Powder Technology 300 (2016) 157–163

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Review

An experimental study of droplet-particle collisions

Sandip K. Pawar [a], Filip Henrikson [a], Giulia Finotello [a,*], Johan T. Padding [a], Niels G. Deen [b], Alfred Jongsma [c], Fredrik Innings [c], J.A.M. Hans Kuipers [a]

[a] Multiphase Reactors Group, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[b] Multiphase and Reactive Flows Group, Department of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[c] Tetra Pak CPS, Heerenveen, The Netherlands

A R T I C L E I N F O

Article history:
Received 27 August 2015
Received in revised form 16 March 2016
Accepted 2 June 2016
Available online 3 June 2016

Keywords:
Agglomeration
Break-up
Spray drying
Particle tracking velocimetry

A B S T R A C T

When spray drying a liquid slurry such as milk, collisions between droplets, partially dried particles and completely dry particles are important because coalescence, agglomeration and breakup events influence the size and morphology of the produced powder. When modelling such a spray drying process, it is therefore important to be able to predict the outcomes of individual binary collisions. Both binary dry particle collisions and binary droplet collisions have individually been thoroughly researched over the years due to their widespread occurrence. The importance of understanding binary particle-droplet collisions has been emphasized more recently. However, the number of available studies is limited and simulation studies usually focus on relatively high capillary number. A theory explaining the transition between different regimes is still lacking. The goal of this study is to provide an experimental data set at low capillary number. These results can be used to validate future theories and simulations. To produce and record particle-droplet collisions, an experimental setup that enables synchronized release of both a particle and a droplet was used. One single hanging droplet was released from above onto a particle that initially was held in place by vacuum suction. A high speed camera was synchronized with the setup, and recorded the collisions. Image files were then analysed in Matlab to find velocities and sizes of the particle and droplet before and after impact. The contrast of particle and droplet against the illuminated background was a key factor in succeeding with this. Different collision outcomes were identified as either agglomeration (merging), where the whole droplet would stick to the surface of the particle, or a stretching separation (breaking), where the droplet collides with the particle in an oblique position and stretches out until a part of the droplet detaches from the liquid sticking to the particle. The formation of satellite droplets, i.e. droplets with a radius significantly smaller than the leaving droplet, was also detected. The relation of these collision outcomes to impact conditions such as Weber number and impact parameter was reviewed and put into regime maps.

Contents

1. Introduction

Spray drying is an essential unit operation for making powder from liquid slurry. It is widely used in different industries such as the

* Corresponding author.
E-mail address: G.Finotello@tue.nl (G. Finotello).

http://dx.doi.org/10.1016/j.powtec.2016.06.005
0032-5910/

chemical industry, the pharmaceuticals industry and the food industry. Generally, a spray dryer comes at the end of the processing line, as it is an important step to control the final product quality. It has some advantages, such as rapid drying rates, a wide range of operating temperatures and short residence times. The morphology of the powder can be controlled to some extent, creating possibilities in several fields where powder production is central. Furthermore, composite particles with a microencapsulated core can be formed for controlled release of an active substance [1].

Spray drying is used frequently in the food industry for producing powders in the form of soup, instant coffee, and milk powder. The desired characteristics of these powders are different but controllable to a certain extent. The most important characteristics for milk powder are good flowability, water solubility, and a limited dustiness, i.e. a low amount of small particles in the final powder. What largely affects all of these characteristics is the degree of agglomeration in the final particles. This is the result of collisions between viscous droplets or primary particles formed from droplets, as well as collisions between viscous droplets and recycled fines, i.e. small dry particles [2].

Many investigations have been made of binary droplet-droplet interactions, see [2] and the references therein. The outcome of such collisions can conveniently be characterized using the Weber number We, the impact parameter b (Fig. 1), and the size ratio Δ [2]. These parameters are calculated as:

$$\mathrm{We} = \frac{\rho_d d v_{rel}^2}{\sigma} \quad (1)$$

$$\mathrm{b} = \frac{2B}{d_1 + d_2} \quad (2)$$

where We is based on the smallest droplet diameter d. An example of how these two parameters determine the outcome of a droplet-droplet collision is shown in the regime map in Fig. 2. The regime boundaries will however change for different small to large droplet size ratios Δ.

The amount of studies investigating binary particle-droplet collisions is very limited. Dubrovsky et al. [4] investigated droplet-particle collisions at relative velocities of 3.4–12.8 m/s, where the particle was smaller than the droplet [4]. A notable difference with droplet-droplet collisions is that no reflexive separation was observed at any velocity. Instead four different outcomes were observed for collisions with low impact parameter. These were particle capture, “shooting through” with satellite droplet formation, gas bubble formation after the particle shot through the droplet, and target destruction where the droplet is turned into fragments. No literature has been found on mid-air collisions where the particle is bigger than the droplet. However, some literature data exists for a fixed particle, where either agglomeration or droplet fragmentation against the surface of the particle is observed for head-on or near head-on collisions [4,5]. Dubrovsky et al. [4] did these experiments with a droplet Reynolds number ranging between 25 and 2500. It was found that coalescence increased with increased viscosity of the droplets and increased size ratio between the particle and the droplet. Shen [5] concluded that the amount of water attached to the particle decreased with increased velocity of the droplet. The experiment was made for two different sizes of droplets and was executed for a number of velocities. Furthermore, the impact parameter was found to have a bigger influence on the mass transfer, compared to the tested Weber numbers. Another difference from binary droplet collisions is that recoiling or bouncing is not as likely to occur. This requires certain conditions which are not met in this study. Specifically, it requires a high contact angle, for instance caused by a hydrophobic surface or a particle sufficiently heated, making the evaporation of the droplet take place in the Leidenfrost regime, causing a thin vapour film to prevent wetting of the particle surface [6,7].

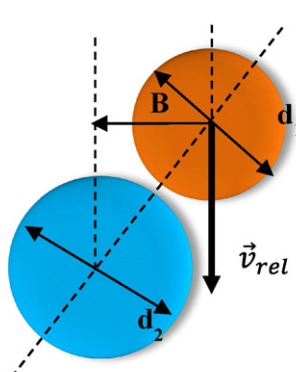

Fig. 1. Geometric and kinetic parameters used to describe the impact parameter, b.

The statistical distribution of water attachment and momentum transfer by particle-droplet collisions is examined in [8]. This work was not focusing on binary collision hydrodynamics, but more on the collision probability and mass transfer statistics. The study was executed using a set of free-falling particles, colliding with a horizontal spray of water and having several collecting bins in the direction of the falling droplets and hit particles. The model for liquid attachment does however neglect size and velocity distributions of the droplets and also the influence of the turbulence in the spray jet.

Mitra et al. [9] focused on the collision hydrodynamics of a small glass particle impacting into a larger stationary droplet. The experimental work was compared with a numerical investigation. The resulting particle sinking times, correlated to the transition from partial to complete penetration, were in good agreement between experiment and simulation. It was found that the effect of capillary and pressure forces were dominant. The analysis was however limited to low We numbers in a range of 0.2–13.5.

The opposite case of small droplets impacting with large particles has also been investigated [10,11]. Hardalupas et al. [10] performed experimental work on liquid drops (160–230 μm diameter) colliding on the surface of a small solid sphere (0.8–1.3 mm diameter). They accurately analysed shape of the impacting droplet observing a retraction of the liquid crown at low droplet velocity and disintegration starting from the rim of the cups for high velocity. Bakshi et al. [11] performed an extensive experimental and theoretical investigation with particular attention to spatial and temporal evolution of film thickness on the target surface. Both these works had as main interest the understanding of the coating of particles. Moreover in both cases the spherical target particle was static, instead of freely moving.

A prime example of numerical investigation on droplet particle collision is given by Gac and Grado [12], who studied the impact of a droplet on differently shaped solid particles. Using the lattice-Boltzmann method (LBM) three collision regimes were identified: (1) coalescence, without droplet fragmentation, (2) ripping and coating, where one part of the droplet deposits and coats the particle and the other part detaches and continues the motion, and (3) skirt scattering, with the formation of a long conical surface “skirt” which breaks into small droplets. We note that this study was focusing on relatively large capillary numbers of order 1, whereas the capillary numbers studied in this work are about two orders of magnitude lower.

We conclude that studies that thoroughly evaluate how mid-air particle-droplet collision outcomes depend on the impact parameter, size ratio and the characteristic Weber number are limited. The main objective of this study is therefore to provide an experimental data set for the outcome of mid-air particle-droplet collisions at relatively low Capillary numbers, which can be used to validate future theoretical and simulation developments. The different collision outcomes include agglomeration and stretching separation, the latter both with and without the formation of satellite droplets. These outcomes are placed in regime maps based on parameters such as the impact parameter and the Weber number. The obtained the experimental results will be based on the analysis of images from a high speed camera. We used water as