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Agglomeration during spray drying: Airborne clusters or breakage at the walls?

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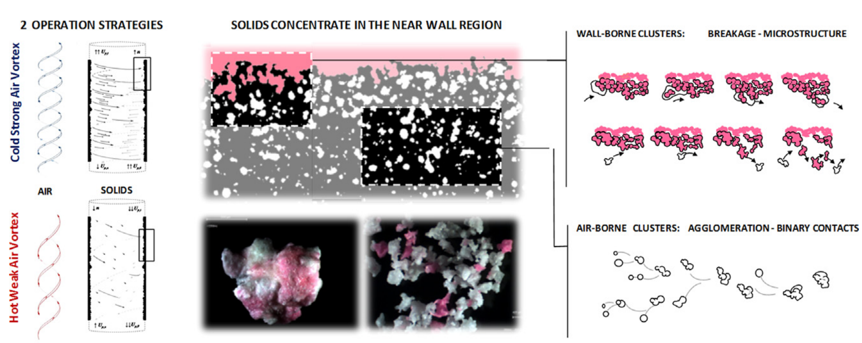
HIGHLIGHTS

- Study of particle growth in a swirl drying tower under varying air flow conditions.
- Four arrangements of spraying nozzles are studied using single and multiple levels.
- Limiting operation strategies are studied: cold strong vortex *vs* hot weak vortex.
- Agglomerates are formed in a dynamic structure of multi-layered wall deposits.
- Wall dynamics can be controlled modifying the kinetic energy of the solid phase.

GRAPHICAL ABSTRACT



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ABSTRACT

Particle agglomeration, wall deposition and resuspension are inherent to many industries and natural processes, and often inter-connected. This work looks into their relation in a confined particle laden swirling flow. It investigates how the size of detergent powder spray dried in a swirl counter-current tower responds to changes in the air flow. Four sets of sprays are investigated under varying combinations of air temperature and velocity that cause the same evaporation. The use of high air velocities accumulates more of the droplets and dry powder in the chamber swirling faster, but it leads to creation of a finer product. Particle-particle and particle-wall contacts are made more frequent and energetic but in turn the swirl troughs the solids to the wall where deposits constantly form and break. Past *PIV* and tracer studies revealed that the rates of deposition and resuspension are balanced; the data discussed here indicate that the dynamic nature of the deposits is a major contributor to particle formation. In contrast with the usual assumption, the product size seems driven not by inter-particle contacts in airborne state but the ability of the solids to gain kinetic energy and break up a collection of clusters layering on the wall. As a result, the dryer performance becomes driven by the dynamic of deposition and resuspension. This paper studies the efficiency of limiting operation strategies and shows that a low temperature design concept is better suited to control fouling phenomena and improve capacity and energy consumption.

1. Introduction

Particle agglomeration is at the core of powder manufacturing. Fluidised beds or granulators (Tan et al., 2006; Fries et al., 2013) are examples of well controlled processes, but particles grow in a

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Nomenclature

A	cross-sectional area of the cylindrical chamber, m^2
C	capacity ratio $C = 1 - ((M_E + M_R)/M_{EP})$, –
D	diameter of the cylindrical chamber, m
d	diameter of the top exit in the dryer, tubular guard, m
f	normalised size frequency in a probability density function, log $(\mu m)^{-1}$
H_A	enthalpy rate for the air taking ambient temperature as reference $H_A = \int_{T_{Amb}}^{T_{A,av}} M_A\, c_{p,A}.dT$, J s^{-1}
$\Delta H_{DA,Sn}$	enthalpy variation between outlet and inlet air in a dry basis, J s^{-1}
$\Delta H_{p,Sn}$	enthalpy variation between the outlet product, elutriates and water vapour and the inlet slurry, J s^{-1}
M	mass rate, kg s^{-1}
M_S	mass rate of slurry sprayed at the nozzle, kg s^{-1}
M_E	mass rate of powder elutriated and collected at the cyclones, kg s^{-1}
M_R	mass rate of oversized product exiting the tower belt, kg s^{-1}
M_P	mass rate of the product exiting the tower belt, kg s^{-1}
M_{EP}	overall rate of powder exiting the spray drying chamber, kg s^{-1}
Oh^2	Ohnesorge number, $Oh^2 = 2\mu_p{}^2/x_p\, \rho_p\, \sigma_p$
Q_{Lat}	latent enthalpy rate of the water vapour generated in the chamber, J s^{-1}
Q_{Loss}	rate of heat lost to the environment, J s^{-1}
Q_{Ex}	rate of heat exchanged in the dryer, J s^{-1}
Q_S	rate of heat transferred to the solid phase, J s^{-1}
q	specific heat transfer rate per m and kg of dry slurry, kJ m^{-1} kg_{DS}^{-1}
$r_{d,o}$	initial net wall deposition rate, g m^{-2} s^{-1}
rH_A	relative humidity of the air, %
T	time averaged temperature, °C
$T_{A,av}$	cross-sectional average air temperature, $T_{A,av} = \int \rho_A U_{A,z} T_A\, dA \,/ \int \rho_A U_{A,z} dA$ where normalised radial profiles for $U_{A,z}$ are taken from isothermal cases (Francia et al., 2015c)
U	time averaged velocity, m s^{-1}
U_{av}	bulk or superficial air velocity, m s^{-1}
$U_{p,Sd}$	particle sedimentation or free falling velocity, m s^{-1}
$U_{p,t}$	particle terminal velocity, m s^{-1}
$U_{p,w}$	particle velocity for the first wall impact, m s^{-1}
X_w	product water mass fraction
z	axial position in the cylindrical chamber measured from the level of the air inlets, m

Greek letters and symbols

η_t	thermal efficiency in the dryer, $\eta_t = (T_{A,IN} - T_{A,EX})/(T_{A,IN} - T_{amb})$
η_h	heat transfer efficiency in the dryer, $\eta_h = Q_S/H_{A,IN}$
Ω_i	design swirl intensity, non-dimensional flux of angular momentum (Francia et al., 2015c)

Subscripts, superscripts and caps

A	for the air phase
DA	for dry air
DS	for dry slurry
E	for the elutriated fraction of powder
EP	for the full powder exiting the tower (elutriated fraction + product from the bottom)
EX	exhaust conditions
IN	inlet conditions
P	for the particle/product exiting the tower from the bottom end
R	for the fraction of oversized powder removed from that exiting from the tower belt

more uncontrolled fashion in dryers (Verdurmen et al., 2004) or cyclones (Alves et al., 2015). Agglomeration is regarded as the result of a collision between two flowing particles or droplets (Sommerfeld, 2001). Impacts to the wall of process units or the material layering there receive less attention (Jin and Chen, 2010; Song et al., 2016). Similarly to the treatment of particle-particle contacts (Sutkar et al., 2015) the collisions of dry or wet particles to the walls are simplified by restitution coefficients (Hastie, 2013; Crüger et al., 2016). In most cases, numerical models of particulate processes neglect deposition or assume that it leads to a static layer of material that plays no role in the overall process. In a sense, the lack of an advanced description of fouling is a handicap of the powder industry. Deposition, consolidation, suppression and resuspension are widely studied in other fields such as sediment and soil dynamics (Harris and Davidson, 2009), nuclear (Lustfeld et al., 2014) and heat transfer engineering (Yeap et al., 2004; Bansal and Chen, 2006), microfluidics (Marshall and Renjitham, 2014), membrane technology (Melián-Martel et al., 2012), combustion and ash deposits (Zbogar et al., 2009) or biotechnology (Chu and Li, 2005).

Ziskind (2006), Li et al. (2011) and the work of Henry et al. (2012), and Henry and Minier (2014) set a clear picture of the state-of-the-art in colloidal and particulate fouling research. Many technologies refer to deal with colloids and/or inertia-less systems that form mono-layered deposits (Soldati and Marchioli, 2009) where fouling is treated essentially as a fluid dynamics problem. Many industries however handle cohesive materials and deal with complex multi-layered deposits. Depending on the case, deposits evolve in time due to the transfer of momentum e.g. deposition and removal processes, heat and mass e.g. drying, sintering, or undergoing chemical reactions e.g. ageing. Such a complex behaviour is not exceptional but the rule in energy and environmental engineering (Abd-Elhady et al., 2007; Lecrivain et al., 2014; Diaz-Bejarano et al., 2016; Alipour et al., 2016), or in materials and powder industries (Adamczyk et al., 2008; Batys et al., 2015; Nakazato, 2015). Studies of multilayered deposits include analysis of stress propagation (Bourrier et al., 2010), clustering (Tanaka et al., 2002; Iimura et al., 2009), kinetic frames (Zhang et al., 2013) and advance experimental set ups (Barth et al., 2013), but in many practical cases, data are scare and engineers cannot predict how fouling responds to operation conditions. This limitation compromises the efficiency in handling powders (e.g. detergents, ceramics, biomass, foods, pharmaceutics) and intensifying their production (e.g. dryers, granulators, mixers, burners, fluidized beds, conveyors).

Spray dryers are particularly challenging because they bring together dry particles with semidried and wet droplets. Our past work studied the origin of agglomeration in swirl counter-current towers and described how the placement of nozzles (Francia et al., 2016a, 2016b) affects the process. *PIV* studies (Hassall, 2011) and a set of tracer experiments (Francia et al., 2015a) also demonstrated that in drying detergent formulas the deposits generated are dynamic structures constantly forming and breaking. One in five particles were found to be the direct result of deposit resuspension but the data suggested many more interact at the wall without becoming permanently fixed. This