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Numerical study of air humidity and temperature distribution in a top-spray fluidised bed coating process

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ABSTRACT

The objectives of this study were to model the air temperature and humidity distributions and to determine expanded bed heights in a top-spray fluidised bed coater using computational fluid dynamics (CFD). For model validation purposes, model-predicted outlet air temperatures and expanded bed heights were compared to those reported in literature. The model-predicted outlet air temperatures at different conditions were found to be overestimated, approximately 3–5 °C higher, while good agreement was found between measured and predicted expanded bed heights. In addition, the model showed good qualitative agreement in the existence of different thermal zones in the fluidised bed with those observed in experiments. In conclusion, the CFD model could be employed to determine the expanded bed height and to characterise the thermal zones in the fluidised bed, while model development, specifically regarding implementation of droplet/particle interactions in the model is still needed to increase the consistency with the experimental air temperatures.

1. Introduction

Fluidised bed coating is a process in which solid particles are individually coated by spraying the coating material, in solution (i.e. aqueous or organic solvent based), onto a bed of fluidised particles. By repeated impact of droplets containing the dissolved coating material onto the solid, fluidised particles and by successive solvent evaporation, a coating layer is gradually built onto the particle surface (Ronsse et al., 2008, 2009; Turchiuli et al., 2011). This technique has been widely applied in numerous industrial processes, for instance, in the chemical and pharmaceutical industry, food process technology and agriculture (Heinrich et al., 2003). For instance in food process technology, Solís-Morales et al. (2009) used a top-spray fluidised bed coater, as an alternative for coating puffed wheat particles with a sweet chocolate cover, as a means to reduce attrition promoted in the conventional pan coating process. Other applications in the food process technology apply to controlled release, protection of the core material against reactive environments, reducing dustiness, taste masking or flavour encapsulation, etc.

Among three types of fluidised bed reactor configurations including tangential-, bottom- and top-spray configuration, the latter in which an aqueous coating solution is sprayed downwards onto the top surface of the fluidised particles is widely applied in the food industry due to its simplicity and versatility (Dewettinck and Huyghebaert, 1999). A schematic overview of a typical top-spray configured fluidised bed coating system is given in Fig. 1. Even though the top-spray configuration has been successfully introduced in the food industry, the occurrence of side effects including the premature spray-drying of the droplets containing the dissolved coating material and agglomeration (i.e. sticking or clumping together of wetted particles) could result in poor product quality and product losses (Dewettinck and Huyghebaert, 1999; Werner et al., 2007). To solve these problems, all phenomena in the coating process including air suspension, particle dynamics, coating solution droplet trajectories and their interactions have to be clearly understood so that appropriate selection of process input variables can be achieved (Teunou and Poncelet, 2002).

As a result of various operating variables (process conditions, material properties, etc.) affecting the coating process dynamics and quality of the resulting product, many attempts have been made to optimise the coating system, improving the reactor design and increasing material efficiency, as reviewed by Teunou and Poncelet (2002). For instance, Atarés et al. (2012) investigated the effects of core particle size and its distribution on the thickness and coating quality. In addition to core material properties, the

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Nomenclature

A_d	droplet surface area (m^2)
C_d	vapour concentration at the droplet surface (mol m^{-3})
C_l	vapour concentration in the bulk gas (mol m^{-3})
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D_v	diffusion coefficient of vapour in the bulk (m^2 s^{-1})
d	particle diameter (m)
f_{v0}	mass fraction of volatile component (–)
H	specific enthalpy (kJ kg^{-1})
h	convective heat transfer coefficient (kJ s^{-1} m^{-2} K^{-1})
h'	convective mass transfer coefficient (m s^{-1})
k_i	thermal conductivity (W m^{-1} K^{-1})
M_d	current droplet mass (kg)
M_{d0}	initial droplet mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
N_i	molar flux of vapour (kmol m^{-2} s^{-1})
N_s	number of solid phases (–)
Nu	Nusselt number (–)
p	pressure (Pa)
Pr	Prandlt number (–)
p_{sat}	saturated vapour pressure at droplet temperature (Pa)
q	heat flux (kJ s^{-1} m^{-2})
Q	heat exchange rate between phases (kJ s^{-1})
R	Universal gas constant (J mol^{-1} K^{-1})
Re	Reynolds number, dimensionless
Sc	Schmidt number (–)
Sh	Sherwood number (–)
T	temperature (K)
t	time (s)
$\vec{v}$	velocity vector (m s^{-1})
X	local bulk mole fraction of water vapour

Greek symbols

α	volume fraction (–)
ρ	density (kg m^{-3})
$\bar{\bar{\tau}}$	stress-strain tensor (kg m^{-1} s^{-2})
μ	shear viscosity (Pa s)
λ	laten heat (J kg^{-1})

Subscripts

bp	boiling point
d	droplet phase
i, j	class or integer
l	fluid or gas phase
m	solid phase m
s	solid phase
ss	steady state
v	vapour
vap	vaporisation

effects of operating conditions including inlet air temperature and spraying rate on quality attributes were studied by Palamanit et al. (2013). Process optimisation has not only been carried out experimentally, but has also been studied by means of mathematical models. Among them, computational fluid dynamics (CFD) has been widely used as a powerful tool to describe multiphase flows in fluidised bed coating processes (Duangkhamchan et al., 2011). In addition, the combination with population balance modelling allows to describe the dynamics of coating layer growth, agglomeration and drying (Ronsse et al., 2007a, 2007b; Mortier et al., 2011). In the last decade, with the advancement of computational techniques and computer hardware capabilities, CFD has been successfully employed as a powerful tool not only to optimise process control and constructional design (Hajmohammadi et al., 2013a, 2013b, 2014), but also to simulate so-called multiphysics phenomena in many systems. As the focus in this research work lies solely on CFD, only this technique will be discussed in more detail. For more details concerning the population balance method in the fluidised beds, the readers are referred to Ronsse et al. (2007a, 2007b, 2008, 2012), Mortier et al. (2011), and Vanderroost et al. (2011).

In multiphase flows such as those in gas–solid fluidised beds, most researchers have either used the Eulerian–Eulerian or the Eulerian–Lagrangian approach. In the Eulerian–Eulerian approach, both the solid and the fluidising gas phases are treated as interpenetrating continua, meaning that both phases are present at any given point in the modelled domain. For each of the phases, the conservation equations (mass, energy and momentum) are solved and are supplemented with interaction terms (such as the drag force) to describe the coupling between both gas and solid phases (Mortier et al., 2011). On the other hand, in the Eulerian–Lagrangian approach, the gas phase is still modelled as a continuum whereas each particle in the system is modelled individually by solving the equation of motion accounting for all forces exerted upon the tracked particle, including collisional forces resulting from particle–particle or particle–wall interactions (Taghipour et al., 2005). Given the large number of solid particles to be tracked in fluidised bed systems, the computational cost of the Eulerian–Lagrangian approach is significantly larger than the Eulerian–Eulerian approach and the latter has been established as the most widely used method to simulate gas–solid fluidised bed systems (Loha et al., 2014).

Apart from difficulties in accurate simulations of gas–solids flows, modelling the formation and evaporation of injected droplets and subsequent agglomeration or layered growth mechanisms in the fluidised bed coating process in the Eulerian–Eulerian framework is extremely difficult. Thus, the Lagrangian approach offers a more natural way to simulate complex micro-level droplet-related processes like phase interaction and evaporation. In Duangkhamchan et al. (2012), both the Eulerian (in combination with a population balance equation to account for the droplet size) and the Lagrangian framework were compared with respect to their capability to model the dispersion of droplets produced by a two-fluid nozzle and it was found that the Lagrangian method gave overall better agreement with the experimental observations. Furthermore, the Lagrangian approach has been widely employed for describing not only the heat and mass transfer taking place at the individual droplet scale, but also for describing the droplet trajectories in a flow field (Nayak et al., 2005).

Even though possibilities for numerically investigating the hydrodynamics of gas–solid fluidised beds as well as heat and mass transfer have been extensively discussed in a number of papers (Wang et al., 2004; Werther and Bruhns, 2004; Nayak et al., 2005; Qureshi and Zhu, 2006; O'Rourke et al., 2009; Zhao et al., 2009; Behjat et al., 2010), limitations for particular systems of the complete CFD model could still be found.

Our research group has attempted to provide the complete CFD model for the top-spray fluidised bed with the global aim to understand the process phenomena taking place in the system and thus, for the CFD model to be used as a tool to optimise process control