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# A DEM-based approach for analyzing energy transitions in granular and particle-fluid flows

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## HIGHLIGHTS

- A DEM-based model for the analysis of energy transition is proposed.
- The approach is tested in granular and particle-fluid systems respectively.
- The connection between energy transitions and structure formation is discussed.
- The relation between the energy transition and the contact between particles is illustrated.

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## ABSTRACT

Granular and particle-fluid flows are widely observed in nature and in industry. Their behaviors are determined by the injection of energy and the subsequent cascade of energy. This work presents a DEM-based approach for the analysis of energy transitions in such flows. The approach can consider the energy injection, dissipation and conversion due to driving forces such as particle-fluid interactions and the gravitational force, particle-particle/wall collisions and frictions. The effectiveness is demonstrated in two systems respectively and the transient and averaged energy transitions are discussed. The results reveal the connection between the formation of a cluster and the variation of energy in fluidized beds. From the viewpoint of energy transition, the results also illustrate the minimization of energy dissipation, the startup of fluidization and the particle flow distribution. Furthermore, the correlation of the contact between particles and the energy transition is demonstrated. The findings should be useful for the understanding of structure formation in fluidized beds and for industrial applications.



## 1. Introduction

Granular and particle-fluid flows are ubiquitous in nature and in industry. They tend to stop because the interaction between macroscopic particles, different to molecular gases, is inelastic and cannot be driven by normal thermal agitation. To keep particles moving, energy should be injected to count-balance the energy dissipation. Therefore, energy injection by, for example, gravity, vibration or flowing fluids and energy dissipation are crucial in understanding and controlling such flows. Naturally, the cascade of energy largely determines the characteristics of flow behaviors such as the state of granular matter (Jaeger and Nagel, 1992; McNamara and Luding, 1998), flow regimes (Li and Kwauk, 1994; Kuang and Yu, 2011; Hou et al., 2012, 2016), wear (Zhang et al., 2012; Chu et al., 2014; Chen et al., 2015) and attrition (Neil and Bridgwater, 1994; Ning and Ghadiri, 2006; Yao et al., 2006; Hare et al., 2011). However, such information of energy flow is limited particularly at a microscopic particle scale and it is still a challenge to understand the macroscopic behaviors of particulate flows from microscopic interactions.

For the analysis of energy flow, there are largely two groups of approaches available to obtain useful information. One group by experimental approaches has been used to study energy loss by measuring particle motion (see, e.g., Burton et al., 2013; Nordstrom et al., 2014), particle position and the force between particles and walls (see, e.g., Sack et al., 2013). Nonetheless, these measurements need delicate designs and experimental devices. Hence, it is costly to comprehensively carry out such experimental studies of energy dissipation in granular systems, and in many conditions, it is difficulty, if not impossible, to obtain some important information such as force transmission or the variation of force chains (Drescher and De Josselin, 1972; Tordesillas, 2007; Zheng and Yu, 2014) and the evolution of microstructures (Mueth et al.,

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2000; Lasinski et al., 2004; Alam and Luding, 2005; Sun and Sundaresan, 2011; Kondic et al., 2012; Ozel et al., 2013).

The other group by numerical approaches has made significant progress in the past decades and is becoming a cost-effective routine to study complex granular systems. This group covers both continuum and discrete approaches. As a representative multiscale method, the energy-minimization multi-scale (EMMS) model is a typical example which has been unified with the two-fluid model (Song et al., 2014). It distributes energy dissipation through the compromising concept and the solution of two stability conditions (Li and Kwauk, 1994). However, the EMMS model has some limitations. For example, the important correlation between flow conditions and the virtual cluster size has not been well formulated in a general way (Wang et al., 2008). There were many efforts dedicated to formulate constitutive relations for the multiscale gas-solid flow (Agrawal et al., 2001, 2013; Sankaranarayanan et al., 2002; Igci et al., 2008; Moreau et al., 2010; Parmentier et al., 2012; Ozel et al., 2013; Masi et al., 2014). Alternatively, starting from particle scale interactions, discrete element method (DEM) or its combined version with computational fluid dynamics (CFD) has been widely used to study particulate and related multiphase flow systems (Zhu et al., 2007, 2008). Among those studies, many efforts were dedicated to elucidating the energy flow characteristics related to the impact of a particle stream onto a pile (Wu et al., 2007), the deformation of dense granular specimen (Hadda et al., 2013), vibrated granular media (McNamara and Luding, 1998), screw feeder (Hou et al., 2014) and pneumatic conveying (Kuang et al., 2012), to name but a few. These studies provide very useful information for understanding particulate flow and the formation of packings and for improving energy efficiency of industrial processes. Somehow, little effort was dedicated to the study of energy flow in the important fluidization systems (Kunii and Levenspiel, 1991), though it is known that energy flow plays a considerable role in the formation of clusters and streamers (Campbell, 1990; Sundaresan, 2000; Agrawal et al., 2001).

In fact, the dynamic behaviors of particles in fluidized beds are governed by the complicated interactions between individual particles, between particles and walls, and between particles and surrounding fluids. Generally, the behaviors of gas fluidization can be classified into four groups A, B, C and D (Geldart, 1973), depending on the properties of relevant fluid and particles. Group B particles are often called coarse particles and could be fluidized when the inlet gas velocity $u_f$ is above the minimum fluidization $u_{mf}$. Thus, two broad flow regimes exist including fixed and fluidized flow regimes, where the fluidized flow regime can be further classified into bubbling (or slugging), turbulent, fast and pneumatic conveying (Bi and Grace, 1995). These flow regimes have been observed from experiments or numerical simulations. However, how the energy is dissipated in different flow regimes is not well understood. Hence, it is important to unravel energy transitions in fluidized beds by using particle scale information for insight understanding and optimal design and control of fluidization systems.

This work presents a DEM-based approach suitable for the analysis of energy transitions in granular and particle-fluid flows. It can consider the energy injection, dissipation and conversion due to driving forces such as particle-fluid interactions and the gravitational force, particle-particle/wall collisions related to plastic and elastic deformation and sliding/static and rolling frictions. The capability of the approach is demonstrated in two typical systems for coarse particles. First, the transient evolution of energy is discussed in the formation of a packed bed driven by the gravitational force. The energy balance is correctly observed and the spatial and temporal distribution of the variation of energy is illustrated. Second, the transitions of flow regimes and the related energy flow are discussed in a fluidized bed driven by particle-fluid interaction forces. Key flow regimes are successfully reproduced and reasonably classified by both the overall pressure drop and the effective contact force. Based on the classification, the characteristics of energy flow are discussed. The findings should be useful for the understanding of structure formation in fluidized beds and for industrial applications.

## 2. Model description

Here, the settling process is only composed of a discrete solid phase, but the fluidization is composed of a discrete solid phase and a continuum gas phase. The solid phase is described by DEM. Thus a particle has two types of motion: translational and rotational. While moving, the particle may interact with its neighboring particles or walls and with the surrounding fluid, through which the momentum and energy exchange takes place. At any given time $t$, the equations governing the motions of particle $i$ of mass $m_i$ and radius $R_i$ in a particle-fluid flow system can be written as:

$$m_i d\mathbf{v}_i/dt = \sum_j (\mathbf{f}_{e,ij} + \mathbf{f}_{d,ij}) + \mathbf{f}_{pf,i} + m_i\mathbf{g}, \tag{1}$$

and

$$I_i d\boldsymbol{\omega}_i/dt = \sum_j (\mathbf{T}_{t,ij} + \mathbf{T}_{r,ij}), \tag{2}$$

where $\mathbf{v}_i$ and $\boldsymbol{\omega}_i$ are the translational and rotational velocities of particle $i$, and $I_i$ =$(2/5 m_i R_i^2)$ is the moment of the inertia of the particle. The forces involved are: particle-fluid interaction force $\mathbf{f}_{pf,i}$, the gravitational force $\mathrm{m}_i\mathbf{g}$ and the forces between particles (and between particles and walls) which include the elastic force $\mathbf{f}_{e,ij}$, and viscous damping force $\mathbf{f}_{d,ij}$. The torque acting on particle $i$ due to particle $j$ includes two components: $\mathbf{T}_{t,ij}$ which is generated by the tangential force and causes particle $i$ to rotate, and $\mathbf{T}_{r,ij}$ which, commonly known as the rolling friction torque, is generated by asymmetric normal contact force and slows down the relative rotation between contacting particles (Zhou et al., 1999; Zheng et al., 2011). If particle $i$ undergoes multiple interactions, the individual interaction forces and torques are summed up for all particles interacting with particle $i$. The equations to calculate the particle-particle interaction forces and torques, and particle-fluid interaction forces are listed in Table 1. Most of the equations have been well established as, for example, reviewed by Zhu et al. (2007). According to the equations in Table 1, the contact forces are related to

**Table 1**
Equations to calculate the forces and torques on particle $i$.

| Force or torque | Equation |
|---|---|
| Normal elastic force, $\mathbf{f}_{en,ij}$ | $-\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}$ |
| Normal damping force, $\mathbf{f}_{dn,ij}$ | $-c_n\left(6m_{ij}E^*\sqrt{R^*\delta_n}\right)^{1/2}\mathbf{v}_{n,ij}$ |
| Tangential elastic force, $\mathbf{f}_{et,ij}$ | $-\mu_s\lvert\mathbf{f}_{en,ij}\rvert(1-(1-\delta_t/\delta_{t,\max})^{3/2})\hat{\boldsymbol{\delta}}_t$ |
| Tangential damping force, $\mathbf{f}_{dt,ij}$ | $-c_t\left(6\mu_s m_{ij}\lvert\mathbf{f}_{en,ij}\rvert\sqrt{1-\delta_t/\delta_{t,\max}}/\delta_{t,\max}\right)^{1/2}\mathbf{v}_{t,ij}$ |
| Coulomb friction force, $\mathbf{f}_{t,ij}$ | $-\mu_s\lvert\mathbf{f}_{en,ij}\rvert\hat{\boldsymbol{\delta}}_t$ |
| Torque by tangential forces, $\mathbf{T}_{t,ij}$ | $\mathbf{R}_{ij}\times(\mathbf{f}_{et,ij}+\mathbf{f}_{dt,ij})$ |
| Rolling friction torque, $\mathbf{T}_{r,ij}$ | $\mu_{r,ij}\lvert\mathbf{f}_{en,ij}\rvert\hat{\boldsymbol{\omega}}_{ij}^n$ |
| Particle-fluid drag force, $\mathbf{f}_{d,i}$ | $0.125C_{d0,i}\rho_f\pi d_{pi}^2\varepsilon_i^2\lvert\mathbf{u}_i-\mathbf{v}_i\rvert(\mathbf{u}_i-\mathbf{v}_i)\varepsilon_i^{-x}$ |
| Pressure gradient force, $\mathbf{f}_{pg,i}$ | $-V_i\nabla p_i$ |

Where $1/m_{ij}=1/m_i+1/m_j$, $1/R^*=1/\mathrm{R}_i+1/\mathrm{R}_j$, $E^*=E/[2(1-v^2)]$, $\hat{\boldsymbol{\omega}}_{ij}^n=\boldsymbol{\omega}_{ij}^n/\lvert\boldsymbol{\omega}_{ij}^n\rvert$, $\delta_t=\lvert\boldsymbol{\delta}_t\rvert$, $\hat{\boldsymbol{\delta}}_t=\boldsymbol{\delta}_t/\lvert\boldsymbol{\delta}_t\rvert$, $\mathbf{R}_{ij}=R_i(\mathbf{r}_j-\mathbf{r}_i)/(R_i+R_j)$, $\delta_{t,\max}=\mu_s\delta_n(2-v)/(2(1-v))$, $\mathbf{v}_{ij}=\mathbf{v}_j-\mathbf{v}_i+\boldsymbol{\omega}_j\times\mathbf{R}_j-\boldsymbol{\omega}_i\times\mathbf{R}_i$, $\mathbf{v}_{n,ij}=(\mathbf{v}_{ij}\cdot\mathbf{n})\cdot\mathbf{n}$, $\mathbf{v}_{t,ij}=(\mathbf{v}_{ij}\times\mathbf{n})\times\mathbf{n}$, $\varepsilon_i=1-\sum_{i=1}^{k_v}V_i/\Delta V$, $x=3.7-0.65\exp[-(1.5-\log_{10}\mathrm{Re}_i)^2/2]$, $C_{d0,i}=(0.63+4.8/\mathrm{Re}_i^{0.5})^2$, $\mathrm{Re}_i=\rho_f d_{pi}\varepsilon_i\lvert\mathbf{u}_i-\mathbf{v}_i\rvert/\mu_f$.
Note that tangential forces ($\mathbf{f}_{et,ij}$ + $\mathbf{f}_{dt,ij}$) should be replaced by $\mathbf{f}_{t,\,ij}$ when $\delta_t \geqslant \delta_{t,\max}$.