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Modeling and simulation of air-assist atomizers with applications to food sprays

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ABSTRACT

The Cascade Atomization and Drop Breakup (CAB) model has been developed originally for pressure atomizers. In this study, the CAB model is modified to accommodate air-assist atomization. The modifications include a change in the product drop distributions, namely, the uniform distribution used in the original CAB model is replaced with a χ-squared distribution with the same average drop size. The second modification addresses the air-assist atomization process. This process is modeled by estimating the Weber number due to the increased relative velocity caused by the air flow. Depending on the value of the Weber number this leads to a catastrophic, or a stripping (sheet-thinning), or a bag breakup. The model changes are validated with experimental data obtained from two different air-assist atomizers using an oil-in-water emulsion. The simulations were performed with a modified version of the *KIVA-3* CFD code, and they showed good agreement with the experimental data.

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1. Introduction

Powders play an important role in food processing. They can be a final product or constitute an intermediate step in a more complex process. Powdered substances can be obtained by means of spray-drying or spray-freezing. Depending on the application, this powder is required to have specific macroscopic properties such as a desired particle size distribution, and microscopic structures such as encapsulations which contain exact amounts of certain components (e.g. nutrients) in each particle (cf. Refs. [1–3]). Therefore, the liquids involved in food sprays can be very complex, typically consisting of multi-phase/multi-component suspensions or emulsions, which have anisotropic structures and can exhibit non-Newtonian and even viscoelastic behavior. Consequently, high-pressure atomizers, which are often used in other applications, are not suited for food sprays because the high pressures needed in this process could alter the complex material structures and thus change essential product characteristics, such as nutrition, taste and shelf life.

Several alternative approaches for a more gentle atomization process have been investigated, both experimentally and computationally. One approach to the generation of small droplets is the laminar rotary atomizer of Walzel [4]. As is discussed in more detail in Schröder and Walzel [5], this experimental approach produces narrow drop size distributions via

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Nomenclature

CAB	cascade atomization and drop breakup
IDSD	initial drop size distribution
$\|\|\ldots\|\|$	Euclidean norm
C_λ	CAB model constant
K_{bu}	breakup frequency
L_{bu}	breakup length
R	specific gas constant
Re	Reynolds number
T	temperature
We	Weber number
a	parent drop radius
d	drop diameter
d_o	nozzle diameter
g	gravity constant
k_1, k_2, k_3	CAB model constants
n	IDSD exponent
r	drop radius
$\bar{r}$	mean drop radius
t	time
u	speed
$\boldsymbol{u}$	velocity
x	spatial coordinate
γ	isentropic coefficient
μ	viscosity
ρ	density
σ	surface tension
θ	spray angle
ω	drop oscillation frequency

Subscripts

IN	inmix nozzle
EX	exmix nozzle
b, s	bag, stripping
bu	breakup
crit	critical
d	droplet
g	gas phase
inj	injection
l	liquid phase
o	initial,nozzle
r	relative
s, c	stripping, catastrophic

Rayleigh breakup of stretching jets and filaments in a rotating environment. A review of the theoretical analysis of the stability and breakup of free liquid jets can be found in Ashgriz and Yarin [6].

A second approach is the use of pressure atomizers at relatively low injection pressures. However, this proved ineffective for the production of powders, as a computational investigation of a highly viscous nutriose liquid spray revealed (cf. Ref. [7]). In fact, as is illustrated in Fig. 1, an injection pressure doubling from 6 bar to 12 bar had almost no influence on the average drop size. The reason for this behavior was the fact that the average drop Weber numbers[1] were mainly sub-critical, i.e., less than $We_{crit} = 12$, and therefore, there was only insignificant breakup activity. In addition, the average drop sizes were considerably larger than required. Using smaller nozzle orifices (which would result in smaller droplets) was also not an option as they were prone to clogging. Looking to overcome the shortcomings of pressure atomizers for food sprays, another approach relies on air-assist atomization. In this approach, an air stream is applied to the liquid jet as it exits the spray nozzle, which increases the relative velocity between the liquid jet and the surrounding air, thus enhancing

[1] The Weber number is defined as $We = \rho_g d u_r^2/\sigma$, where ρ_g is the gas density, d the drop diameter, u_r the relative gas-drop velocity, and σ is the surface tension.

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