

Evolution of the temperature distribution of granular material in a horizontal rotating cylinder

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Abstract. Accurate prediction of the particles' temperature distribution and the time required to heat up the particles is important to maintain good quality products and economical processes for several industrial processes that involve thermal treatment. However, we do not have quantitative models to predict the average temperature or particles' temperature distribution accurately. In this article, we carry out DEM simulations and compute the temporal and spatial evolution of the distribution of the particles' temperature in rotating cylinders. We present typical examples for different particle properties and operating conditions. The temperature distribution follows what is referred to as a uniform distribution with well defined mean and standard deviation values. Our analysis of these statistical parameters can assist in the prediction of the time required to heat up granular materials and the design of efficient processes.

1 Introduction

Several industrial processes involve thermal treatment of granular materials in rotating drums (also referred to as kilns or calciners) [1–5]. The temperature of the particles is raised to a given temperature such that the desired processes take place. For a good product quality and efficient process, it is required to raise the temperature of the particles uniformly with a minimum processing time. However, the temperature of the particles does not increase at the same rate in most cases. The variation of the particles' temperature is caused by 1) heat transfer processes in the radial direction [7, 8] and 2) the dispersion of the particles in the axial direction as the particles flow through the rotating kiln [9]. To achieve economical and high quality production it is essential to understand these two processes in detail.

Several experimental, numerical, and theoretical have been done to study the heat transfer in granular materials in rotating drums [1–8, 10–14]. Based on experiments in rotating calciners and theoretical work based on penetration theory [2, 4, 14], it was shown that the heat transfer coefficient of the bulk granular material can be predicted from the fill level, speed of rotation, and the *bulk* thermal properties of the granular materials and powders. However, there are some difference among the models that were developed in these studies [11]. The heat transfer in granular flows is a complex processes and several factors may have contributed to the variation in these models. One of the factor could be the accuracy in the measurement of

the bulk thermal properties. Quantifying the accurate bulk thermal conductivity and heat capacity is very crucial for developing accurate models. Bulk properties are not inherent only to the particles, but also depend on the interstitial fluid (air) and boundary conditions, which might add to the discrepancy in the models. Yet another factor could be the presence of more than one heat transfer mechanisms at the same time [2, 14, 15]. At low temperatures, the heat transfer is dominated by conduction through contact between particles. In addition, conduction through thin gas layer in the vicinity of the contact area between particles and contact area between particles and wall could have a significant contribution to the heat transfer process [14]. At higher temperatures, greater than 700 C, radiation may dominate the heat transfer process. Most of the models in the literature discussed above are limited to low temperature (less than 200 C) experiments and simulations. In the presence of hot air inflow, usually referred to as direct heating processes, the convective heat transfer should be also incorporated in the model [6]. However, developing a complete model that includes all the heat transfer mechanisms is very challenging.

To improve the existing models, it is essential to relate the properties of individual particles to the bulk properties of the granular material. Recently, Emady et al [8] and Yohannes et al [7] introduced dimensionless time parameters that depend on the particle properties and operating conditions. One of the most important time parameters, τ_p , quantifies the time required to heat up a single particle resting on a horizontal wall. τ_p is a function of the thermal, mechanical, physical properties of the particle.

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These two studies showed that the time required to heat up the bulk granular material can be predicted based on τ_p and the time a particle spends in contact with the wall in rotating drums, τ_c .

In this paper, we use 3D discrete element method (DEM) simulations to study the evolution of temperature of individual particles when heat is transferred by conduction through inter-particle and particle-wall contacts. DEM is suited for this purpose, since the method is essentially based on tracking individual particles, and the particles' interaction among themselves and the boundary. In DEM, all the input material properties, including the thermal properties, are properties of the individual particles and no assumption has to be made about the bulk property. This is one of the great advantages of using DEM simulation instead of other methods, such as the finite element method [6], which require bulk material properties as an input. The results from DEM simulations can be used to predict these bulk properties based on particle properties. Using DEM, we show the evolution of the spatial and temporal distribution of particles' temperature and discuss how the results can be used to predict the average temperature and temperature distribution of the bulk granular materials.

2 Numerical Experiments

We run several DEM simulations in rotating drums with periodic boundary condition along the axial direction. The particles are spherical, cohesionless, and elastic. The particle-particle and particle-wall contact force follows Hertz-Mindlin contact theory [16–19]. In this contact theory, the particles are allowed to deform when they are in contact. Due to the deformation of the particles, a contact area is formed through which heat conduction can occur. The contact area is assumed to be circular with a radius of a . In the simulations, the deformation of the particles is represented by the overlap (δ) between a pair of particles (or between a particle and the drum wall). a is computed as $\sqrt{2R\delta}$, where R is the effective radius of a pair of contacting particles. Then, the heat flux (Q_{ij}) is computed based on the a as,

$$Q_{ij} = H_c(T_j - T_i) \quad (1)$$

where H_c is the heat conductance, T_i and T_j are the temperatures of particle i and j , respectively. $H_c = 2ka$, where k is the effective thermal conductivity of the particles [20]. Based on the Q_{ij} the rate of change of temperature for any particle is computed as

$$\frac{dT_i}{dt} = \frac{Q_i}{\rho_i C_{pi} V_i} \quad (2)$$

where ρ_i , C_{pi} , and V_i are the density, specific heat capacity, and volume of particle i . Q_i is the summation of all Q_{ij} related to particle i .

The drum wall temperature T_w is kept constant during the entire simulation, while the initial temperature of the particles T_o is set to 298 K. Hence, heat is supplied

Table 1. Material properties

Material property (symbol) [unit]	Value
average particle size (d_p) [mm]	2, 4, 8
particle density (ρ) [kg/m ³]	120 - 15560
shear modulus (G) [Pa]	10 ⁶ -10 ⁸
Poisson's ratio (ν)	0.25
thermal conductivity (k) [W/mK]	0.3 - 3000
specific heat capacity (C_p) [J/kg·K]	880
particle initial temperature (T_o) [K]	298
coefficient of restitution (e)	0.2, 0.9
coefficient of friction (μ)	0.4, 0.9

Table 2. operating conditions

Operating condition (symbol) [unit]	Value
drum diameter (D) [cm]	15-120
rotation speed (ω) [rpm]	0.1 - 60
fill level (F_L) [%]	5-45
drum wall temperature (T_w) [K]	578

to the particles only through direct heating from the drum wall, and we did not include any other heat sources such as heat generated due to frictional energy dissipation. The simulations are run until the average temperature of the particles \bar{T} approaches T_w . The thermal, mechanical, and physical properties of the particles were varied in order to understand the effect of each property on the heat transfer process. In addition, the operating condition such as the diameter of the drum, the speed of rotation, and the fill level were also varied. The list of material properties and operating conditions is shown in Tables 1 and 2, respectively. We did not find any noticeable change in the heat transfer process when we changed the coefficients of friction and restitution.

3 Results

Initially, the temperature of the particles that are in contact with the wall increases, and the heat is transferred to the bulk granular materials through inter-particle contacts. This type of heat transfer can be considered as pure heat conduction. In addition, heat is transferred when the heated particles, which were in contact with the wall, are pushed to the surface of the flowing layer of the granular materials. This type of heat transfer can be considered as heat transfer through granular convection [21]. Fig. 1 shows the temperature of the particles at different time steps for one simulation. As can be seen from the figure, the particles in contact with the wall and particles at the surface of the granular materials have higher temperature than the particles in the core of the bulk material. Eventually, the core particles are also heated and the temperature of the particles becomes uniform. The rate of heating and the pattern of the spatial distribution of the particles' temperature depends on the operating condition and the particles properties [7, 8].

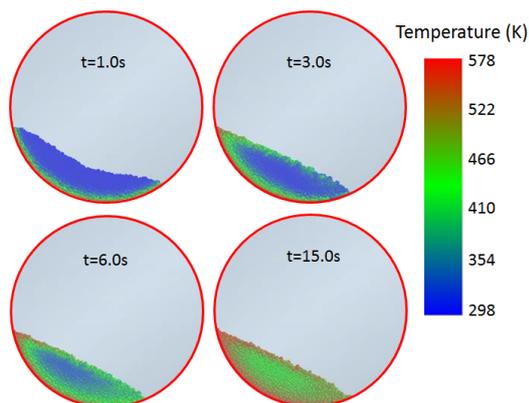


Figure 1. Snapshots from one simulation at different time steps to show the evolution of the particles' temperature. The color bar represents the temperature of the particles. $k = 3000\text{W/mk}$, $\omega = 3\text{rpm}$, $F_L = 15\%$, and $d_p = 2\text{mm}$.

During the process, the temperature of a particle does not increase monotonically during a simulation. Fig. 2 shows the fluctuation of the temperature of one particle with respect to \bar{T} . The fluctuations are larger during the early stages of the simulation, when the difference between T_w and \bar{T} is large. The deviations decays continuously as the heating process is continued. Fig. 2 also shows the radial position (radial distance from the center of the drum) of the particle. It can be noted that the temperature of the particle rises significantly when the particle is in contact with the drum wall (when radial distance of the center of the particles is equal to $\frac{D}{2} - \frac{d_p}{2}$). Most of the time, the rise the particle's temperature is followed by a sharp decrease in temperature, which corresponds to the particle being trapped in the bulk or pushed to the surface. If the particle is brought to the surface, the particle tends to circulate back the bottom layer (in contact with the wall) which causes a significant increases of particle's temperature again. On the other hand, if the particle is trapped inside the core, the temperature of the particle increases with \bar{T} of the system ($T - \bar{T} \approx 0$).

Fig. 3 shows a typical plot for the evolution of particles' temperature during the simulation and the volume averaged temperature for the bulk granular material. All particles do not have the same temperature at a given time and they do not follow the same path towards the final temperature. However, the average temperature increases monotonically throughout the simulation. The lower bound of the particles' temperature is also more uniform than the upper bound of the particles' temperature, where deviation from the mean is very large. This indicates that largest changes in the particle's temperature occur when the particles are in contact with the heated wall. When the particles are away from the wall, their temperature drops to the average temperature of the bulk.

Fig. 4 shows the probability distribution function $f(T)$ for the particles' temperature at different time steps. At

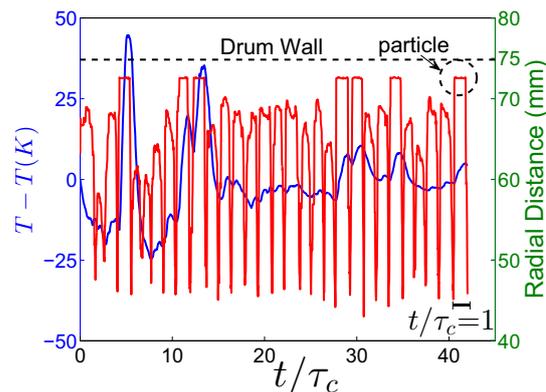


Figure 2. Temperature fluctuation ($T - \bar{T}$) of a particle (on the left, blue) and radial distance of the particle from the center of the drum (on the right, red) vs t/τ_c . The drum has a diameter $D = 15\text{ cm}$ (The horizontal dashed line indicates the radius of the drum (75mm)). The radial distance is constant when the particle is in contact with the wall. The contact duration equals to τ_c .

$t=0\text{s}$, all particles have the same temperature $T_o = 298\text{K}$ and $f(T)$ is a delta function. For most of the simulation duration $f(T)$ resembles a uniform distribution (also known as rectangular distribution). However, the width of the $f(T)$ changes during the heating process, and finally reaching a delta function when the temperature of all particles reach $T_w = 578\text{ K}$. Statistically, the width of a uniform distribution is given by minimum temperature T_{min} and the maximum temperature T_{max} . The lower bound of T_{min} is T_o and the upper bound of T_{max} is T_w . However, for the simulation data where $f(T)$ is not perfectly a uniform distribution and where T_{min} and T_{max} are not clearly defined, the average temperature \bar{T} and the standard deviation σ_T of the temperature are the more robust parameters to characterize the temperature distribution. Recently, Yohannes et al [7] showed that \bar{T} and σ_T can be predicted based on ϕ (where $\phi = \frac{\tau_p}{\tau_c}$).

4 Discussion

Accurately predicting the temperature distribution, which includes accurate prediction of \bar{T} and σ_T , is crucial for improving the quality of the final product after processes that involve thermal treatment of particles. Ideally, it is desirable to heat up the particles uniformly, at the same rate. However, it is not always possible to attain the same temperature for all of the particles as shown in Figs. 1, 3, and 4. Yohannes et al [7] have shown that for certain conditions, when the value of ϕ is sufficiently large, σ_T is very low. In general, high ϕ values correspond to slow heating rate. In terms of particle properties, high ϕ values correspond low thermal conductivity, high specific heat capacity, high stiffness, and high density of particles. In terms of operating conditions, high ϕ corresponds to low fill level and high speed of rotation. To improve the uniformity of the final product for a given material, particularly a material with high thermal conductivity and low density, decreasing the fill level or increasing the speed of rotation can be used as a solution.

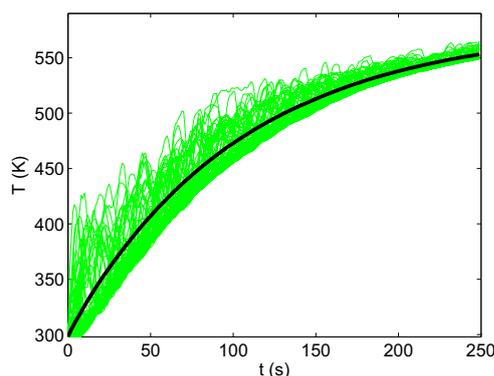


Figure 3. The evolution of individual particle temperature: individual particles temperature (green) and \bar{T} (black). $D=15\text{cm}$, $k=30\text{W/mk}$, $\omega = 3\text{rpm}$, $F_L = 15\%$, and $d_p=4\text{mm}$.

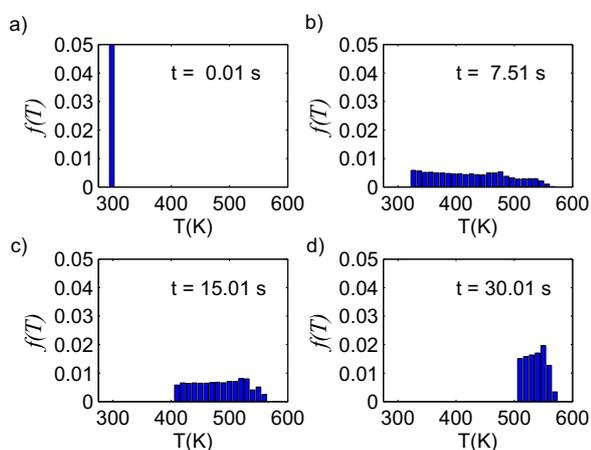


Figure 4. Probability distribution function $f(T)$ of individual particles' temperature at a) $t=0.01\text{s}$, b) $t=7.5\text{s}$, c) $t=15.0\text{s}$, and d) $t=30.0\text{s}$. $D=60\text{cm}$. $k=3000\text{W/mk}$, $\omega=9\text{rpm}$, $F_L=15\%$, and $d_p=4\text{mm}$.

Other mechanisms can also be used to improve the uniformity of the temperature of the particles. One such mechanism is addition of baffles (sometimes referred to as lifters or flights) to the calciners [22, 23]. In these studies, it was shown that the uniformity of the particles' temperature is improved by the addition of baffles, and the uniformity improves significantly when the number of baffles is increased. The baffles enhance the mixing process in the rotating drum and, therefore, reduce the number of particles that remain in the cooler core of the bulk granular materials. Combining the predictive models developed by Yohannes et al [7] and effect of other mechanism, such as baffles and dams, the uniformity of temperature distribution can be improved significantly. Most of the studies, including the current one, that attempted to quantify the temperature distribution are limited to conductive heat transfer through contacts between particles. It is also very important to develop such models for radiative and convective heat transfer for granular materials in rotating drums, as these two heat transfer mechanisms are also very common in many processes.

Acknowledgements

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