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Mixing time and power consumption during blending of cohesive food powders with a horizontal helical double-ribbon impeller

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ABSTRACT

The mixing time and power consumption of a helical double-ribbon impeller during blending of normal corn starch and icing sugar were studied. The approach took into account representative physical, flow and frictional properties of individual components and a 50:50 (w:w) blend, operating conditions and impeller characteristic dimensions. Physical tests showed the powders to be cohesive, hyperfine/superfine, with fair to good flow properties and different internal friction coefficient. Operating conditions played an important role in mixing time. Power consumption data were correlated with relevant powder physical properties; bulk density (ρ_b) and friction coefficient (μ_i), system dimensions; impeller volume (V_I) and length (L_I), and operating conditions; load ratio (f) and impeller speed (N), by the relationship $P = 0.21[(\rho_b \mu_i)(V_I L_I)(fN)g]$. A dimensionless correlation between the power number ($N_P = P/\rho_b D_o^3 N^5$) and the effective cohesion number ($N_{Ce} = [\rho_b D_o^4 N^2/F_C][K_p(f)/f]$) was obtained for the impeller; N_P decreased with increasing N_{Ce}.

1. Introduction

Food powders are common format of food materials. The volume and types of powder production is increasing day-by-day as this is a stable form of the food that is easy to use, pack, distribute and handle (Cuq et al., 2013). In the food industry, the main objective of mixing is to reduce non-uniformities and gradients in concentration, color, texture, or taste between different parts of the mixture (Barbosa-Cánovas et al., 2005). The diverse characteristics of food powders make their mixing a complicated operation. Contrary to model powders, e.g. glass beads, which are made up of homogeneous, spherical, mono-disperse and inert particles, food powders display a huge heterogeneity in size, shape, and structure (Cuq et al., 2013). In addition, most food powders are known to be cohesive, which means that their attractive interparticle forces are significantly high relative to the particle's own weight (Peleg, 1983). As a rule of thumb, the particle size below which cohesive effects are important for dry materials can be taken as 100 μm (Rao and Nott, 2008).

The evaluation of powder mixture quality seems to be a constant preoccupation for industries that need to ensure very precise control over their mixing process (Cuq et al., 2013). The degree of mixing required is determined by end use (Bridgwater, 2012). Mixing quality is mainly affected by the mixer type and design, including size, shape and paddle geometry, rotational speed, mixing time, and also by the types of powder being mixed. A wide variety of food powders are commonly mixed in horizontal ribbon mixers. In food industries, mixing processes are still largely conducted in batches, due to the greater flexibility and lower installation costs of this system in comparison to continuous processes (Barbosa-Cánovas et al., 2005). Mixing practice for food applications is still based on a combination of "know-how" and science. The available knowledge is not enough to determine how the quality and stability of mixtures depend on powder properties and mixing processes (Cuq et al., 2013). Therefore, emphasis should be placed on the need to understand the dynamics of the phenomena that occur in the stirred vessel.

Methods of predicting the process performance characteristics of mixing equipment involve correlations of dimensionless groups and model relationships (Uhl and Gray, 1966). An important consideration in the design of an agitated system is the power required to drive the impeller. A few correlations of power consumption of the impeller, with geometric and equipment operating variables, and physical properties of solids have been published for particulate systems in comparison with fluids. Among research works in this field are those of Makishima and Shirai (1968) who derived the ratio of inertia force to shearing stress, and the power number from experiments with various powders in a vertical blade mixer. Sato et al. (1977) studied the relation between torque in horizontal

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Notation

C	cohesion (kPa)
C_b	bottom clearance (m)
CI	compressibility index (%)
$D[v, 0.5]$	median diameter of food powder particles (μm)
D_i	diameter of inner ribbon (m)
D_o	diameter of outer ribbon (m)
D_T	vessel diameter (m)
e	porosity (%)
$e_{\max}$	maximum porosity (%)
f	load ratio (dimensionless)
F_C	cohesive force (N)
g	acceleration due to gravity (m/s^2)
h	height of powder pile (m)
K_P	impeller constant
L_I	length of helical double-ribbon impeller (m)
L_i	axial length of inner ribbon of the helical double-ribbon impeller (m)
L_o	axial length of outer ribbon of the helical double-ribbon impeller (m)
L_T	vessel length (m)
n	number of pitches (dimensionless)
n_i	number of pitches of inner ribbon (dimensionless)
n_o	number of pitches of outer ribbon (dimensionless)
N	rotational speed (rpm)
N_C	cohesion number (dimensionless)
N_{Ce}	effective cohesion number (dimensionless)
N_s	total number of samples in Eq. (4)
N_P	power number
p_i	pitch of inner ribbon (m)
p_o	pitch of outer ribbon (m)
P	mixing power (W)
r	radius of powder pile
R	regression coefficient
t	time (min)
t_M	mixing time (min)
T	net mixing torque (Nm)
T_R	residual torque (Nm)
T_T	average torque with powders in the vessel (Nm)
V	vessel volume (m^3)
V_I	volume of helical double-ribbon impeller (m^3)
w_i	width of inner ribbon (m)
w_o	width of outer ribbon (m)
W	powder mass (kg)
x_i	experimentally determined average concentration
x_s	sample concentration

Greek letters

α	angle of repose of food powders (°)
ϕ_i	angle of internal friction (°)
φ	coefficient of mixing rate (min^{-1})
μ_i	friction coefficient (dimensionless)
ρ_b	bulk density (kg/m^3)
ρ_p	bulk particle density (kg/m^3)
ρ_T	bulk tapped density (kg/m^3)
σ	normal stress (kPa)
σ_s	relative standard deviation
σ_0	intercept in Eq. (5)
τ	shear stress (kPa)

mixers and operating conditions, physical properties of powders, and dimension of the mixer. Masiuk (1987) studied the effect of the rotation speed, load ratio and moisture content of one type of sand on power consumption. Knight et al. (2001) investigated the effects of the mass of powder, and the bowl radius on the torque drawn by an impeller of vertical axis in high speed mixers handling granular solids of low cohesion; their data were satisfactorily represented by a dimensionless torque group. André et al. (2012) used dimensional analysis to study mixing time and power consumption of a planetary mixer for blending food powders, and correlated the Power number with the Froude number.

The aims of this study were: (1) to determine the mixing performance of a helical double-ribbon impeller during mixing of normal corn starch and icing sugar; (2) to correlate power consumption data with relevant physical properties of powders, system dimensions and operating conditions by means of dimensional analysis. The results presented here provide an understanding of the powder physical properties important to mixing and a useful correlation to predict the energy required for the agitation process of cohesive food powders in this particular mixer, to be used as an engineering tool in process design of solids mixing.

2. Materials and methods

2.1. Raw materials

Food powders included normal corn starch provided by Globe AA (CPIngredients, México) and icing sugar from Arenas Distribución (México). These components were chosen because normal corn starch is not soluble in cold water, while icing sugar is completely soluble and can be used to trace the homogeneity within the mixing vessel.

2.2. Mixing equipment

The experiments were performed in a custom-made U-shaped stainless steel trough equipped with a helical double-ribbon impeller as shown in Fig. 1. The dimensions of the equipment are shown in Table 1. The impeller has one inner and one outer ribbon that rotate in opposite directions. The shaft of the impeller was coupled concentrically to the bearings of the vessel allowing the main axis to be aligned and properly coupled to a torquemeter (S. Himmelstein & Co., model 2801 T (25-0), USA). The torquemeter was coupled to a DC motor (Control Techniques Worldwide, USA) provided with a variable speed control box (Boston Gear, USA). The out signal of the measured torque was amplified and displayed in a modular readout unit (6-201, 66032, S. Himmelstein & Co., USA). The rotational speed of the motor shaft was measured with a contact tachometer (Cole-Parmer, model 08204-80, USA).

2.3. Powder properties

2.3.1. Physical properties

Moisture content of the powders was measured in a thermobalance (OHAUS, MB45, Switzerland). Bulk density, ρ_b, was

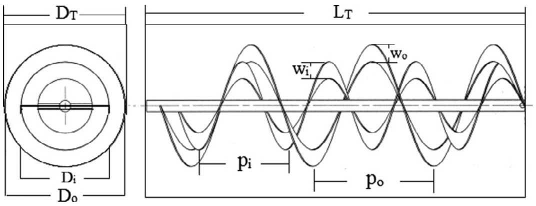

Fig. 1. Helical double-ribbon impeller.