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On the characterization of spray unsteadiness and its influence on oil drop breakup during effervescent atomization

Agnes Kleinhans[a,*], Kostadinka Georgieva[a], Moritz Wagner[b], Volker Gaukel[a], Heike P. Schuchmann[a]

[a] Institute of Process Engineering in Life Science, Section I: Food Process Engineering, Karlsruhe Institute of Technology, Kaiserstraße l2, 76131 Karlsruhe, Germany

[b] Qudosoft GmbH & Co. KG, Schwedter Str. 263, 10119 Berlin, Germany

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ABSTRACT

The present study focused on the effervescent atomization of oil-in-water emulsions with a special look at the unsteadiness occurring in the internal mixing pneumatic atomizer at certain process conditions. Spray drop size measurements were conducted using a laser diffraction spectrometer at a data acquisition rate of 250 Hz to analyze changes over time. Different characteristic values for the spray morphology and behavior were studied for their suitability to describe timely changes and their effect on spray results. It was found that the flow pattern inside the mixing chamber of the atomizer not only influences the averaged spray drop size but also its temporal fluctuation. Oil drops of atomized emulsions broke up at all investigated ALR, however, no measurable influence of spray unsteadiness was found with the chosen nozzle design.

1. Introduction

Atomization of emulsions is a common task in various fields like the pharmaceutical industry, agriculture or food engineering. Mainly for pharmaceutical (e.g. [1]) or food industries, the spray drying applications of atomized emulsions are of interest, for example during formulation of instant products. Several authors investigated the mechanism and efficiency of encapsulation of fatty or oily compounds in a suitable spray-dried matrix (e.g [2–4]). Since spray drying is a very rapid process, the size and location of the oil drops inside the spray drops will not change any further and hence reflect the structure of the resulting powder [5,6]. The investigations so far focused on the interaction of matrix, emulsifier, thickener and oil properties and their influence on encapsulation efficiency [1,7–17]. It was shown that the oil drop size in the atomized liquid is an important parameter for encapsulation of oil. As shown by several authors [18–20], the initial oil drop size (before atomization) may be altered by the atomization process. The breakup of the disperse phase during atomization is often stated as undesired, while it could also be of advantage in some applications. A controlled change of oil drop size during the atomization process could also be used to replace or reduce the prior emulsification step. Knowledge of the relevant parameters for oil drop breakup during atomization is of interest in both cases – either to inhibit or to induce oil drop breakup.

The atomizer type and its geometry have a significant effect on the size distribution of the spray dried powders. In terms of spray drop sizes and product quality, the most important atomizer characteristics are uniformity of drop-size, control over the drop-size distribution, and homogeneity of the spray [5]. The effervescent atomization is a special type of internal mixing pneumatic atomization known for the formation of different two-phase flow patterns upstream of the atomizer nozzle orifice [21]. In previous research, three promising atomizer geometries (see Fig. 1) have been applied to atomization of food liquids as well as of food based emulsions [18,22–25].

The target of this study was to determine the impact of process parameters and atomizer geometry on spray stability, i.e. the time-resolved spray drop size, as well as the breakup of oil drops of an atomized oil-in-water emulsion. To the best knowledge of the authors, there has been no such investigation of these parameters concerning the effervescent atomization of an emulsion so far.

* Corresponding author.
E-mail addresses: agnes.kleinhans@kit.edu (A. Kleinhans), kostadinka.georgieva@yahoo.de (K. Georgieva), moritz.wagner@qudosoft.de (M. Wagner), Volker.Gaukel@kit.edu (V. Gaukel), Heike.Schuchmann@kit.edu (H.P. Schuchmann).

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Nomenclature

ALR	Air-to-liquid ratio by mass /-
ACLR	Air-Core-Liquid-Ring nozzle
D	Diameter /mm
L	Length /mm
q_0	Frequency density distribution /1/μm
Q_0	Cumulative density distribution /-
$x_{05,0}$	5th percentile of the distribution /μm
$x_{50,0}$	Median drop diameter /μm
$x_{95,0}$	95th percentile of the distribution /μm
$x_{1,2}$	Time-averaged Sauter mean diameter /μm
$x_{time;1,2}$	Time-dependent Sauter diameter /μm
$x_{1,2;oil}$	Oil Sauter mean diameter /μm
η	Viscosity /mPa s
λ	Viscosity ratio /-

Subscripts

c	Continuous phase
d	Disperse phase
e	Emulsion
g	Gas
l	Liquid
m	Mixing chamber
o	Orifice

2. Material and methods

For all of our investigations internal mixing pneumatic atomizers were used. Two of these devices were types of effervescent atomizers. The third device was a newly designed nozzle called ACLR (air-core-liquid-ring). To establish a two-phase flow in all geometries, gas enters the liquid in the mixing chamber through a number of injection holes in the mixing chamber wall. The resulting two phase flow in the atomizer nozzle, is then atomized at low pressure (e.g. 2–4 bar). One of the most important process parameters affecting the flow pattern in the mixing chamber is the ratio of atomization gas mass flow and liquid mass flow called the air-to-liquid ratio by mass (ALR)—(gas mass flow rate $\dot{m}_g$, liquid mass flow rate $\dot{m}_1$) [26–28]:

$$ALR = \frac{\dot{m}_G}{\dot{m}_L} \quad (1)$$

Stähle et al. [29] showed that the pattern of the two-phase flow inside the mixing chamber is also influenced by the liquid viscosity η. Depending on the ALR and the liquid viscosity, bubbly, slug or annular flow develops within the mixing chamber. Bubbly flow was found only for low viscous liquids e.g. water. At liquid viscosities above 14 mPa s, annular flow was formed for all investigated ALR (0.02–0.47). Whereas slug flow was obtained for high viscosities (>60 mPa s) and low ALR (ALR < 0.03) [29].

After entering the nozzle orifice, the two-phase flow changes again. For bubbly or annular flow in the mixing chamber, a more or less stable annular flow was found in the nozzle orifice resulting in stable atomization. Slug flow in the mixing chamber, however, induced heavy fluctuations, as the nozzle orifice was temporarily filled only with liquid and therefore a liquid jet left the nozzle instead of the desired annular film. In these cases, atomizing pressure was too low for atomization [23,30].

2.1. Atomization nozzles

2.1.1. Effervescent atomizers

Both used effervescent atomizers (Atomizers 1 and 2) were outside-in atomizers with a single nozzle orifice as described by Sovani [31]. Gas injection geometry of Atomizer 1 (see Fig. 1a) was designed according to Huang et al. [32] and is also described by Stähle et al. [29]. The gas injection holes are located on 6 equidistant rings containing 4 holes each which can be also seen in detail in Fig. 1a. The injection hole patterns of neighboring rings are rotated by 45° relative to each other. The diameter of each of the 24 holes was 1 mm. This resulted in a total gas injection area of 18.85 mm^2. For Atomizer 2, the total gas injection area was scaled down to 1.76 mm^2. The amount of injection holes was reduced to 9 with a diameter of 0.5 mm each (Fig. 1b), as described by Schröder et al. [33,34]. Both atomizers had a mixing chamber diameter d_m of 6 mm as well as a nozzle orifice diameter d_O and length l_O of 1.5 mm. The mixing chamber length l_m, which is defined as the length between the last row of the injection holes to the inlet of the nozzle orifice, was 30.5 mm for Atomizer 1 and 36.5 mm for Atomizer 2.

2.1.2. Air-Core-Liquid-Ring (ACLR) nozzle

In order to achieve a continuous annular flow pattern inside the mixing chamber and exit orifice for all ALR, the ACLR atomizer was constructed [22]. In this device, the compressed air is injected into the liquid by a capillary. The idea was adopted from Groom et al., 2005 [35] where a good spraying performance was shown for the

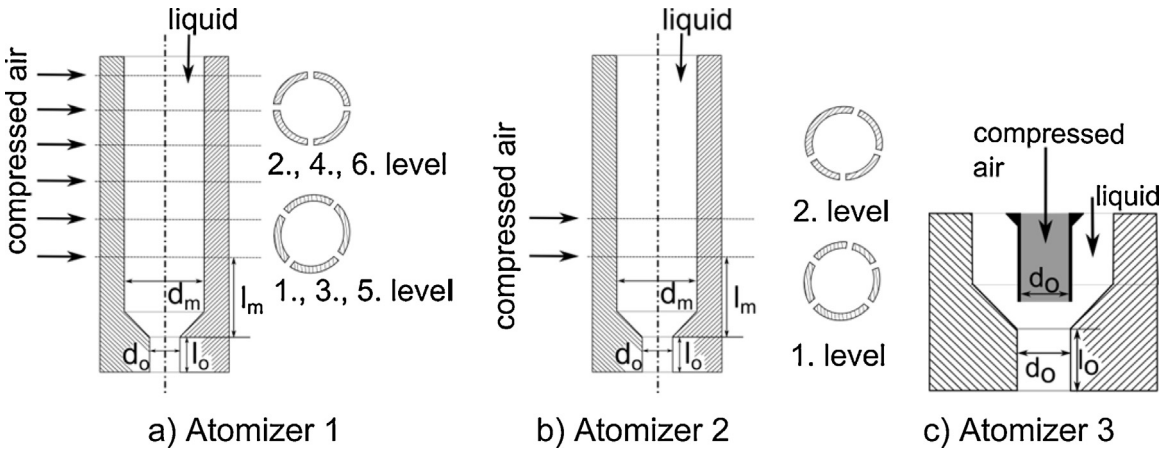

Fig. 1. Used atomizers: 2 effervescent atomizer and an Air-Core-Liquid-Ring nozzle.