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Experimental Analysis of Spatial Evolution of Mean Droplet Diameters in Effervescent Sprays

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Effervescent atomization has established itself in the past decade as a promising alternative to conventional spray formation mechanisms. A great effort is currently being put into understanding the involved phenomena and developing numerical models to predict outcomes of processes relying on effervescent atomizers (i.e. spray combustion, coating, drying). This still proves to be a formidable challenge as effervescent atomization is a complex process involving two phase flow.
The presented paper focuses on mean droplet sizes and how they vary throughout effervescent sprays at different operating conditions. The experiment was performed using Phase Doppler Anemometry (PDA) and the droplet data were collected in multiple locations varying both axially and radially. At each measurement location the Sauter Mean Diameter (SMD) was computed. The preliminary results show that closer to the spray nozzle the bigger droplets are concentrated in the spray core, while the small droplets are in the peripheral regions. However, this trend is slowly reversing with increasing distance from the spray nozzle. Finally, from a certain distance the initial trend is completely reversed with the small droplets being in the spray core, while larger droplets are found closer to the edge of the spray. Moreover, this phenomenon seems to be independent of operating conditions. Reasons for such behaviour are suggested and discussed. Furthermore, SMD sensitivity to operating conditions is analysed.

1. Introduction

In the field of spray combustion, especially in oil furnaces and combustors, effervescent atomizers (twin fluid atomizers with internal mixing) introduced by Lefebvre et al. (1988) are quickly gaining on popularity over more traditional forms of atomization (Kermes et al., 2012). The spray formation process in this type of atomizers does not rely solely on high liquid pressure and aerodynamic forces, instead a small amount of gas, usually air, is introduced in the liquid before it exits the atomizer and a two phase flow is formed (Jedelský et al., 2007). When the mixture exits through the nozzle, the pressure drop forces the gas bubbles to expand causing the liquid to break up. This breakup mechanism allows the use of lower injection pressures and larger nozzle diameters without compromising the drop-size distribution (Babinsky and Sojka, 2002). The only obvious drawback of this method, apart from the need to have a source of pressurized gas, is its complexity originating from the two-phase flow inside the nozzle. This complexity is the major challenge in finding accurate mathematical and numerical models that could be used as an aid to designers of burners and furnaces. Extensive experimental research is ongoing in the area of effervescent sprays aimed at providing validation data for numerical models in terms of Sauter mean diameter (SMD). The Sauter Mean Diameter is defined as a diameter of a representative droplet having the same volume/surface area ratio as the whole spray. As pointed out in (Broukal and Hájek, 2011a), this can be a very rough approach, since even if the global SMD of the spray in question is in good agreement with measurements, local SMD values may be significantly different and thus cause faulty numerical predictions. Moreover, as shown in (Juslin et al.,1995) and more recently by (Broukal and Hájek, 2011b) and, sprays often exhibit multimodal behaviour in drop size distributions, which further raises the question about legitimacy

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Table 1: Operating conditions

Measurement	Mass flow rate [kg/h]	GRL [%]	Liquid pressure [kPa]	Gas pressure [kPa)
#1		5	34.5	55.2
#2	31.2	10	89.6	144.1
#3		15	144.8	234.4
#4		5	72.4	103.4
#5	42	10	182.7	250.3
#6		15	289.6	386.1
#7	60	5	165.5	200
#8		10	310.3	399.9

Table 2: Measurement points overview

		Radial distance from spray axis [cm]					
Axial distance [cm]	5	0	0.5	1	1.5	2	2.5
	10	0	1	2	3	4	
	15	0	1	2	3	4	5

of using a single representative diameter. To remedy this, more detailed information is needed to make really sensible validations. Namely, data about radial distribution of droplet size and velocity would be desirable (or equivalently depending on spray angle), especially for the case of large nozzles in industrial burners. In the last decade few papers can be found that address the issue of radial drop size distribution and radial SMD evolution sprays. Park et al. (2009) employed the wave breakup model to investigate biodiesel spray generated by two pneumatic nozzles. He takes into account various fuel and ambient conditions and focuses on SMD evolution. Along with axial SMD evolution, also radial SMD evolution was reported. Unfortunately, only three radial SMD were disclosed. In (Pougatch et al., 2009) an effervescent spray model is presented and applied to water-air atomization. Radial drop diameter evolution is predicted at various axial positions, but no comparison with experimental data has been made. Recently the situation has improved as more researchers focus in more detail on a complex effervescent spray measurement (Li et al., 2012). Lian-sheng et al. (2012) performs a detailed experimental measurement of effervescent spray combustion. The work reports various radial SMD and axial drop size distributions. Also, a swirl effervescent atomizer is employed and the influence of swirl on spray angle is demonstrated. However, the liquid mass flow rates are still in a lab-scale region with a maximum of only 10 kg/h.
The purpose of this study is to perform an experimental study with emphasis on SMD spatial evolution (both axial and radial) at various operating conditions that can be regarded as large-scale.

2. Experimental setup

The experimental measurements where performed at Maurice J. Zucrow Laboratories at Purdue University, USA using a Dual PDA apparatus. The PDA is a non-intrusive optical technique, on-line and in-situ. Due to the nature of the technique, optical access to the measurement area is needed, which can be sometimes limiting for on-site industrial measurements. Since the method requires particles to be spherical (or only slightly deformed), measurements must be taken at a sufficient distance from the discharge orifice. Also, the method is not suitable for very dense spray regions. The measurement device consists of a laser based optical transmitter, an optical receiver, a signal processor and a software for data analysis.
The spray was generated using vertically positioned effervescent atomizer described in (Jedelský et al., 2009) as E38 with nozzle diameter 2.5 mm. As seen in Table 1, eight various sprays have been measured varying in gas-liquid-ratio (GLR) and mass flow rate. At each operating condition data from 17 measurement points have been collected. The measurement points where divided among three planes perpendicular to the spray axis at distances 5, 10 and 15 cm from the nozzle tip. At each plane the points where distributed radially in an equidistant fashion starting from the spray axis (see Table 2). The working liquid was water and atomizing gas air, both at room temperature.

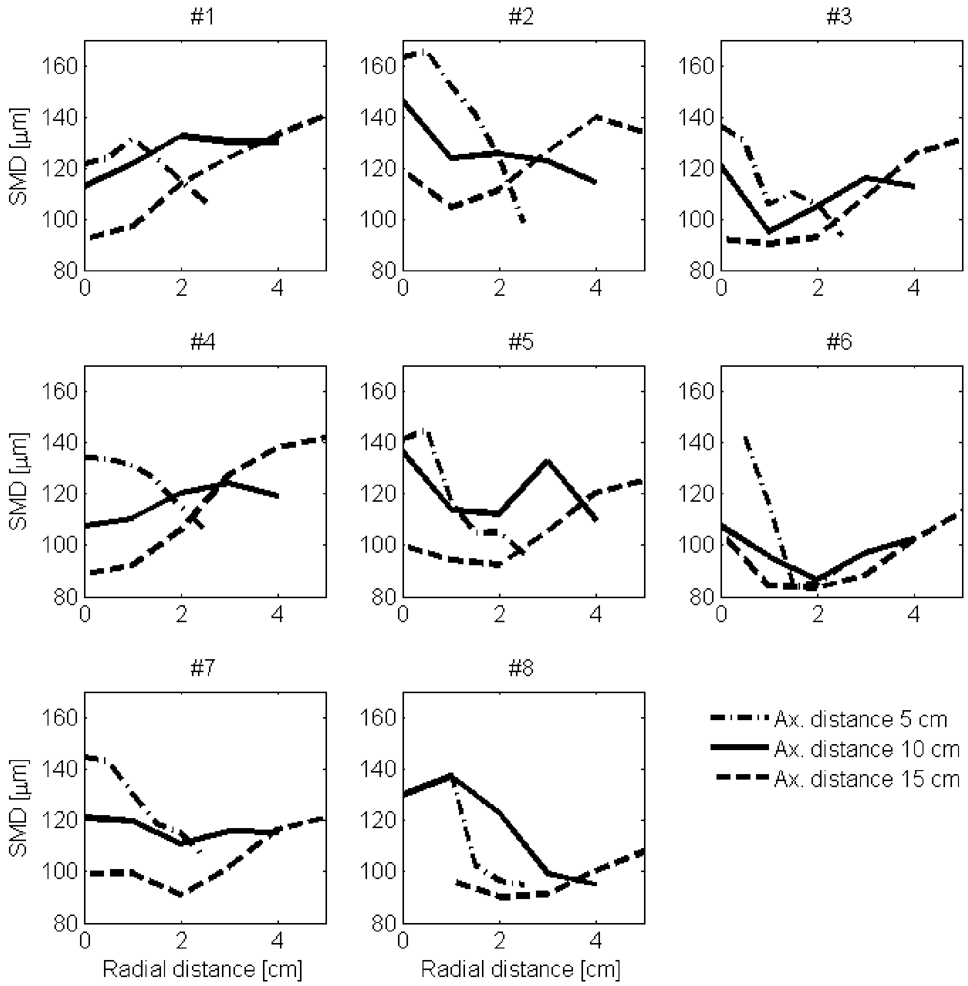

Figure 1: Radial SMD evolution at various axial distances for operating conditions #1 to #8

3. Results and discussion

For combustion applications it is general practice to use SMD as a way of simplifying the spray in question. As shown in the previous paragraphs, a single value of SMD is not always suitable for global spray description. However, SMD can still be very useful to describe the spray locally. And in order to get a global spray description, multiple SMDs are needed.

The present work reports numerous measurements, in which drop size data were acquired at 17 locations for each of 8 different sprays. Four measurement points yielded no data due to the local spray behaviour and experimental setup (one in #6 and three in #8). Figure 1 shows the radial evolution of SMD at various axial distances for operating conditions #1 to #8. In the region close to the spray nozzle (axial distance 5 cm) the SMD decreases monotonically with radial distance. This trend is valid for all operating conditions with only few exceptions (#1, #2, #3), which are exhibiting decreasing SMD nonetheless. On the other hand, SMD in the region further downstream (axial distance 15 cm) follows almost an opposite trend, when SMD increases with radial distance. The trend is fairly monotonous at low GLR (#1, #4 and #7) but with higher GLR local minima and maxima start to appear, although the overall increase in SMD between the spray core and rim is still obvious. Somewhere between these two axial distances must lie a region where the transition between the two aforementioned trends occurs. Again, at low GLR (#1, #4 and #7) the SMD evolution at axial distance 10 cm is quite flat, indicating the possible transition between the decreasing and increasing SMD trends, but more measurements would be needed to confirm this hypothesis.

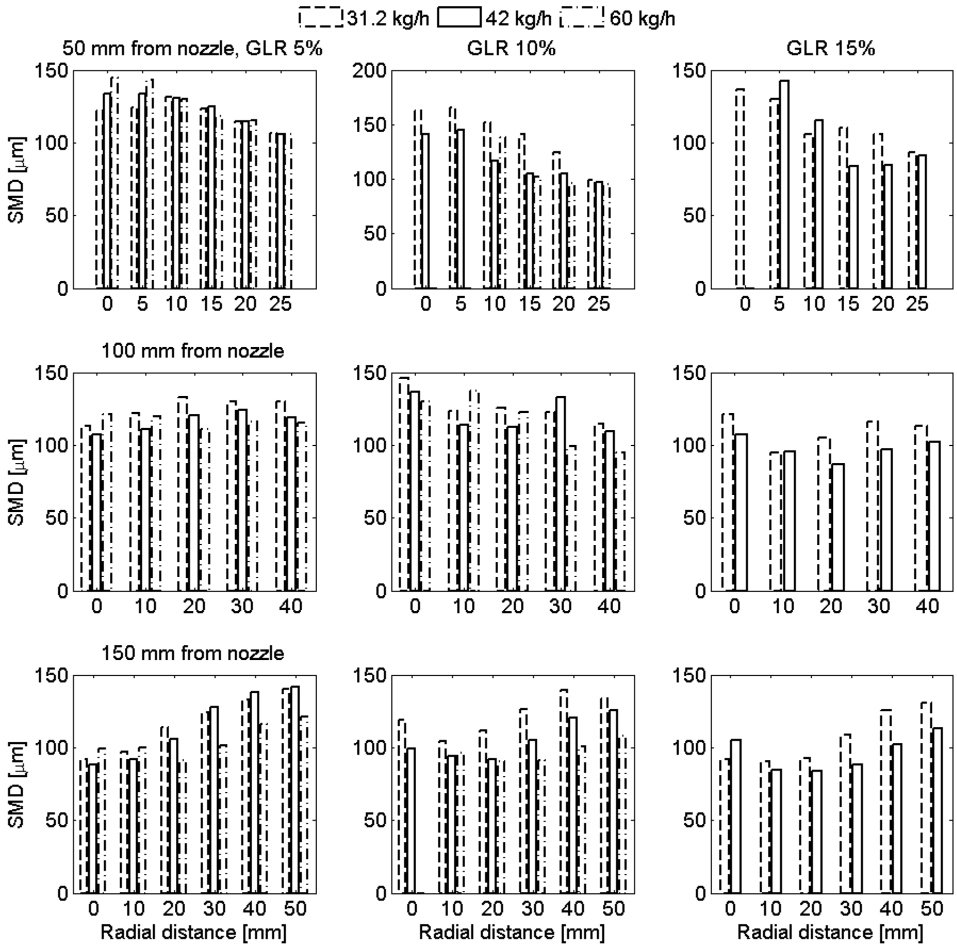

Figure 2: Effect of mass flow rate on SMD at various axial distances and GLRs

One of the possible explanations for the change of SMD radial evolution is that downstream in the spray rim region lower velocities favour drop coalescence. This could be supported by the fact that the SMD in the spray core decreases with axial distance, similarly to the radial SMD evolution trend in the close-to-nozzle regions. In both these cases relative velocities are still high preventing drop coalescence and promoting secondary breakup. On the other hand in the peripheral regions further downstream the velocities decrease enough to allow droplets to coalesce increasing the local SMD.

Data represented in Figure 2 show the effect of mass flow rates on local SMD values. Rows represents axial distances and columns different GLRs. In general it can be said that outside of the spray core, increase in mass flow rate leads to decrease of SMD. The situation in the spray core is not as clear. In some cases (e.g. GLR 5 % and axial distance 5 cm) the SMD in the core increases with mass flow rate. In few other cases there is no clear trend and it looks like mass flow rate has only little effect on SMD (cases with GLR 5 % and 15 %). One thing to note is that the SMD values in the spray core have a peak for GLR 10 %. This points to a change in two-phase flow regime inside the atomizer and is also consistent with the findings of Ochowiak et al. (2010), where a transition between the bubbly and annular regime was found to be at approximately GLR 7 % for water-air mixture.

The effect of GLR on local SMD at various mass flow rates is displayed in Figure 3. No clear dependency can be inferred in the core region of the sprays. This is partly due to the fact pointed out in the previous paragraph, being that the core SMDs are highest for GLR 10 %. In the spray rim regions however, the SMD gradually decreases with increasing GLR. This trend has only few exceptions, most notably in the case of 31.2 kg/h and axial distance 5 cm, where the SMD of GLR 10 % is highest both in the core and outside of the core.

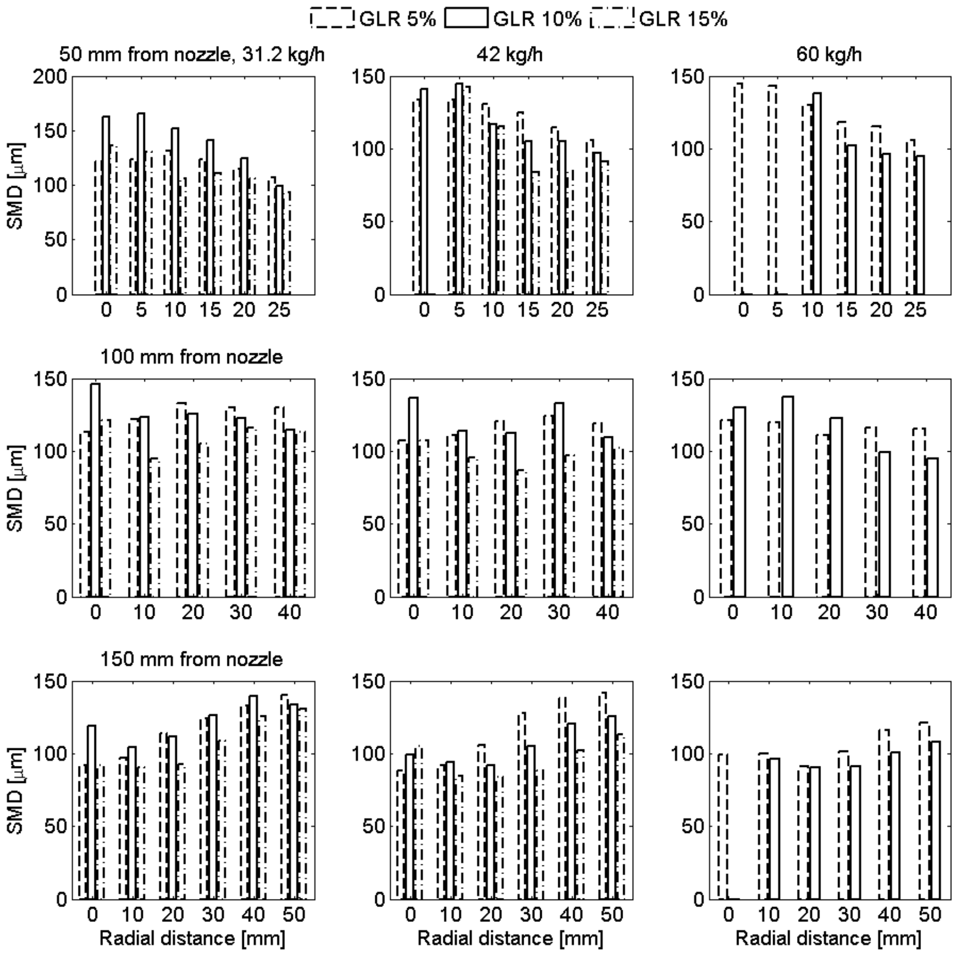

Figure 3: Effect of GLR on SMD at various axial distances and mass flow rates

More detailed analysis of particle drop size distributions instead of the local SMDs is required in order to enhance the understanding of the mechanisms that govern the behaviour of effervescent sprays. Previous results of a study performed on a smaller scale have already shown e.g. that multimodality of drop size distributions is quite common (Broukal and Hájek, 2011b). An adequate method to represent effervescent spray in numerical computations involving liquid fuel combustion should resolve these features in sufficient detail.

4. Conclusions

The present work discloses results of an experimental study focused on local SMD values in industry-scale effervescent sprays. The effect of mass flow rate and GLR on local SMD has been investigated based on numerous experimental data. Examining SMD values varying both axially and radially has shown that while in the regions closer to the spray nozzle SMD decreases toward the spray edge, in the regions further downstream this trend is completely opposite. This finding holds true regardless of the operating conditions. An explanation is proposed to explain this behaviour. The presented results are unprecedented as they take into account local properties of effervescent sprays. Previously published experimental work in the area of effervescent sprays is extensive, but often omits more detailed spatial analysis of drop sizes, namely SMD in the radial direction. The present work aims to remedy this deficiency. The results furthermore accentuate the effervescent spray complexity and can be of significant aid to future researchers in providing a solid foundation ground on which future numerical models for effervescent sprays can be validated.

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