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Dimensional analysis of a planetary mixer for homogenizing of free flowing powders: Mixing time and power consumption

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HIGHLIGHTS

- ▶ An innovative planetary mixer was used for homogenizing free flowing powders.
- ▶ Mixing times were determined using a method based on image processing.
- ▶ Dimensional analysis was validated by experimental results.
- ▶ Generalized power and mixing numbers were defined.
- ▶ Θ_M represents the path to achieve an imposed degree of homogeneity.

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ABSTRACT

Powder mixing is crucial to the processing stages in many industries. However, there is still a paucity of information about the effects of process parameters on mixing efficiency. This paper investigates the homogenization of free flowing granular materials with a planetary mixer, TRIAXE®, examining the effect of the ratio of impeller rotational speeds (N_R/N_G) on the mixing process.

First, a dimensional analysis carried out with mixing time and power consumption as target variables, established that both a Froude number and N_R/N_G controlled the process for the given free flowing powder mixture and planetary mixer.

A further theoretical approach also suggested that these two dimensionless ratios which control hydrodynamics can be reduced to a modified Froude number providing that the maximum linear velocity achieved (u_{ch}) by the planetary mixer is introduced, replacing the dual impeller rotational speeds (N_R and N_G).

Mixing time and power experiments validated the above hypothesis. Homogeneity tests performed in a granular media showed that the length of path achieved by the impeller governs the obtained mixing level.

Finally, this work reflected that (i) dimensional analysis was also well suited to model powder homogenization with a planetary mixer. (ii) A concise set of dimensionless numbers governing mixing phenomena can be deduced through the introduction of the maximum linear velocity as obtained in previous studies on gas/liquid and miscible liquids mixing processes.

1. Introduction

Powder mixing is an important unit operation in a wide variety of industries involved in solids processing. The end-use properties of products of the pharmaceutical, food, plastics and fine chemicals industries, often depend on process history which includes thermal and mechanical actions of dry mixers and/or contact machines (e.g. for encapsulation, agglomeration, etc.). These properties are usually determined through a formulation procedure involving costly evaluations of biological activities to determine the composition, dosage and form of a drug. Although constant efforts are devoted to this aspect, little is known about the manufacturing process itself which makes the study of mixing and mixtures a key subject for both academic and industrial product and process engineers [1–3].

Once a scale of scrutiny of a mixture is set, its homogeneity is usually defined on a statistical basis, considering samples of like size. In industrial practice, when n samples are considered, the

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Nomenclature

c_b	bottom clearance, m
d	characteristic length, m
d_{p1}	diameter of powder 1, m
d_{p2}	diameter of powder 2, m
d_s	diameter of horizontal part of planetary mixer, m
D	diameter of turbine part, m
Fr	Froude number
Fr_G	Froude number based on gyrational speed of agitator
Fr_M	generalized Froude number based on tip speed
H	agitator height, m
H_L	liquid height, m
N	speed of agitator, s^{-1}
N_G	gyrational speed of agitator, s^{-1}
N_R	rotational speed of agitator, s^{-1}
Np	power number
N_{pG}	power number based on gyrational speed of agitator
Np_M	generalized power number based on tip speed
P	power, W
t	time, s
t_m	mixing time, s
$t_{m99\%}$	mixing time for X_M = 0.99, s
T	vessel diameter, m
u_{ch}	maximum tip speed of agitator, m s^{-1}
$u_{impeller\ tip}$	impeller tip speed, m s^{-1}
x	massic composition of the powder
X_M	mixing index

Greek letters

μ	viscosity of viscous medium, Pa s
ρ	density of viscous medium, kg m^{-3}
ρ_1	density of powder 1, kg m^{-3}
ρ_2	density of powder 2, kg m^{-3}
Θ	mixing time number
Θ_G	modified mixing time number based on gyrational speed of agitator
Θ_M	modified mixing time number based on the characteristic speed u_{ch}
σ^2	experimental value of the variance
σ_0^2	initial value of the variance
σ_∞^2	minimum value of the variance

homogeneity of a mixture is judged by comparing the coefficient of variation (CV) of the distribution of the sample composition of a key ingredient to a standard value. In the pharmaceutical industry, a mixture exhibiting a coefficient of variation greater than 6% is rejected as non-conform [4]. The variance σ^2 of the mixture can also be used. For batch operations, the dynamics of the mixing process are monitored by examining the changes of variance with time. Such a curve usually features a quick decrease in variance due to the efficiency of convection mechanisms in reducing the intensity of segregation at a macro scale, followed by a much slower decrease due to micro scale particle diffusion. This latter plateau region sometimes exhibits oscillations which are classically attributed to a competition in particle segregation. Mixing kinetics determine mixing time, the time corresponding to the smallest value of variance [5–8].

Different mixer geometries and agitation devices exist usually based on empirical methods [9]. The use of chemical engineering tools, such as correlations between dimensionless numbers, ought to be considered to improve knowledge on the mixing powder media [10]. However, the traditional method of dimensional analysis applied for liquids including a Reynolds number cannot be derived since no apparent viscosity can be introduced. As such, empirical correlations involving Froude number have often been used for many systems: generalities and correlations [11,12]. One may refer to the correlations of Sato et al. for a horizontal drum mixer [13] or a ribbon mixer [14], the relations of Entrop for a screw mixer [15]. Planetary mixers are often used to optimize mixing processes. Pioneer and more intensive works on non-conventional mixers have been conducted by Tanguy and co-workers. However, if we focus only on planetary mixers defined as combining dual revolution motion around two axes, the literature is still scarce [16–23]. Most of these works concern mixing of miscible fluids. Few of them deal with foaming fluids [24] or granular media [25].

For the investigated planetary mixer (the Triaxe system), Delaplace et al. [22,23] proposed a definition of power and mixing numbers when mixing viscous liquids. Originally built for operating with viscous fluids [21], this mixer has also shown its capability to achieve good mixtures of granular products [25]. However, currently, there is a lack of knowledge concerning dimensionless ratios controlling the mixing of granular materials with such a Triaxe system. The objectives of this work are twofold: (i) to perform dimensional analysis governing mixing time and power consumption in a planetary mixer for the case of granular materials, (ii) to validate this approach by experimental results obtained with a pilot-scale planetary mixer.

2. Theory

2.1. Dimensional analysis for conventional mixing in solid phase

An agitated vessel without baffles equipped with an impeller mounted vertically and centrally is schematically shown in Fig. 1.

For such a mixing system subjected to a gravity field, with a given stirrer type and under given installation conditions (vessel diameter, agitator height, bottom clearance and solid height, see Fig. 1), mixing time t_m depends on agitator diameter, material parameters of the medium (densities (ρ_1, ρ_2), particle size (d_{p1}, d_{p2}) and solid/solid fraction (x)) and speed of the agitator:

$$F_1(t_m, d, T, H, C_b, \rho_1, \rho_2, d_{p1}, d_{p2}, x, N, g) = 0 \quad (1)$$

Introducing $\Delta\rho = \rho_2 - \rho_1$, this list of relevant parameters can be rewritten as

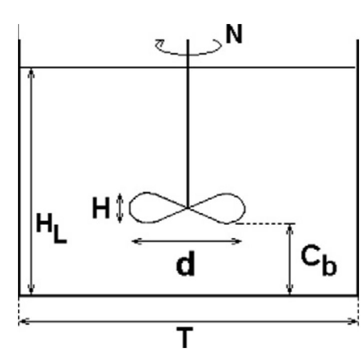

Fig. 1. Classical geometric parameters and notations used for mixing vessel equipped with an impeller vertically and centrally mounted in a tank.