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Influence of feed viscosity on the two-phase flow inside the exit orifice of an effervescent atomizer and on resulting spray characteristics

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ABSTRACT

The effervescent atomizer, originally developed for combustion applications, is reported to atomize viscous liquids into small drops at low working costs. This offers the possibility to enhance the energy efficiency of spray drying foodstuffs by the atomization of a higher concentrated feedstock. For a stable drying process a steady formation of small drops must be ensured which depends mainly on the two-phase flow inside the exit orifice. In this study, the influence of the viscosity of a food based liquid on the flow pattern inside the exit orifice was investigated by measuring the time-dependent gas phase distribution using an optical sensor. Further, the spray in the near nozzle region as well as the shape and the size of the spray drops was characterized by means of shadowgraphy. The results indicate an atomization into small and spherical drops when an annular flow is formed inside the exit orifice. In contrast, very large and deformed spray drops are present for a slug flow, which are critical for spray drying purposes.

1. Introduction

Spray drying is a widely used technique to convert food based liquids into powdery products with enhanced shelf life and tailored properties (Chen & Mujumdar, 2008). To ensure a stable process, the spray drop size must be sufficiently small to facilitate particle formation within the available drying time. Regarding the energy efficiency of the drying process, spray dryers should be operated at the highest possible dry matter content of the liquid feed (Masters, 2002). Unfortunately, the viscosity of most food based feed stocks increases sharply with an increasing dry matter content (Rao, 2014). This in turn leads to larger spray drops and hence to a longer drying time. As a consequence, extensive wall deposits endanger a stable drying process and the production of an acceptable product quality. Amongst conventional atomizers solely pneumatic nozzles are able to atomize viscous liquids adequately (Bayvel & Orzechowski, 1993). However, they require large amounts of compressed air which makes their operation quite expensive on an industrial scale (Masters, 2002).

Hence, there is a requirement for an atomizer which is capable of atomizing highly viscous liquids into small spray drops at low air consumption. Reports from literature indicate that the effervescent atomizer – originally developed for combustion applications – is potentially suitable to satisfy the aforementioned demand (Buckner & Sojka, 1991, 1993; Konstantinov, Marsh, Bowen, & Crayford, 2010; Schröder, Günther, Wirth, Schuchmann, & Gaukel, 2013; Sovani, Sojka, & Lefebvre, 2001; Stähle, Gaukel, & Schuchmann, 2014). In an effervescent atomizer, the atomization air is introduced into the liquid at some point upstream of the exit orifice in a well designed way to form a two-phase flow (Chin, 1995). The patterns of the two-phase flow in the mixing chamber are generally categorized as annular flow, slug flow and bubble flow (Konstantinov et al., 2010). For a given nozzle geometry, the flow patterns are mainly influenced by the air-to-liquid ratio by mass (ALR) as well as by the viscosity of the liquid (Baker, 1954; Sovani et al., 2001; Stähle et al., 2014). The flow pattern in the mixing chamber dominates the amount of the available atomizing air related to the liquid inside the exit orifice which, in turn, dominates the atomization itself (Avulapati & Ravikrishna, 2012; Catlin & Swithenbank, 2001; Kim & Lee, 2001). Hence, the flow pattern inside the exit orifice is the most important one. Recent research reveals that the flow inside the exit orifice assumes either an annular flow or a slug flow irrespective of the flow pattern present inside the mixing chamber. This is due to a considerable expansion of the gaseous phase as the mixture accelerates in the contraction between the mixing chamber and the exit orifice (Shepard, 2011). In case of an annular flow in the exit orifice, the liquid is squeezed into a thin annular sheath whereas the air travels with high velocity in the core. Hence, small spray drops result from high shear rates acting on the liquid. However, for a slug flow inside the exit orifice the amount of the available atomizing air temporarily drops down to very low values. As a consequence, only very low disruptive forces act upon the liquid resulting in very large spray drops. Further, as the plugs carry different amounts of liquid, a complete suppression of the

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atomization is possible. A solid liquid jet may exit the atomizer under these circumstances (Avulapati & Ravikrishna, 2012). An implementation of the effervescent atomizer to spray drying is impossible in this case.

In a former study of our group, the influence of the ALR and the liquid viscosity on the two-phase flow pattern within the mixing chamber of an effervescent atomizer was investigated (Stähle et al., 2014). The ALR was varied in a range of 0.01 to 0.51, whereas a range of viscosity of 1–308 mPa·s was investigated. The observed flow patterns are schematically depicted in Fig. 1 and are shortly discussed in the following section.

In the case of water ($\mu = 1$ mPa·s), an annular flow is formed for a high ALR (Fig. 1). However, the annular flow for water is unstable, which leads to a time-dependence of the liquid volume flow rate (Chen & Lefebvre, 1994; Huang, Wang, & Liao, 2008). For the lowest ALR investigated a bubble flow is formed, whereas the diameter of the bubbles is larger than the diameter of the exit orifice. A slight increase in liquid viscosity to $\mu = 14$ mPa·s stabilizes the flow pattern to a stable annular flow throughout the investigated ALR range (Fig. 1). Since the amount of the liquid was increased in order to reduce the ALR, the thickness of the annular liquid increased as the ALR decreases. For the highest investigated viscosity of $\mu = 308$ mPa·s an annular flow is existent in the mixing chamber for a high ALR (Fig. 1). However, due to the high viscosity large waves are formed on the surface of the annular liquid ring. The waves never grow so large that they cut off the central air core from the exit orifice. With decreasing ALR the flow pattern transforms to a slug flow where air slugs are separated by liquid plugs. Overall, the influence of the ALR and the liquid viscosity on the flow patterns inside the mixing chamber is well documented. However, only little is known about the link between the flow patterns in the mixing chamber and the ones inside the exit orifice, even though the latter are crucial for atomization.

In this study, an optical sensor according to Lörcher (2003) was used to investigate the influence of the ALR and the viscosity on the time-dependent gas phase distribution within the exit orifice. Further, shadowgraphs were taken to characterize the spray. The results provide indispensable information about the applicability of the effervescent atomizer in spray drying of viscous foods.

2. Material and methods

To ensure that the same flow patterns are existent within the mixing chamber as the ones described in reference to Fig. 1, the test liquids and the test rig as well as the nozzle geometry itself were the same as in the study of Stähle et al. (2014). The relevant information is briefly given in the following sections.

2.1. Test liquids

Aqueous solutions of maltodextrin (C*Dry MD 01910, Overlack GmbH, Groß-Rohrheim, Germany) were used to vary the viscosity of the investigated liquids. Concentrations of 0, 30 and 50% by dry matter content were prepared whereas a moisture content of 5.42% of the powder was considered. The liquid viscosity μ was measured by means of a rotational rheometer (MCR 301, Anton Paar GmbH, Graz, Austria) equipped with a coaxial cylinder geometry (CC27). The temperature was set to 25 °C and shear rates in the range of 1 s^{-1} to 1000 s^{-1} were applied. The solutions showed a Newtonian flow behavior and the viscosity μ was 1 mPa·s, 14 mPa·s and 308 mPa·s for the liquids with a maltodextrin concentration of 0%, 30% and 50%, respectively. To measure the surface tension of the solutions, a bubble shape tensiometer was used (PAT-1, Sinterface Technologies, Berlin, Germany). Before each measurement the system was carefully calibrated to known values from literature with purified water. The surface tension of all investigated liquids was constant within the inspected measurement time range of 0 s to 600 s. With increasing maltodextrin content of 0%, 30% and 50% the surface tension of the solutions at 25 °C was 72 mN/m, 74 mN/m and 76 mN/m, respectively. To measure the density, a pycnometer was used. With increasing dry matter content the density at a temperature of 25 °C was 1000 kg/m^3, 1131 kg/m^3 and 1241 kg/m^3, respectively. Overall, an increase in maltodextrin concentration results in a pronounced increase in liquid viscosity compared to other relevant parameters.

2.2. Test rig

To pump the solutions an eccentric screw pump (2NL 20A, Erich Netzsch GmbH & CO. Holding KG, Selb, Germany) was used at constant rotational speed. To vary the liquid volume flow rate Q_L, a bypass line and a needle valve were used. The liquid flow rate was measured with a gear-wheeled flow meter (VSI 04/16, VSE GmbH, Neuenrande, Germany). Air was used as atomization gas which was pressurized to a constant value of 0.4 MPa. To meter its flow rate a thermal gas mass flow controller was used (High-Tech EL-Flow, Bronkhorst Mättig

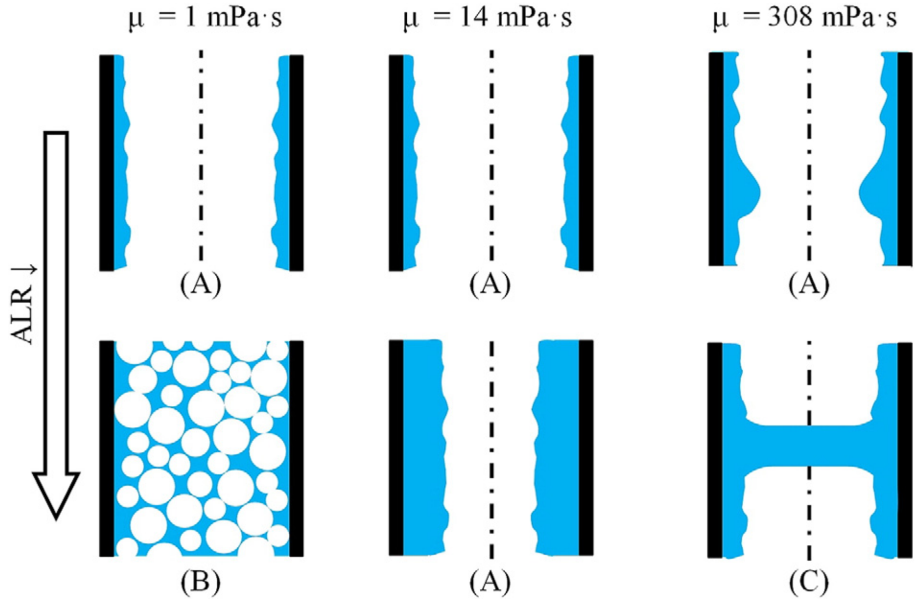

Fig. 1. Influence of liquid viscosity and ALR on the flow patterns inside the mixing chamber: (A) annular flow; (B) bubble flow; (C) slug flow.