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Growth of a wet agglomerate rolling down an inclined granular bed

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Abstract. Drum granulation is a size-enlargement process in which liquid binder is sprayed on to granular material for the nucleation of wet agglomerates bound by the capillary and viscous force of the liquid. The rotation of the drum causes the relative motion of the agglomerates with respect to the surrounding granular material leading to their densification as well as their growth, and/or breakage. The granular flow in a rotating drum is characterized by a solid like bulk region which undergoes rigid body rotation and a small fluid-like flowing layer near the free surface with sufficient shear during the flow. To gain a deeper understanding of the behaviour of the wet agglomerates within the flowing free surface layer region, we investigate the growth of a single wet agglomerate placed in a granular bed in an inclined periodic chute. In order to investigate the role of the process parameters and the material properties, we study the effect of the initial granule size, liquid content, binder surface tension and binder viscosity on the granule growth. We find that the granule growth increases with the initial granule size and binder surface tension. The effect of liquid content on growth rate suggests a liquid limit beyond which increasing liquid content does not increase the growth rate. Increasing the viscosity of the liquid binder leads to a distinct granule growth behavior characterized by alternating slow and rapid growth periods.

1 Introduction

Drum granulation is a size-enlargement process which is used to improve bulk-level properties of granular material like flowability, and particle-level properties like size, strength and density [1]. In this process, granular material is agitated in a rotating drum along with a liquid binder. This process results in the particles agglomerating due to the surface-tension and viscous force of the liquid binder to form larger particles called granules or agglomerates (used interchangeably in this work). The granular flow in rotating drum is characterized by a solid-like bulk region which undergoes rigid body rotation and a small fluid-like flowing layer near the free surface with sufficient shear during the flow [2]. In order to understand the growth of a wet agglomerate in the free surface flowing layer of a rotating drum, we consider a simpler system with much smaller number of particles, namely an inclined periodic chute as shown in Figure 1. This simple system retains the key aspects of gravity driven flow of grains with sufficient shearing and permits much faster simulations due to reduced number of particles.

Very few studies [3–5] have investigated the behavior of a single wet agglomerate under shear. Hassanpour et al. [3] studied the effect of agglomerate size on its deformation and breakage behavior under shear using DEM simulations with JKR approach to model cohesion. They found that larger agglomerates were able to resist deformation better due to higher hydrostatic stresses relative to the deviatoric stresses experienced by the agglomerate. They also studied the combined effect of the surface energy and the agglomerate size on deformation and breakage of agglomerate under shear and found that below a critical surface energy even the larger agglomerates undergo breakage [4]. Vo et al. [5] studied the elongation, breakage and erosion of a wet agglomerate inside a shear flow and found that all the three effects increase with increasing inertial number of the flow and decreasing cohesion.

The studies of a wet agglomerate in a shear flow have focused primarily on the breakage and deformation behavior and have studied the effect only a few parameters. In the present work, we study the growth of a single wet agglomerate placed in a granular bed in an inclined periodic chute using DEM simulations. We vary the initial granule size, the liquid content, the surface tension and the viscosity of the liquid binder to study the effect of the various process parameters and material properties relevant for drum granulation [1].

2 Simulation methodology

In this work, the motion of particles in a periodic chute is modeled using the discrete element method (DEM) [6]. DEM is a Lagrangian approach in which the positions of a collection of discrete particles are evolved in time using Newton's laws of motion [6]. The acceleration of the particles is due to the combined effect of gravitational force as well as particle-particle, particle-wall, and fluid-

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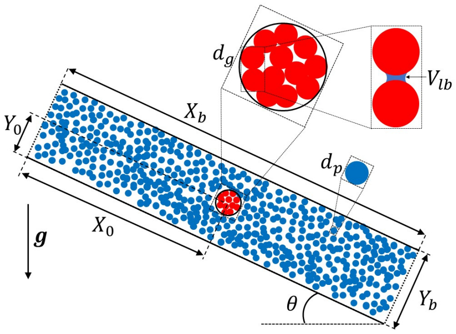

Figure 1. 2D schematic of a three-dimensional periodic chute inclined at an angle θ showing a single wet agglomerate placed in it. Red and blue circles represent wet and dry particles respectively. The schematic is not to scale.

Table 1. Particle properties, binder properties, and operating conditions.

Property	Value
Particle diameter d_p	0.5 mm
Particle density ρ	2900 kg/m^3
Young's modulus	5.7 MPa
Poisson ratio	0.3
Restitution coefficient	0.2
Sliding friction coefficient	0.5
Surface tension γ_{lv}	$[10-73]$ mN/m
Binder viscosity η	$[1-100]$ mPa s
Liquid content V_l/V_p	$[0.1\% - 30\%]$
Bed dimensions X_b, Y_b, Z_b	(120x10x60) d_p
Inclination angle θ	30^o
Initial granule diameter d_{g0}	$[3-5]\, d_p$
Initial granule position X_0, Y_0, Z_0	$0.5 \times (X_b, Y_b, Z_b)$

particle interactions in DEM. Forces are calculated at every timestep and the equations of motion are integrated to obtain the velocities and positions of all the particles in the system. The particle-particle contact force is resolved using force-displacement models which depend on the normal and tangential overlaps between particles. The non-linear viscoelastic contact model Hertz-Mindlin [6] is used to model the particle-particle and particle-wall contact force. The liquid mediated particle-particle interaction is typically modeled using a binary pendular liquid bridge force between particles [7]. The literature on wet granular material shows that the transition from binary pendular liquid bridge regime to funicular regime occurs between liquid content $V_l/V_p \sim 3$ to 23% [8]. However, Herminghaus et al. [8] have shown that wet granular material at higher liquid contents in the funicular regime can be modeled using binary pendular liquid bridge force due to the filigree morphology of liquid clusters. The liquid bridge force is the summation of the viscous force and the capillary force due to the presence of liquid bridge between particles. In the present work, the viscous force was modeled according to Nase et al. [9] and the capillary force according to Rabinovich et al. [7]. The properties of the particles, binder liquid and operating conditions used in the present work are given in Table 1. For each simulation, dry particles were first inserted in a simulation box and allowed to settle under the gravitational force. Then simultaneously the orientation of the gravitational force was changed according to the inclination angle θ and particles within a predefined spherical region were made wet with liquid content V_l/V_p.

3 Granule size measurement

While the identification of granule and measurement of its size is an important topic of ongoing research, in this work a simple definition of a granule was used broadly in line with the granulation literature [10]. Specifically, a granule is a network of particles connected via binary liquid bridges such that there exists a path via binary liquid bridges connecting every particle-pair in the network. This common definition used in the literature is modified slightly to exclude particles with insufficient liquid content from the analysis on the basis of a Bond number criterion. The algorithm for identifying the granule is as follows:

1. For every particle, compute the Bond number associated with it. The Bond number as defined here represents a particle's ability to capture and retain a new dry particle using the capillary force of liquid bridge relative to the weight of the new particle:

   $$Bo = \frac{6\gamma_{lv}(V_{lb}/V_p)^{1/3}}{\rho g d_p^2} \tag{1}$$

   Here, V_{lb} is liquid bridge volume, and V_p is the particle volume. The factor $(V_{lb}/V_p)^{1/3}$ accounts for the fact that a particle with larger liquid content will form a liquid bridge with larger volume and hence larger capillary force.
2. If the Bond number of the particle is lower than a threshold critical Bond number Bo_c, then the particle is neglected from further analysis of granule size. The threshold used in the present work is determined empirically as $Bo_c = 2$.
3. Construct a network using the particles with $Bo \geq Bo_c$ as the nodes and the capillary force between the particles as the edges between the nodes.
4. Compute the connected components in the network using a breadth-first search algorithm [11].
5. The connected component with the largest number of original wet particles (inserted at $t = 0s$) is identified as the granule.

4 Results and discussion

We report DEM simulation results showing the effect of material properties like the liquid content of the initial granule $(0.1-30\%)$, the surface tension $(10-73$ mN/m$)$ and viscosity $(1-100$ mPa s$)$ and effect of a process parameter, the initial granule size $(3-5d_p)$. For each case, three different simulations were performed by varying the initial granule position by $\pm d_{g0}$ and the standard deviation was plotted as confidence bounds around the markers.

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Figure 2(a) shows the effect of the initial liquid content of the granule on its subsequent growth. Granules with very low liquid contents (0.1%, 0.3%) were not able to sustain the stresses imposed by the surrounding dry granular flow since the liquid bridge force decreases with decreasing liquid bridge volume [7]. On the other hand, granules with high liquid content (5%, 10%, 30%) undergo growth from $\sim 6d_p$ to $\sim 7-8d_p$. Interestingly, increasing liquid content of the granule beyond 5% did not lead to increased growth suggesting a saturation of the strength provided by liquid content to the wet granular material (Figure 2(b)). A similar effect was also found experimentally by Herminghaus et al. [8]. Granules with intermediate liquid contents (0.5%, 1%) undergo some growth at early times ($t \sim 2s$) but they are unable to sustain the stresses for longer times and reduce in size subsequently.

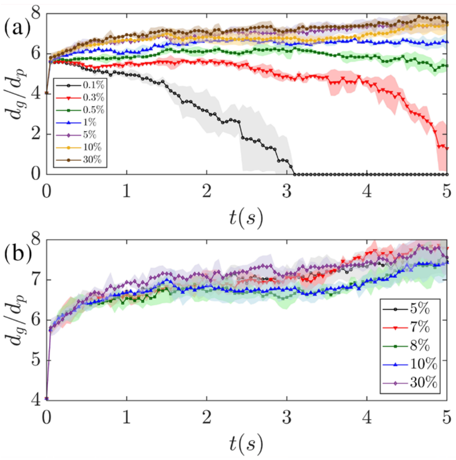

Figure 2. Effect of liquid content V_l/V_p on granule size evolution. Here $d_{g0} = 4d_p$, $\gamma_{lv} = 73$ mN/m, $\eta = 1$ mPa s, $\theta = 30^o$. (a) $V_l/V_p \in \{0.1, 0.2, 0.3, 0.5, 0.7, 1, 5, 10, 30\}\%$ and (b) $V_l/V_p \in \{5, 7, 8, 10, 30\}\%$.

Three different granules having a total of 16, 38 and 75 wet particles are used in this study. Using the definition of an equivalent spherical diameter for determining the size of the granule d_g having N particles of size d_p packed with a solid fraction ϕ, the granule size is calculated as $(N/\phi)^{1/3}d_p$. Assuming $\phi \approx 0.6$, the initial size of the granule turns out to be $3d_p$, $4d_p$ and $5d_p$. The total liquid content of the granule is kept constant while varying the granule size. Thus, the $3d_p$ size granule has 23.7% liquid content on each of its constituent particles, the $4d_p$ size granule's constituent particles have 10% liquid content each, and the $5d_p$ size granule's constituent particles have 5.1% liquid content on each of them. Figure 3 shows the effect of initial granule size on its subsequent growth. The $3d_p$ granule grows to $\sim 6d_p$, the $4d_p$ granules grows to $\sim 7.5d_p$, and the $5d_p$ granule grows to $\sim 9d_p$. Therefore, not only did the larger granules grow to a larger size after $5s$, they also grew at a faster rate. Importantly, the larger granules did not experience a reduction in their growth despite having lower liquid content per particle. This observation further suggests the saturation effect with increasing liquid content as observed in Figure 2.

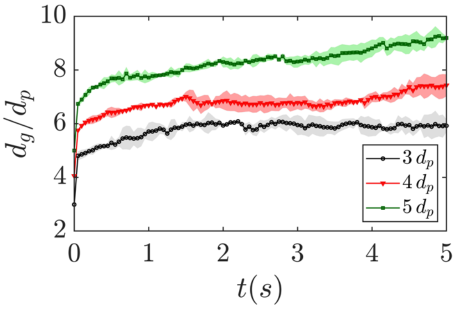

Figure 3. Effect of initial granule size d_{g0} on its subsequent evolution. Here $\gamma_{lv} = 73$ mN/m, $\eta = 1$ mPa s, $\theta = 30^o$.

Figure 4 shows the effect of surface tension of the liquid binder on the granule growth. We observe that the granule with very low surface tension binder (10 mN/m) is not able to sustain and gets dispersed into its constituent particles. Similarly, the granule with 15 mN/m surface tension binder experienced consistent erosion of particles and no net growth, albeit it did not completely vanish. Granules with intermediate surface tension binder (20, 40 mN/m) exhibited some growth at early times. As the flow evolves, the shear rate in the bed increases and the granules are unable to sustain the initial growth at later times. The higher average shear rate in the bed leads to attrition of particles from the granule. In contrast, the granule with higher surface tension (73 mN/m) is able to sustain its growth even at long times. Experimental studies on drum granulation [1] typically study the effect of binder viscosity on the granule size distribution since the binder viscosity can vary a few orders of magnitude with binder concentration while the surface tension does not vary even one order of magnitude. However, the present results indicate that the surface tension can have a very strong effect on the granule growth rate despite a relatively small variation.

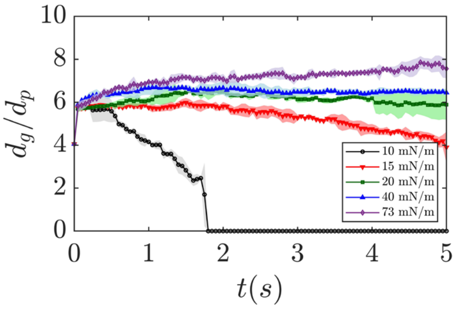

Figure 4. Effect of surface tension γ_{lv} on granule size evolution. Here $d_{g0} = 4d_p$, $\eta = 1$ mPa s, $\theta = 30^o$, $V_l/V_p = 30\%$.

Figure 5 shows the effect of binder viscosity on granule growth. The granule with binder viscosity of water (1 mPa s) experiences rapid growth till $\sim 1s$ followed by a period of slow growth till $5s$. The granule with intermediate viscosity binder (10 mPa s) experiences rapid growth rates similar to the low viscosity binder granule (1 mPa s) till $\sim 1s$ followed by a period of slow growth till $\sim 3.5s$.

Subsequently, the intermediate viscosity granule (10 mPa s) shows a significant increase in growth rate attaining size $\sim 9d_p$. In contrast, the high binder viscosity granule (100 mPa s) experiences a period of slow growth till $\sim 1s$ followed by a short period of rapid growth till $\sim 1.5s$ followed by a period of no/slow growth till $5s$. All the granules exhibit a distinct growth behavior with a period of no/slow growth followed after a period of rapid growth and this effect is more pronounced for granules with higher binder viscosity (10 and 100 mPa s). This distinct growth behavior observed in simulations is similar to the sequential consolidation-growth pattern observed in experiments [1] in which the liquid binder is transferred from the wet core particles to the dry shell particles due to consolidation during the slow growth period followed by period of rapid accumulation of surrounding dry particles over the wet shell particles.

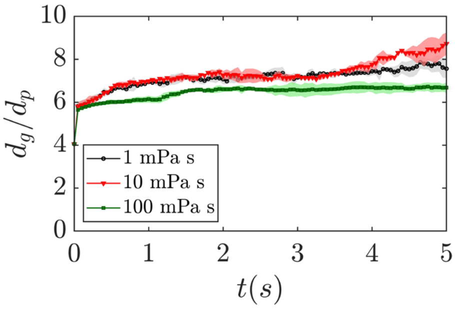

Figure 5. Effect of liquid viscosity η on granule size evolution. Here $d_{g0} = 4d_p$, $\gamma_{lv} = 73$ mN/m, $\theta = 30^o$, $V_l/V_p = 30\%$.

The distribution of the high viscosity liquid to the dry particles of the bed also affects the flow behavior of the bed near the granule which in turn affects the growth of the granule. A better understanding of these issues requires more detailed investigations that will be carried out in the future.

5 Conclusion

We study the growth of a wet agglomerate placed in a dry granular bed flowing in an inclined periodic chute using DEM. We find that the granule growth rate increases with the liquid content, the initial granule size, and the binder surface tension. Granules below a certain minimum liquid content and surface tension are not able to sustain under the shear imposed by the surrounding dry granular flow. The granule growth rate did not increase substantially beyond a minimum liquid content. Granule growth was substantially affected by changes in the binder surface tension. Increasing the binder viscosity led to a more complex effect with distinct growth behavior showing periods of slow as well as rapid growth suggesting an alternating consolidation growth pattern.

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