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Size-dependent coalescence kernel in fertilizer granulation—A comparative study

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ABSTRACT

Granulation is a key process in several industries like pharmaceutical, food, fertilizer, agrochemicals, etc. Population balance modeling has been used extensively for modeling agglomeration in many systems such as crystallization, aerosols, pelletisation, etc. The key parameter is the coalescence kernel, $\beta(i,j)$ which dictates the overall rate of coalescence as well as the effect of granule size on coalescence rate. Adetayo, Litster, Pratsinis, and Ennis (1995) studied fertilizer granulation with a broad size distribution and modeled it with a two-stage kernel. A constant kernel can be applied to those granules which coalesce successfully. The coalescence model gives conditions for two types of coalescence, Type I and II. A two-stage kernel, which is necessary to model granule size distribution over a wide size distribution, is applied in the present fluidized bed spray granulation process. The first stage is size-independent and non-inertial regime, and is followed by a size-dependent stage in which collisions between particles are non-random, i.e. inertial regime. The present work is focused on the second stage kernel where the feed particles of volume i and j collide and form final granule ij instead of $i+j$ (Adetayo et al., 1995) which gives a wider particle size distribution of granules than proposed earlier.

1. Introduction

Granulation is a size enlargement process that produces granules with controlled properties from liquid or particulate feeds. In this process fine particles combine to form agglomerate by spraying a liquid binder on the dry powder bed. It is a key process adopted in various industries like pharmaceuticals, detergent, agricultural products, food, agrochemical, etc. Key granule properties important for product quality, granule size distribution and porosity, are in turn fixed by the rate and the extent of various macroscopic growth mechanisms in the granulation process, e.g., nucleation, consolidation, coalescence, layering, etc., which have been clearly identified and classified (Kapur, 1972; Sastry, 1975). Granulation is adopted to improve the density and flowability of material, reduce dustiness and co-mixing of materials which will otherwise segregate and form cake (Ennis, Li, Tardos, & Pfeffer, 1990; Ennis & Lister, 1997).

In fluidized bed granulation a granulating liquid, containing a binding agent, is sprayed on a hot fluidized bed of particles. This process can be represented by two continuously repeating consecutive steps. The first step is the wetting of the fluidized particles by the sprayed liquid and agglomeration of particles by liquid bonds. The second step is the formation of solid bonds by drying the existing liquid bonds. Therefore, granulation in fluidized bed can be considered as a succession of a wetting process followed by a drying process. As solvent evaporates from the binder solution, the particles undergo various relative displacements with respect to one another. It is assumed that the binder is well dispersed on the bed particles.

In most particulate process where particle number is more important than mass, a balance over the population of materials of a given size in the system is necessary. The population balance is a widely used model for granulation and has been studied by different workers, Cryer (1999), Ennis and Lister (1997), Liu, Litster, Iveson, and Ennis (2000), Liu and Cameron (2001), and Liu and Litster (2002). This is also applicable for granulation process where the size distribution, in addition to granule structure and voidage, is a pathfinder of the final product. The population balance is a statement of continuity that describes how the particle size distribution changes with time and position.

The mechanism behind the granulation process is divided into three stages: wetting and nucleation, growth and consolidation, attrition and breakage (Iveson, Lister, Hapgood, & Ennis, 2001; Litster, Smit, & Hounslow, 1995). In this paper only coalescence of granules is considered and how this coalescence occurs in inertial and non-inertial regime is discussed.

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Nomenclature

D_{pi}	initial particle size fed to the granulator, μm
i, j	particle size (volume boundary of ith and jth section)
k_1, k_2	kernel parameters
m_i	mass of particle of size i
n_i	number of particles of size i
T_{gi}	inlet gas temperature, °C
T_b	temperature of the bed particles, °C
U_{og}	superficial gas velocity, cm/s

Greek symbols

$\beta(i,j)$	coalescence kernel for granules with volume i and j
ρ_p	density of particle, gm/cm^3

Dimensionless number

St	Stokes number (initial kinetic energy)/(dissipated energy)

This paper presents a population balance model using a two-stage coalescence kernel for urea granulation. The present model gives a wider particle size distribution. The model proposed by Adetayo, Litster, Pratsinis, and Ennis (1995) showed that the collision between the granules of size (i and j) gives a narrower size distribution ($i+j$) as compared to the present work in which collision occurs to form the granules of size (ij).

2. Theory

2.1. Concept of population balance

The population balance is a statement of continuity for particulate systems. It follows the changes in particle size distribution as particles are born, die, grow or leave the control volume.

Smoluchowski (1917) developed a mathematical model, the flow box model, for the coalescence of particles where the number of particles of each size has been recorded. The essence of this model is to track the flow of particles as they coalesce from one size to another. The flow box model consists of particles leaving size i and j, entering size $i+j$. *A differential equation for* $n_l(t)$ is now derived by examining the rate at which particles enter and leave size l. Particles leave size l when collisions occur with any particle of size $m \geq 1$. Particles enter size l when size m and (l–m) particles coalesce. The final differential equation for $n_l(t)$ explaining the coalescence as given by Smoluchowski can be written as

$$\frac{dn_l}{dt} = \frac{1}{2}\sum_{m=1}^{l-1}\beta_{m,l-m}n_m(t)n_{l-m}(t) - n_l(t)\sum_{m=1}^{\infty}\beta_{l,m}n_m(t). \quad (1)$$

2.2. Coalescence kernel

The coalescence kernel $\beta_{i,j}$, an important parameter in population balance modeling, is a measure of the frequency of successful coalescence between two particles of volumes i and j. Coalescence kernel studies for wet granulation process by different workers (Adetayo & Ennis, 1997; Adetayo, Litster, & Desai, 1993; Adetayo et al., 1995; Litster et al., 1995; Liu et al., 2000; Ouchiyama & Tanaka, 1975; Ramabhadran, 1975; Sastry & Fuerstenau, 1970) have shown quite conclusively that fertilizer granulation can be satisfactorily explained only by a sequential combination of a size-independent and dependent kernels. In the first stage of non-inertial regime of granulation, the probability of successful coalescence following a collision is independent of particle size and collision velocity and depends on binder distribution. In this stage the rate of collision is independent of particle size and this stage is a random process. So the first stage kernel is a constant like

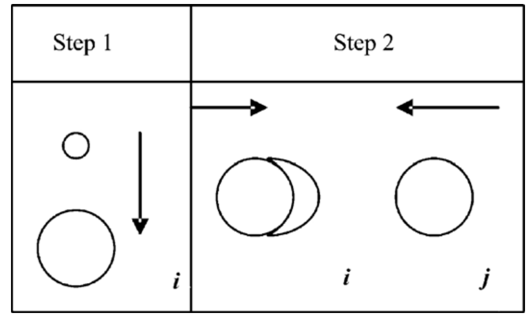

Fig. 1. Modeling of a two-stage agglomeration process.

$$\beta_{i,j}^{\{1\}} = k_1. \quad (2)$$

2.3. Characteristic of two stage kernels — (i) constant and (ii) size-dependent

A granule is a particle matrix partially or fully saturated with the binder liquid. Fig. 1 shows a two-stage kernel. Eq. (2) (constant kernel) does not predict the final granule size distribution and the surface mean diameter of granule at the end-point of granulation process. In granulation process both mechanism and kernels should be determined to describe the growth. In first stage kernel, the feed particles are within the non-inertial regime of growth where granule deformation can be neglected, all collisions result in successful coalescence provided that binder is present or active. So in this stage, the coalescence occurs via a random or size-independent kernel, which is only a function of liquid loading y, given by

$$\beta_{i,j} = k_1 = k^* f(y). \quad (3)$$

The growth favored by liquid loading $f(y)$ strongly depends on wetting properties. For random growth, it may be shown that the average granule size is given by

$$a = a_0 e^{k_1 t_1}, \quad (4)$$

where a_0 is the initial nuclei size and $k_1 t_1$ is the extent of granulation [t and t_1 need to be defined]. Fig. 2 presents the variation

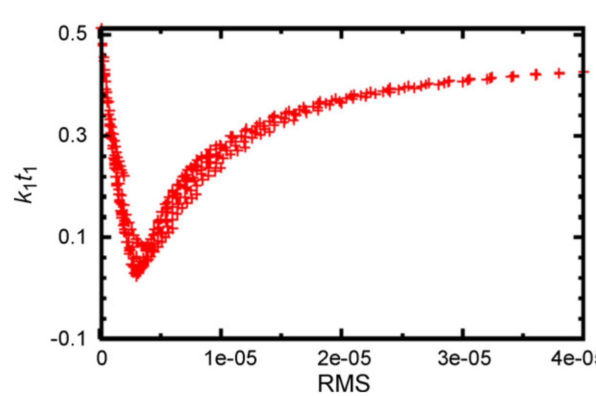

Fig. 2. Variation of root mean square deviation between the predicted and experimental particle size distribution and k_1t_1, for initial particle size of 327.5 μm, operating gas velocity of 65.8 cm/s, inlet air temperature of 30 °C, and moisture content of 8.7% (wt%). The best estimate of k_1t_1 corresponds to the minimum in the curve.