



An experimentally validated criterion for skim milk powder deposition on stainless steel surfaces



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ABSTRACT

Predicting the deposition during the production of milk powder has been identified as a possible avenue to creating new designs and selecting processing conditions that minimise particle deposition. Numerous studies have looked at characterising various aspects of milk powder deposition, agglomeration and caking. Present literature lacks a fundamental and validated criterion that describes the deposition of skim milk powder particle (SMP) impacts with short contact times (<1 s). In this paper standard solutions to the contact mechanics problem of a spherical elastic particle with an adhesive surface impacting a rigid plate at normal and oblique angles form the basis of a derivation of a semi-empirical criterion that describes whether a particle sticks after impacting a wall. To validate the criterion, the determining factors of skim milk powder deposition, which are air temperature, water activity (i.e. relative humidity), plate (or wall) temperature, and particle size, velocity and impact angle, are isolated and experimentally tested using the Particle Gun technique.

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1. Introduction

Predicting dairy and food powder deposition in spray dryers, auxiliary processes and heat recovery equipment using Computational Fluid Dynamics (CFD) has emerged as an area of significant research interest (Jin and Chen, 2010). A key input function to these computer models is a wall boundary condition/criterion that evaluates whether a powder particle sticks or rebounds. Reported in literature is a wide range of experimental powder stickiness characterisation tests (Boonyai et al., 2004), however there is a lack of a detailed and complete criterion that expresses the critical combination of conditions, including air temperature, humidity, impact velocity and angle, particle mass, etc., that results in deposition.

Current criteria for modelling particle deposition using CFD in literature have been simple in nature with critical values being somewhat arbitrarily selected before modelling results are compared to experimental results for validation. Harvie et al. (2002) formulated a simple wall boundary deposition criterion focused solely on a fixed $(T - T_g)_{crit}$, where T is the air temperature and T_g is the glass transition temperature of the major amorphous component of the powder. Woo et al. (2008) based their wall capture criterion on a fixed critical normal velocity without respect to the surrounding air conditions. Woo et al. also gave no supporting

experimental evidence for the choice of critical normal velocity and coefficient of restitution. Zhao (2009) built on the approach of Woo et al. by applying a critical normal capture velocity that was dependent on the air temperature and humidity, i.e. $T - T_g$. However Zhao did not consider the effect of oblique particle impact angles in his criterion. Jin and Chen (2010) applied the concepts of critical pseudo Ohnesorge (a ratio of viscosity to surface tension) and Webber (the fluid's inertia compared to its surface tension) numbers to determine particle attachment. Jin and Chen give no basis for their selection of critical Ohnesorge and Webber numbers other than the modelling trends somewhat follow experimental results.

Besides CFD wall boundary criterion Palzer (2005) applied a classic model for viscoelastic contact to derive a critical contact time, which if exceeded indicated deposition and/or agglomeration would occur. Palzer's model assumed that sintering as described by the Frenkel equation was the relevant process for developing the adhesion force. This model, however, has been shown to be invalid for SMP in situations where the contact times are short (<1 s) as is the case with the experimental tests such as the Particle Gun stickiness test (Murthi et al., 2010).

Whether a particle, such as Skim Milk Powder (SMP), deposits or rebounds is determined by the particle's kinetic energy, which upon contact is transferred to potential elastic energy and plastic deformation, compared to the bond strength between the particle and the surface (or another particle). Numerous studies dating back to the elementary work of Hertz (1881) in the late nineteenth century have studied the theoretical and experimental aspects of

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Nomenclature

Roman

a	dimensionless constant
a_w	water activity
B	proportionality constant in Eq. (8)
D_1	dimensionless constant in Eq. (1)
D_2	temperature constant in Eq. (1), °C
d	particle diameter, m
E	energy, J
F	force, N
G	shear modulus, Pa
k	dimensionless constant in Eq. (2)
m	mass, kg
P	pressure, Pa
RH	relative humidity, %
r	particle radius, m
T	temperature, °C
T_g	glass transition temperature, °C
W_a	work of adhesion, J
Y	Young's modulus, Pa
Y^*	modified Young's modulus, Pa

Greek

γ	adhesion bond strength, J/m ²
δ	penetration depth, m
Θ	impact angle, °
λ	dimensionless group of properties
ν	Poisson's ratio
ρ	density, kg/m ³

Subscripts

a	adhesion
$crit$	critical
l	lactose
n	normal
p	particle
pd	plastic deformation
rot	rotational
s	sticking
t	tangential
w	water

the normal impact of spherical balls on plates. This body of literature includes work on elastic (Hertz, 1881), elastic–plastic (Thornton and Ning, 1998), plastic, and viscoelastic spheres (Brilliantov et al., 2007).

The aim of this study is to derive and experimentally validate a criterion that describes the adhesion of SMP onto a flat, polished stainless steel surface. Factors contributing to deposition that are studied include: air temperature and humidity, particle size and mass distribution, impact velocity and angle, and plate temperature. To describe these effects on particle deposition, a simple elastic contact model with adhesion is derived and its constants solved by fitting the model to experimental data. Furthermore, data from several literature sources are reviewed and included when validating the model. This validated deposition criterion may prove useful to be applied as a wall boundary condition in Computational Fluid Dynamics models to predict where deposition will occur in processing equipment for optimising equipment design.

2. Theory

2.1. Developments in the understanding of SMP surface stickiness

Early experimental studies on the stickiness characteristics of food and dairy powders looked at stickiness development in situations where contact between particles occurred for extended periods of time (Wallack and King, 1988). Focus was given to measuring temperature (T) and relative humidity (RH) conditions that caused sudden coalescing of dairy powder particles leading to agglomeration and caking (Hennigs et al., 2001). Stickiness tests have also been developed to mimic the operation of various unit operations such as lab-scale spray drying (Chen et al., 1993; Kota and Langrish, 2006), fluidised bed drying (Zuo, 2004), cyclone separation units (Intipunya et al., 2009), and dryer exhaust gaseous heat exchangers (Walmsley et al., 2013b, 2013c). The Particle Gun test, which uses an impingement jet and fires particles at a flat plate, was constructed to simulate shorter contact times and to acutely study the effects of airflow dynamics (Paterson et al., 2007).

The surface stickiness of food and dairy powders is intricately related to the concepts of glass transition temperature and viscosity (Downton et al., 1982). In amorphous materials, such as SMP, the glass transition temperature, T_g , identifies the boundary

between the material being in a non-sticky glassy state or a sticky rubbery state. The major amorphous component in SMP is Lactose, which accounts for about half of SMP by weight. For air temperatures below T_g , the viscosity is high and molecular movements of surface lactose are subdued. Above T_g , molecular mobility rapidly increases while the surface viscosity lowers. Liquid bridges may then readily form between two particles and between particles and solid surfaces. Further temperature increases above T_g continues to lower viscosity. The amount the air temperature is above T_g , i.e. $T - T_g$, is logarithmically related to viscosity, μ , as described by the Williams et al. (1955) equation, where D_1 is a dimensionless constant and D_2 is a temperature constant for a given amorphous composition. Hence, $T - T_g$ is a non-linear measure of stickiness through viscosity.

$$\text{Log}\left(\frac{\mu}{\mu_g}\right) = \frac{-D_1(T - T_g)}{D_2 + (T - T_g)} \quad (1)$$

The glass transition temperature of a material is strongly dependent on the moisture content and water activity at the surface of the particle. For two component substances Gordon and Taylor (1952) suggested a modified rule of mixtures equation was sufficient to calculate the glass transition temperature of the material, which for SMP may be applied to lactose and water (Hennigs et al., 2001),

$$T_g = \frac{T_{g,l} + kX_{eq}T_{g,w}}{1 + kX_{eq}} \quad (2)$$

where T_g is the glass transition temperature of SMP, X_{eq} is the equilibrium moisture content on a dry basis, $T_{g,l}$ is the glass transition temperature of lactose, $T_{g,w}$ is the glass transition temperature of water and k is a constant. Since X_{eq} is weakly dependent on temperature, Brooks (2000) successfully developed a polynomial model to relate a_w (or RH) to T_g with high accuracy,

$$T_g = 530.66a_w^3 + 652.06a_w^2 - 366.33a_w + 99.458, \quad [0 < a_w < 0.575] \quad (3)$$

where a_w is the water activity. However Brooks' equation is limited to the water activity range stated and beyond this range, the model is unreliable. As a result Eq. (2) may be applied, in combination with the appropriate sorption isotherm that links particle moisture

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