ with small deviations caused by both flow and dimensional measurement uncertainty. Moreover, for larger atomizers, the $C_D$ is systematically smaller for higher $Re_p$. This is a well-known fact [6,7].

### 3.2 Spray parameters

Due to the different operating pressures used in this study, only the SCA and the liquid circumferential distribution are evaluated because droplet sizes are difficult to compare.

The spray generated by the PS atomizer is in the form of a hollow conical liquid sheet, which disintegrates into ligaments in relatively far from the atomizer. The typical spray shape is shown in Fig. 3, where the atomizer II is revealed. Note that SCA is slightly increasing with a $Re_p$ along with simultaneous decrease in the break-up distance, which has been well documented in the past [6]. In our case, it is more pronounce for larger atomizers, as shown in Fig. 5. However, the SCA is rapidly decreasing with increasing atomizer size. This behaviour was not expected, even when the large atomizers were operated at much lower $p_l$. The empirical correlation from [6] predicted only a minor 3% decrease in *SCA* values for large atomizers. This effect must be evaluated in more detail in future. The smallest atomizer generated non-symmetrical spray with a much smaller SCA than other atomizers. This match well with findings in the previous chapter and suggest that probably the inlet ports are not correctly 3D printed. As a result of the small dimensions, it was impossible to cut the atomizer and inspect the inlet port structure without changing it by the cut itself.

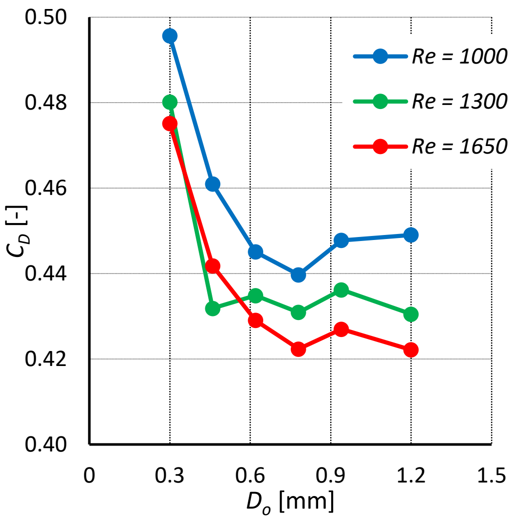


**Fig. 2**. Effect of $D_o$ on $C_D$.

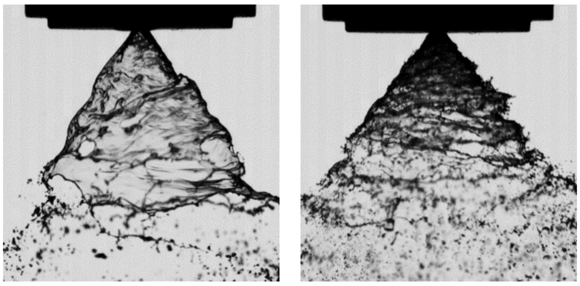

**Fig. 3**. Spray shape at $Re_p$ = 1000 and 1620 for Atomizer II ($D_o$ = 0.46).

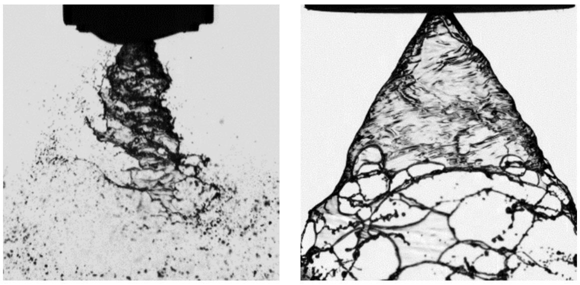

**Fig. 4**. Spray shape at $Re_p$ = 1320 for Atomizer I and VI ($D_o$ = 0.3 and 1.2 mm).

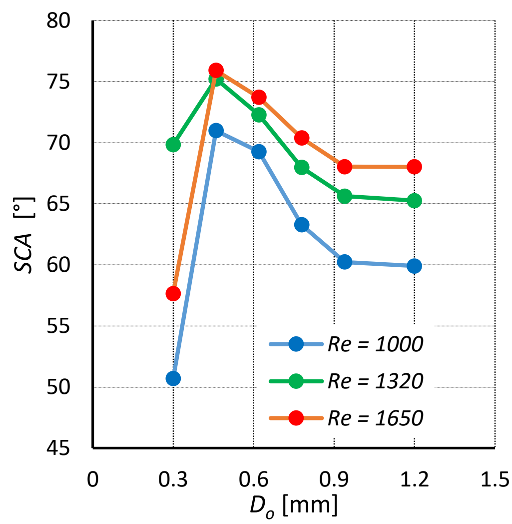


**Fig. 5**. Effect of $D_o$ on *SCA*.

The liquid circumferential distribution assessed by means of $C_v$ in Fig. 6 shows only small differences among the atomizers II-VI. There was a minor decrease in the $C_v$ value with $Re_p$. This was observed in the past [8], where similarly sized atomizers produced by CNC machining reach very similar $C_v$ values of 0.2. Note here that the atomizer I exhibits much higher $C_v$ values due to non-symmetrical spray.

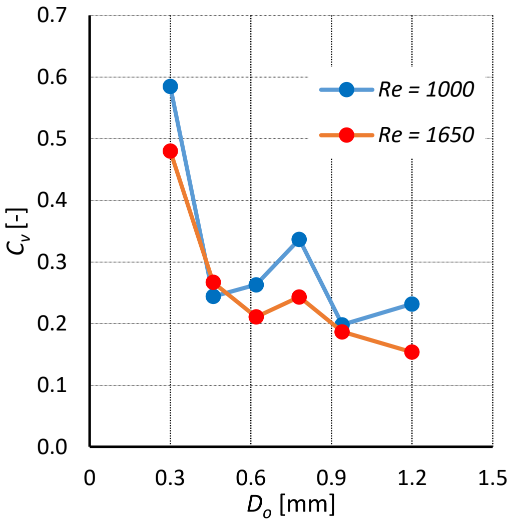


**Fig. 6.** Effect of $D_o$ on liquid circumferential distribution.

### 3.3 Exit orifice print quality

The precision of the 3D print was investigated using an optical microscope by observing the quality of the exit orifice. There were almost no deviations from the perfect circle for atomizers with $D_o > 0.6$ mm. Even the atomizer II, which is shown in Fig. 7, achieved relatively good circularity with the smallest diameter of 0.454 mm and the largest of 0.471 mm. An area accuracy differs less than 2% from the model size, and it is even improving for larger atomizers. However, there are notable round edges on the exit orifice, which might cause a slight opening of the SCA for the smallest version. The overall surface roughness is sufficiently low for PS atomizers.

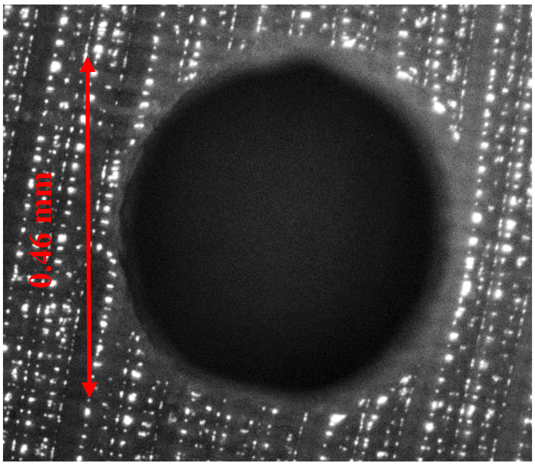


**Fig. 7**. The exit orifice of atomizer II ($D_o$ = 0.46).

## 4 Conclusion

Six differently sized pressure-swirl (PS) atomizers with exit orifice diameters ranging from 0.3 to 1.2 mm were printed on a low-end SLA printer. The results indicate that the smallest atomizer was not correctly printed. It exhibits increased $C_D$, poor circumferential uniformity, and also narrow spray cone angle. However, slightly larger atomizer with 0.46 mm exit orifice diameter yield spray quality very similar to the CNC machined versions. A cheap SLA printer can be used for the reproducing and rapid prototyping of PS atomizers if their minimal feature size is approximately greater than 0.5 mm. The printed atomizers withstand 1 MPa of water overpressure without any notable damage.

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