Suitability of different twin-fluid atomizer types for CO_2 capture in spray columns

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Abstract

Post-combustion-capture of primary greenhouse gases is one of the global warming reduction methods. Twin-fluid atomizers can be used for spraying of aqueous ammonia solutions, which scrub CO_2 from flue gasses. This process requires well-tailored spray characteristics, such as mean drop size, drop size distribution and droplet density. Spray cone angle (*SCA*), and droplet velocity are additionally relevant in spray mixing and droplet-gas interactions in spray columns. Choosing a relevant atomizer and optimum operation regime allow for effective solvent utilization in the flue gas scrubbing process.

The present work examines four different twin-fluid atomizers operated at an inlet pressure of 0.05, 0.1 and 0.2 MPa with gas-to-liquid ratio (*GLR*) 2.5, 5 and 10%: classic effervescent atomizer with single exit orifice, multi-hole effervescent atomizer with four exit orifices and two novel “impinging” effervescent atomizers with impingement angles of 20° and 45°. Their spray structure and *SCA* were analysed using high-speed visualisations. The droplet size and velocity in the spray were probed using a phase-Doppler analyser (PDA). Impinging effervescent atomizers shows favourable spray characteristics for spray columns application as smaller *RSF*, uniform velocity and larger spray cone angle.

Keywords

CO_2 capture; Twin-fluid atomizers; Phase-Doppler anemometry; Spray characteristics

Introduction

CO_2 is one of the most produced gasses released into the atmosphere. European Union aims to reduce CO_2 and eventually became CO_2 neutral society. However, the current energy mix still requires carbon-based fuels due to their reliability, and their importance as a backup power source will also last in the future. Therefore, to achieve a carbon-neutral economy, the flue gases must be de-carbonised. A simple way of post-combustion CO_2 capture uses column reactors with sprayed absorbents. The atomizer, as the key component, must generate appropriate droplet sizes and spray shape. Effervescent atomizers are an excellent option for efficient usage in spray columns due to their energy efficiency and ability to atomize high-viscous liquids.

Nevertheless, some spray parameters limit the practical usage of the effervescent technique in CO_2 scrubbing. The spray typically features a wide droplet size range, narrow spray cone angle (*SCA*), or high droplet momentum. The CO_2 scrubbing requires a rather monodisperse spray and tailored *SCA* to cover all column area. The spray characteristics can be modified by the operating regime and the atomizer geometry, including change in internal parts and exit orifice configuration.

Many different atomizer designs were used for the CO_2 capture technology in the past. Bandyopadhyay et al. [1] used a critical-flow atomizer and investigated the influence of atomizing air pressure and solvent flow rate on droplet Sauter mean diameter, *SMD*. This atomizer generated a rather polydisperse spray with high-velocity droplets. Diffusion of CO_2

from the surface to the droplet core is a slow process. Therefore larger droplets are usually not fully saturated with CO_2 for reasonably sized spraying columns. The chemical reaction time for smaller droplets is sufficient, the droplets are saturated, but they cannot capture more CO_2. For highly polydisperse sprays, the amount of charged CO_2 is therefore always sub-optimal. Monodisperse atomizers or sprays with narrow droplet distribution are more appropriate. Cho et al. [2] investigated mesh with very small orifices for droplet generation of 300 µm sized droplets. This atomizer creates monodisperse droplets with a uniform spatial and temporal distribution. Kuntz et al. [3] used two differently sized pressure atomizers. When both atomizers were operated at the same flow conditions, the larger one obviously generated larger droplets with a lower surface area of the droplets, and the CO_2 capture rate deteriorated. This paper focuses on internally mixed twin-fluid atomizers in several modifications. These atomizers are suitable for atomization of high viscous liquids, such as DEA or TEA (diethanolamine or triethanolamine) [4, 5], and require low inlet pressure and a small amount of atomizing gas, which lowers the operation cost. Dimensions of the flow areas of twin-fluid atomizers are relatively large, which prevents clogging. The effervescent atomization was developed in 1980 by Lefevre and co-workers [6]. Many authors investigated the influence of operation parameter and atomizer geometry on spray droplet size [7], spray cone [8], near-nozzle spray structure and discharge coefficient [9]. The primary attention was devoted to studying the effect of atomizer internal geometry on atomization. The number, diameter and location of aerator holes in the mixing chamber were studied in [10]. The multi-hole aerator produced narrower droplet size distribution [10, 11]. The impinging configuration, which is successfully used to enhance spray quality from plain orifice atomizers, is introduced here. This setup is expected to provide a wider spray cone and encourage droplet collisions, which may enhance the secondary atomization of large droplets and coalesce the smallest ones.

Material and Methods

This chapter briefly describes the experimental apparatus is provided. Water was used as the test liquid. Its mass flow rate was measured using Coriolis mass flow meter Mass 2100 Di3 fitted with the Mass 6000 transmitter (Siemens AG, GE) with accuracy ± 0.1% from actual flow rate. The airflow rate was measured by the FMA-A2100 mass flow meter (Omega Engineering, USA) with accuracy ± 1% from the actual flow rate. The inlet liquid and air pressures were metered by a DMP 331i (BD SENSORS s.r.o, CZ) with a measurement uncertainty of 1.5 kPa.

Phase Doppler anemometry

The spray droplets' size and velocity were probed using a two-component fibre-based commercial PDA (Dantec Dynamics A/S Skovlunde, DK) in the axial distance of Z = 100 mm from the exit orifice. Non-coincidence velocity mode was used. The PDA setup is illustrated in **Figure 1** and **Table 1**. The repeatability of velocity, droplet diameter (D_{10}), and Sauter mean diameter (*SMD*) measurement was ± 0.5 m/s, ± 1.1 µm and ± 1.8 µm, respectively. The measurement range of droplet diameter was 243 µm.

The droplet size range was determined using the relative span factor (*RSF*), see equation 2. To cover the whole spray with a single parameter, integral relative span factor (*IRSF*) was derived as the *RSF* weighed by data-rate and representative area, see equation 3.

$$RSF = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \tag{2}$$

$$IRSF = \frac{\sum_i r_i RSF_i f_i}{\sum_i r_i f_i} \tag{3}$$

Where $D_{V0.9}$ [μm] is the droplet diameter, indicating 90% of spray volume contained in droplets smaller than this diameter. $D_{V0.5}$ [μm] is mass median diameter, and $D_{V0.1}$ [μm] is the droplet diameter, which indicates 10% of spray volume contained in droplet sizes smaller than this value. f_i [Hz] is the droplet data rate, and r_i [m] is the radial distance from the spray centre axis. The integral Sauter mean diameter (*ISMD*) provides the global representation of *SMD* and was derived as data-rate and area-weighted *SMD* in a similar way as *IRSF*.

Table 1. PDA setup

Parameter	*Value*	
Laser power output	0.3 W	
Scattering angle	60 °	
Receiver mask	B	
Receiver spatial filter	0.1 mm	
The focal length of transmitting/receiving optics	500/800 mm	
Wavelength	488 nm	514.5 nm
Velocity component	Axial	Radial
Velocity centre [m/s]	38.6	0
Velocity span [m/s]	77.2	73.2
Sensitivity [V]	750	900
Signal gain [dB]	8	12

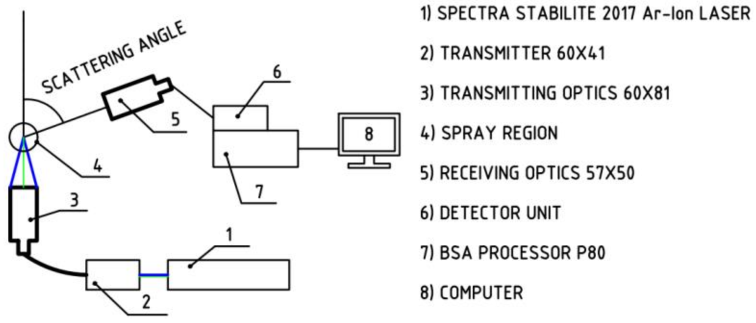

Figure 1. Experimental setup of PDA

High-speed visualization

A high-speed camera FASTCAM SA-Z type 2100K-M-16GB (Photron, Japan) was used to capture the instantaneous image of the spray. The camera frame-rate was set to 60,000 fps with a shutter speed of 1 μs. The Led light model HPL3-36DD18B (Lightspeed Technologies, USA) was used to illuminate the spray with a light pulse duration of 400 ns. In total, 4000 instantaneous images were captured for each record.

Atomizer geometry

Internal mixing twin-fluid atomizers were used. The geometry of aerator holes is illustrated in **Figure 2,** and it was kept constant. Several exit orifices were tested, including standard single orifice effervescent atomizer (1hole), multi-hole effervescent with four exit orifices (4hole) and impinging configuration with two orifices angled by 20° (2hole20) and 45° (2hole45), see **Figure 2**. The atomizers were operated at three pressure regimes of 0.05, 0.1 and 0.2 MPa and three *GLR* regimes of 2.5, 5 and 10%.

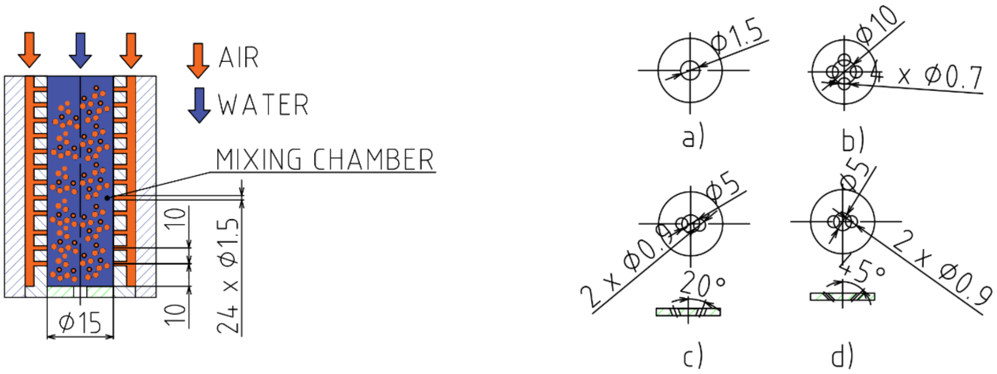

Figure 2. Left: Internal geometry of the atomizer, right: configuration of exit orifice a) 1hole, b) 4hole, c) 2hole20, d) 2hole45

Results and Discussion

This part is divided into three sub-chapters. The first one deals with the spray structure; the second one focuses on radial spray characteristics for one selected regime, while the third one compares the global parameters for various operating regimes.

Spray cone angle and spray structure

The spray structure, shown in **Figure 3**, was recorded directly behind the liquid discharge point. The single-orifice configuration discharges a relatively stable liquid stream with very narrow *SCA* (see its value in **Figure 4**). The *SCA* slightly increases with *GLR* as $SCA \sim GLR^{0.09}$ and with inlet pressure as $SCA \sim P_{in}^{0.21}$. It is consistent with [12], where the increase in *SCA* with *GLR* and pressure was observed as well. With increasing the *GLR,* the influence of inlet pressures diminished[12]. The four-orifice variant produces four independent liquid streams, each one with a similar *SCA* trend as the single-orifice atomizer. However, the overall spray width remains rather constant as the liquid streams slightly converge toward the spray centre. It is independent of the operating regime. Note here that for low *GLR*, each orifice discharges a liquid stream with a different structure indicating inhomogeneous air/liquid distribution over the mixing chamber area. This may produce unequal spray quality.

The impinging variants yield a wide spray cone in the impinging plane as expected. The *SCA* is given by inclination of the orifices and is almost independent of the operating regime. The liquid streams of the 2hole20 type collide roughly 4 mm downstream the atomizer tip where separated ligaments appear. It causes some visible droplet collisions. Different outcome was observed for the 2hole45 atomizer. In this case, the liquid streams collide 1 mm downstream, where the primary atomization is incomplete for *GLR* 2.5, 5 and 10%. This causes the formation of larger droplets, see *GLR* 2.5% in **Figure 3**, where pattern typical instead for plain-orifice impinging jets appears.

Radial characteristics

The radial distribution of axial velocity, data-rate, mean droplet diameter (D_{10} and *SMD*) is shown in **Figure 5**. The behaviour of the 1hole atomizer corresponds well with other observations of similar construction [13]. It exhibits a sharp velocity maximum in the spray centreline with a large number of small droplets. The 4hole version yields similar distribution with slightly lower velocity maximum and larger droplets in the spray centre but with comparable drop size at spray boundary. It is evident that four separate streams rapidly converge into one stream with a spray shape similar to the 1hole atomizer. Moreover, no traces of discreet liquid streams were found 100 mm downstream of the atomizer.

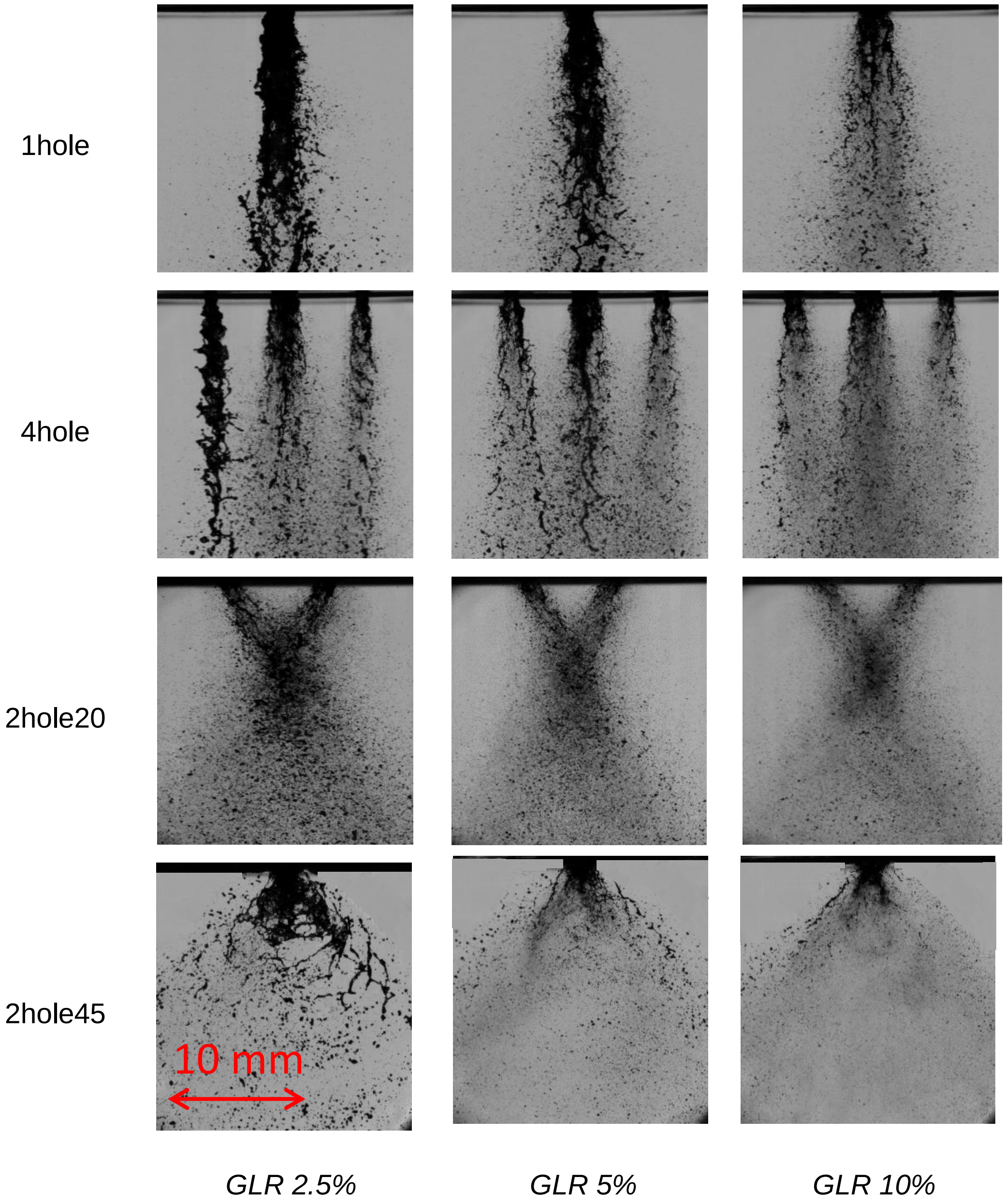

Figure 3. Spray structure

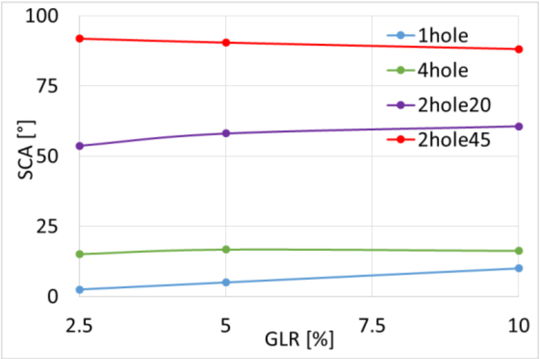

Figure 4. Spray cone angle

The impinging atomizers differ each other as expected. The 2hole20 produce wider spray with a roughly one-halve axial velocity value. The droplets are larger in the spray centre, but the size minimum is still present there. The 2hole45, with the broadest *SCA*, exhibits very different spray morphology. The axial velocity profile is flat with two faint velocity maxima in the positions, where the liquid streams are expected (-40 and +50 mm). Opposite trends in the radial profiles of droplet size were observed compared to the other versions, with a local maximum in the spray centre. Note here that the spray from both impinging atomizers creates an elliptic pattern, but only the main axis is discussed here. Yet, the spray symmetry is worse compared to 1hole atomizer. This might be linked with manufacturing precision or with internal flow sensitivity to the off-axial orifices configuration as discussed for 4hole version along with **Figure 3**.

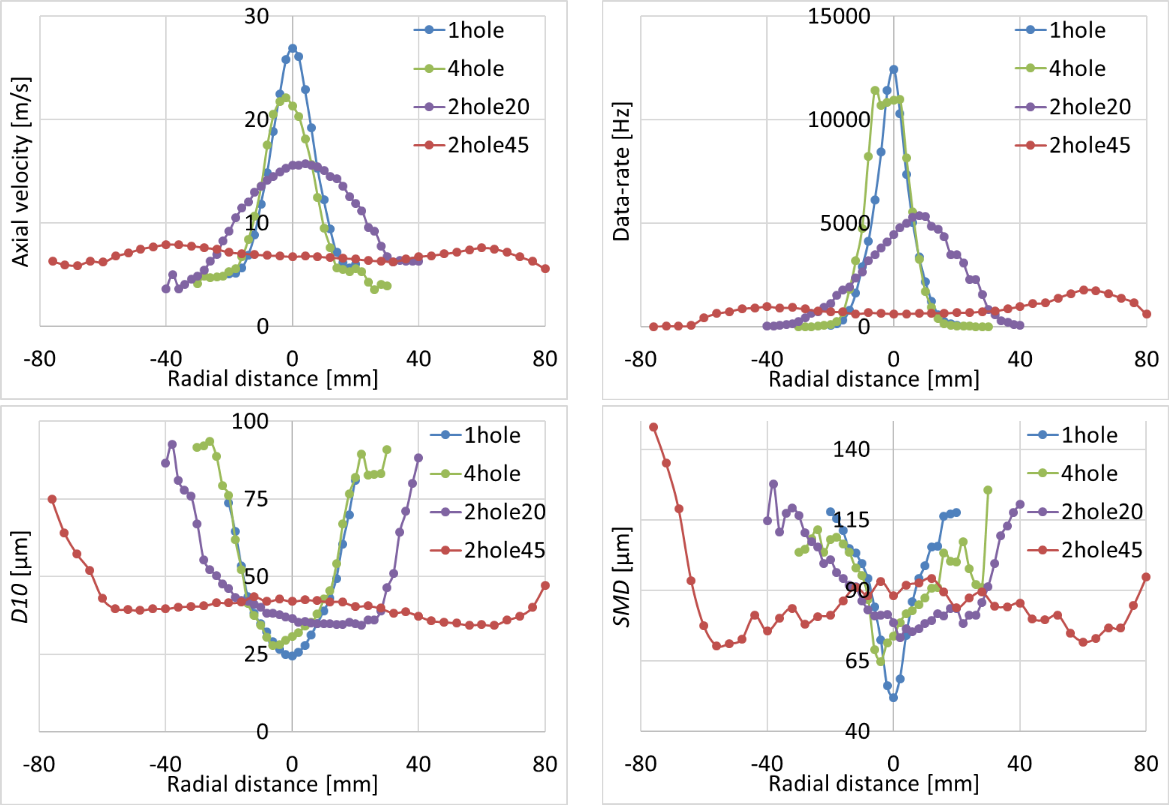

Figure 5. Radial spray characteristics for inlet pressure 0.1 MPa and *GLR* 5 %

Global *ISMD* and *IRSF*

The global spray representations *ISMD* and *IRSF* as a function of *GLR* for different pressure regimes are illustrated in **Figure 6**. The *ISMD* consistently decreases with *GLR* and inlet pressure for all the configurations, which is typical effervescent atomizer behaviour [12]. The 1hole atomizer exhibits $ISMD \sim GLR^{-0.12}$ and $ISMD \sim P_{in}^{-0.05}$. The 1hole and 4hole versions outperformed the impinging ones in 2.5 and 5% *GLRs*. The 4hole generated smaller droplets in all regimes compared to the standard 1hole atomizer. This can be linked with the exit orifice size, as smaller orifices produce smaller droplets. However, its *IRSF* is significantly larger.

The *ISMD* of impinging atomizers strongly depends on *GLR.* Both variants feature lower *ISMD* at 10% *GLR* compared to the non-impinging types*.* The 2hole20 gives systematically smaller *ISMD* compared to the 2hole45, with its about 30% larger *ISMD* compared to the non-impinging type for *GLR* 2.5%. It confirms the observation in **Figure 3**, where larger droplets emerge from the liquid stream collision. It suggests that impinging point close to the atomizer exit orifice may cause insufficient bubble expansion and large droplets on the spray periphery.

The droplet size distribution width, represented by *IRSF*, significantly increases with *GLR* and only slightly with P_{in} regardless of the atomizer used. Note that this is in contrast

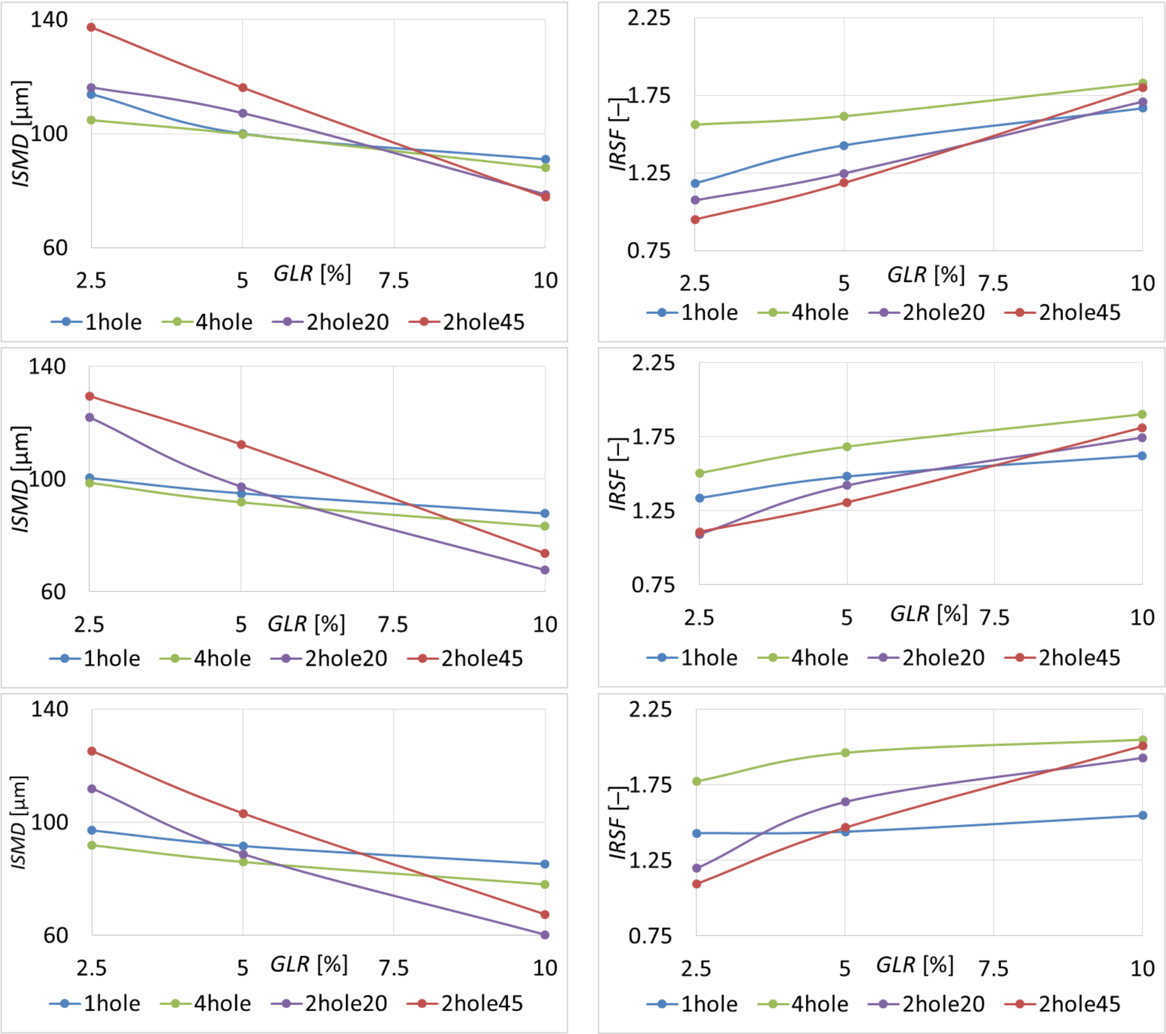

Figure 6. From top: 0.05, 0.1 and 0.2 MPa, Left: *ISMD*, Right: *IRSF*

to [12], where *IRSF* was found decreasing with *GLR*. However, the image-based droplet sizing technique used in [12] might underestimate the number of small droplets generated in the high *GLR* regime. The impinging atomizers produce lower *IRSF* for *GLR* = 2.5 and 5% for low pressure than the classic 1hole version.

Conclusions

Four different internally mixing twin-fluid atomizers were experimentally investigated using Phase-Doppler Anemometry and a High-speed camera. The differentiating parameter was the exit orifice geometry. Single exit orifice was compared with four-orifices configuration. Two new impinging atomizers were designed in order to reduce *IRSF* and create a wide spray cone. The multi-hole atomizer outperforms a single orifice in terms of *ISMD* but yields higher *IRSF.* The spray quality of impinging versions was sensitive to *GLR.* For *GLR* < 5%, they feature higher *ISMD* but slightly smaller *IRSF* compared to the non-impinging types. For *GLR* = 10%, it performs the opposite way. It is recommended to place the impinging location outside the primary atomization zone; however, more research must be conducted to confirm this conclusion. Also, further internal flow study of the atomizer with multiple off-axial orifices should improve its internal geometry design. Impinging atomizers produce larger spray cone angle, smaller droplet *RSF* with more uniform droplet velocity for low *GLR* and pressure regimes. This spray characteristics and low energy requirements are favourable in spray columns. Results of this study suggests the suitability of the new type of atomizer for spray columns applications. Further study of impinging effervescent atomizers is needed.

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Nomenclature

$D_{V0.9}$	Volume diameter [µm]	$ISMD$	Integral Sauter mean diameter [µm]
$D_{V0.1}$	Volume diameter [µm]	$IRSF$	Integral relative span factor [-]
$D_{V0.5}$	Mass median diameter [µm]	P_{in}	Injection pressure [MPa]
D_{10}	Mean diameter [µm]	RSF	Relative span factor [-]
f_i	Droplet data rate [Hz]	r_i	Radial position [m]
GLR	Gas-to-liquid mass ratio [–]	SCA	Spray cone angle [°]

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