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A dimensional analysis approach for modelling the size of droplets formed by bi-fluid atomisation

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ABSTRACT

This paper presents a dimensional analysis (DA) § approach of the atomisation process using a bi-fluid nozzle, allowing to predict droplet sizes of model solutions and skimmed milk concentrates in large ranges of operating conditions. Experimental results confirmed the atomisation mechanism described in the literature, by underlining that the spraying operation is controlled by the coupling of liquid physicochemical properties (viscosity, surface tension, density) and operating conditions (air pressure and liquid flow rate). It was also highlighted that droplet coalescence occurs from a certain distance to the nozzle, counteracting the atomisation mechanism and leading to a reincrease in the droplet size when moving away from the nozzle. Consequently, the modelling of droplet size by DA was improved by adapting the model coefficients of the dimensionless process relationship to the involved mechanisms: either atomisation only close to the nozzle outlet or atomisation followed by droplet coalescence at longer distance to the nozzle.

1. Introduction

Wet agglomeration processes are used in the food industry to improve powder functionalities, such as wettability, solubility, and flowability. These processes involve the formation of liquid binder droplets by atomisation, which is a critical step, as it directly influences the wetting of fine powder particles and their ability to adhere one to each other and form agglomerates (Iveson et al., 2001; Litster and Ennis, 2004; Mandato et al., 2012; Saad, 2011). Besides, it has been evidenced that the droplet size produced by atomisation is highly correlated to the sizes of final particles in spray-drying and wet agglomeration processes (Cuq et al., 2013; Hede et al., 2008a; Iveson et al., 2001; Jimenez-Munguia, 2007; Leuenberger et al., 2006; Marmottant, 2001; Parikh, 2006). As a consequence, modelling droplet formation will help to better understand and characterise the mechanisms involved in spray-drying and wet agglomeration processes. The current study is in line with these concerns, as it aimed at developing a model by DA that allows the prediction of droplet size of different sprayed liquids in various operating conditions, with a particular emphasis on the evolution of droplet size with the distance to the nozzle outlet.

The general mechanism of liquid atomisation by bi-fluid nozzles is outlined below (Beau, 2006; Chigier, 1976; Hede et al., 2008a; Lefebvre, 1980; Mandato et al., 2012; Marmottant, 2001; Nguyen and Rhodes, 1998). Pumping the liquid through the nozzle results in the formation of a liquid jet at the nozzle outlet, which interacts with the surrounding atomising air at higher velocity. The air–liquid velocity difference causes high frictional forces on the liquid surface, inducing its deformation and the apparition of liquid filaments that are further disrupted into smaller and smaller droplets (Marmottant, 2001).

The influence of operating conditions on droplet size can be deduced from the above-mentioned mechanism. Increasing the air–liquid velocity difference at the nozzle outlet, either by lowering the liquid flow rate or raising the air pressure, results in smaller

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Nomenclature

a_j for $j = 0–6$	model coefficients (–)
A_A	air orifice area (m^2)
A_L	liquid orifice area (m^2)
ARE_{max}	maximal absolute relative error (%)
d_{50}	mean droplet diameter in volume (m)
$d_{50,exp}$	experimental droplet size (m)
$d_{50,model}$	predicted droplet size (m)
g	gravitational acceleration ($9.81\ m\ s^{-2}$)
L	distance to the nozzle outlet, i.e. distance from the nozzle outlet at which the droplet size was measured (m)
$\dot{m}_A$	air mass flow rate ($kg\ s^{-1}$)
$\dot{m}_L$	liquid mass flow rate ($kg\ s^{-1}$)
$MARE$	mean absolute relative error (%)
$NMRSE$	normalised mean root squared error (%)
Oh	Ohnesorge number (–)
P_A	relative air pressure (Pa)
Q_A	air volumetric flow rate ($m^3\ s^{-1}$)
Q_L	liquid volumetric flow rate ($m^3\ s^{-1}$)
T_A	air temperature (ambient, 18 °C, 291.15 K)
T_L	liquid temperature (ambient, 18 °C, 291.15 K)
u_A	air velocity at the nozzle outlet ($m\ s^{-1}$)
u_L	liquid velocity at the nozzle outlet ($m\ s^{-1}$)
We	aerodynamic Weber number (–)
μ_A	air viscosity ($kg\ m^{-1}\ s^{-1}$)
μ_L	liquid viscosity ($kg\ m^{-1}\ s^{-1}$)
π_i for $i = 1–10$	dimensionless numbers obtained by dimensional analysis (–)
π_T	target dimensionless number, i.e. dimensionless droplet size (–)
σ	liquid surface tension ($kg\ s^{-2}$)
ρ_A	air density ($kg\ m^{-3}$)
ρ_L	liquid density ($kg\ m^{-3}$)
$\varphi_{A,int}$	air orifice internal diameter (3.4 mm)
$\varphi_{A,ext}$	air orifice external diameter (4.8 mm)
φ_L	liquid orifice diameter (0.8 mm)

droplets. Several literature studies confirmed this trend (Chigier, 1976; Nguyen and Rhodes, 1998; Nukiyama and Tanasawa, 1939; Lefebvre, 1980); furthermore, it was pointed out that air pressure is a crucial process parameter in the atomisation operation (Chigier, 1976; Ehlers et al., 2010; Hede et al., 2008a; Juslin et al., 1995; Lefebvre, 1980; Mandato et al., 2012; Nguyen and Rhodes, 1998).

The geometrical features of the nozzle are also linked to fluid velocities at the nozzle outlet (Cuq et al., 2013; Mandato et al., 2012). At constant liquid and air flow rates, the larger the air orifice area and/or the smaller the liquid orifice area, the lower the air–liquid velocity difference at the nozzle outlet, and thus the larger the droplets.

The influence of physicochemical properties of sprayed liquids is more intricate to evaluate, owing to their interactions with operating parameters. The main physicochemical properties (viscosity, surface tension, and density), jointly varying when changing the liquid composition, are related to the ability of the liquid phase to resist break-up by frictional forces (Hede et al., 2008a; Lefebvre, 1980; Mandato et al., 2012; Marmottant, 2001).

Viscosity gauges the ability of a fluid to resist deformation by shear stress; thus, it is expected to moderate the impact of frictional forces in the atomisation mechanism. Even though a marked increase of droplet size is expected at higher viscosity and has been evidenced for some nozzle geometries (Ejim et al., 2010; Hede et al., 2008a; Lefebvre, 1980; Nukiyama and Tanasawa, 1939), the recent experiments carried out by Mandato et al. (2012) on model solutions did not permit to conclude about the influence of viscosity on liquid atomisation with bi-fluid nozzles. Indeed, opposite trends were found depending on the value of liquid surface tension, presumably owing to the control of the atomisation process by operating conditions rather than liquid physicochemistry.

Surface tension is known to characterise the resistance of a liquid surface to stretching, and thus is opposed to the creation of new liquid surfaces subsequent to droplet formation. This has been evidenced with low viscosity liquids (≈1 MPa s) like water (Chigier, 1976; Hede et al., 2008a; Lefebvre, 1980; Mandato et al., 2012), but it seems that the influence of surface tension becomes negligible at high viscosity when using bi-fluid nozzles (Lefebvre, 1980; Mandato et al., 2012).

Last, the complex influence of liquid density on droplet size has not totally been elucidated yet. Hede et al. (2008a) suggest that high density liquids produce more compact sprays that are less exposed to frictional forces, resulting in larger droplets. This was experimentally evidenced by Hede et al. (2008a), Lefebvre (1980), and the process relationship proposed by Mandato et al. (2012).

Droplet size is also expected to be greatly affected by the distance to the nozzle outlet (Cuq et al., 2013; Ehlers et al., 2010; Mandato et al., 2012), as the atomisation mechanism produces liquid elements that decrease in size when moving away from the nozzle outlet: first, liquid jet; then, liquid ligaments and large droplets; finally, small droplets (Marmottant, 2001). However, other phenomena take part in the shaping of droplets, like droplet coalescence that forms larger droplets and thus counteracts the atomisation mechanism. Differences in size and velocity within the droplet population may result in droplet collision and coalescence, mainly depending on the droplet surface tension (Ehlers et al., 2010). Therefore, close to the nozzle outlet, where the atomisation mechanism predominates, the droplet size is expected to decrease with the distance to the nozzle. Then, under the increasing influence of the coalescence mechanism when moving away from the nozzle, an attenuation of the droplet size decrease or even a reincrease in the droplet size can occur (Lefebvre, 1980).

In order to address this phenomenological complexity, a semi-empirical modelling approach by DA seems appropriate, as DA is an interesting process engineering tool that has recently showed efficiency in modelling food processes involving numerous process parameters (Delaplace et al., 2012; Hassan et al., 2012; Petit et al., 2013). Also, the suitability of DA for modelling liquid atomisation by mono- and bi-fluid nozzles was demonstrated by the pioneer work of Mandato et al. (2012).

In the literature, diverse empirical relationships adapted to various nozzle designs (mono- or bi-fluid, internal or external mixing) have been proposed (Hede et al., 2008a; Jimenez-Munguia, 2007; Lefebvre, 1980; Nguyen and Rhodes, 1998), but they suffer from some limitations (Hede et al., 2008a) that preclude their direct application to the atomisation of food liquids:

- experimental data were obtained with model solutions only (water, aqueous solutions of glycerol, kaolin suspensions, etc.) in narrow ranges of operating conditions,
- a very small number of process parameters was explicitly considered; unfortunately, the distance to the nozzle was rarely one of those.