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Unification of EMMS and TFM: structure-dependent analysis of mass, momentum and energy conservation

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HIGHLIGHTS

- A structure-dependent energy analysis of the gas–solid fluidization is presented.
- The structure-dependent analysis unifies the TFM and EMMS.
- The scale-dependency of the EMMS stability condition deserves further efforts.

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ABSTRACT

The two-fluid model (TFM) has been widely applied in simulation of various multiphase flow systems. In particular, for fine-particle circulating fluidization, the drag force plays a critical role whereas the classic drag models based on empirical correlations of homogeneous fluidization are found inadequate. Therefore, various approaches have been proposed in recent years to account for the effects of meso-scale structure on the drag force, in which the energy-minimization multi-scale model (EMMS) has received rapidly growing applications.

However, the relationship between the TFM and EMMS has not been clarified to enable their combination. To solve this problem, we present a structure-dependent analysis of mass, momentum and energy conservation equations. This analysis is rooted in the structure-dependent multi-fluid model (SFM), which details the composition of drag forces and energy consumptions and their relationships with consideration of meso-structures. With assumption of homogeneous structures, it reduces to the TFM equations; for steady-state systems with structures, it restores the force balance equations, equal pressure drop relation and energy relationship of the EMMS. In future, the scale dependence of this analysis deserves more efforts to understand the applicability of the EMMS stability condition on different scales.

1. Introduction

The meso-scale structures play an important role in characterizing gas–solid fluidized system (Agrawal et al., 2001; Li and Kwauk, 1994). In continuous change with respect to time and space, they may manifest the dilute and dense phases, alternately, which can be described by certain bi-modal distribution in terms of bubble-emulsion or broth-cluster flow patterns depending on the operating conditions and material properties (Cui et al., 2000; Hartge et al., 1988; Li and Kwauk, 1994, 2001; Li et al., 1998; Lin et al., 2001; Ren et al., 2001). The meso-scale structures have significant effect on the flow, heat and mass transfer and reaction rate of the fluidized systems, whereas a classical continuum method, such as the two-fluid model (TFM), does not include explicitly the parameters for meso-scale structures (Gidaspow, 1994). Therefore, more and more efforts in recent years have been devoted to the research on how to include the effects of these unresolved, meso-scale structures in computational fluid dynamics (CFD) simulations. (Agrawal et al., 2001; Dong et al., 2008; Igci et al., 2008; Li and Kwauk, 1994; O'brien and Syamlal, 1993; Wang and Li, 2007; Yang et al., 2003; Zhang and VanderHeyden, 2002). Generally, these efforts can be classified into two directions, reflecting the controversial viewpoints: *Whether there are sub-grid structures that cannot be resolved by the TFM even with high grid resolution*? (Agrawal et al., 2001; Lu et al., 2009; Syamlal and Pannala, 2011; Wang et al., 2010). High resolution simulations of gas-particle flows via two-fluid models are found to be able to yield fine structures at length scales as small as 10 particle diameters (Agrawal et al., 2001), but some argued that these fine structures are not real features of gas-particle flows and the TFM is hence an inadequate manifestation of the continuum

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description of the gas-particle flow (Lu et al., 2009; Sundaresan, 2011). Thus, if the answer to the above question is negative, considering the formidable cost of such high resolution simulation, one could, in principle, extract constitutive models for two-fluid models through highly resolved simulations of kinetic theory based model equations in periodic domains (Andrews et al., 2005; Igci et al., 2008; Parmentier et al., 2012; Schneiderbauer and Pirker, 2013). If the answer is positive, however, one should appeal to fully resolved simulation methods, such as direct numerical simulations (DNS) (Dijkhuizen et al., 2010; Xiong et al., 2012), which are expected to be the final and best solutions but are restricted by their high demand in computational resources. Thus they are applied only in small-scale practice over periodic domains to extract structure-dependent closures for higher level simulations. Alternatively, one could explore new models with consideration of meso-scale structures. The energy-minimization multi-scale model (EMMS) and its follow-ups provide exactly the latter efforts in looking for alternative models for continuum description with meso-scale structures (Li and Kwauk, 1994; Wang and Li, 2007; Yang et al., 2003; Hong et al., 2012).

Bear in mind the bi-modal distribution in gas–solid fluidization, we know that the flow behaviors of the gas (solid) in the dilute and dense phases are quite different, and then their conservation equations should be set up differently. From the EMMS principle (Li and Kwauk, 1994; Li and Huang, 2014), the steady state of gas–solid flow is determined by the alternate appearance between the dense state dominated by $\varepsilon=\min$ and the dilute state dominated by $W_{st}=\min$. If averaged, this mechanism will be distorted and blurred out. Based on this idea, Hong et al. (2012) proposed the structure-dependent multi-fluid model (SFM), in which four sets of conservation equations were derived for gas and solid in both the dilute and dense phases, respectively. As shown by Hong et al. (2012), when particles can be well described by an average value, or, the local equilibrium is satisfied, the SFM equations reduce to the TFM; if the dilute-dense two-phase structures are set for steady state, the SFM reverts to the mass and force balance equations of the EMMS (Li and Kwauk, 1994). Thus, both the TFM and the hydrodynamic part of the EMMS can be viewed as a specific case of the more generalized SFM, or, the SFM unifies the TFM with the EMMS in terms of the mass and momentum conservation equations.

Furthermore, the EMMS distinguishes itself from the other hydrodynamic models with its stability condition, which is presumed according to the principle of compromise in competition (Li and Kwauk, 1994; Li and Huang, 2014), in terms of the minimization of energy consumption for suspending and transporting particles for a fluidized bed. Thus, to better understand the EMMS and its relationship with the TFM and SFM, it is necessary to analyze the energy consumption and dissipation with respect to the dilute-dense bi-modal structure. As the structure-dependent analysis of the mass and momentum equations has been detailed in our previous work (Hong et al., 2012; 2013), in this article, we will mainly focus on the structure-dependent energy analysis, aiming to show the composition of energy consumptions and compare it with the stability condition of the EMMS.

The following energy analysis is rooted in the SFM conservation equations. First, we analyze the composition of energy consumption and energy relationships in gas–solid fluidized beds using the SFM. Then, the results under steady state are compared with the EMMS, highlighting the physical meaning of the energy terms defined in the EMMS. Finally, the scale-dependency of the stability condition of the EMMS is discussed.

2. Energy analysis with SFM

2.1. Energy conservation of the gas phase

In Hong et al. (2012), the gas–solid flow in any control volume is divided into four parts: dilute-phase gas, dilute-phase solid, dense-phase gas and dense-phase solid, among which there are mass and momentum exchanges. First, we use the SFM to analyze the composition of energy consumption and energy relationships of the gas phase, whose conservation equations can be written as follows using model A(Gidaspow, 1994):

Continuity equation for the dense-phase gas:

$$\frac{\partial}{\partial t}(f\varepsilon_c\rho_g)+\nabla\cdot(f\varepsilon_c\rho_g\mathbf{u}_c)=\Gamma_g. \tag{1}$$

Momentum equation for the dense-phase gas:

$$\frac{\partial}{\partial t}(f\varepsilon_c\rho_g\mathbf{u}_c)+\nabla\cdot(f\varepsilon_c\rho_g\mathbf{u}_c\mathbf{u}_c)=-f\varepsilon_c\nabla p+\nabla\cdot(f\boldsymbol{\tau}_c)+f\varepsilon_c\rho_g\mathbf{g}-f\mathbf{F}_c+\Gamma_g\mathbf{u}_g^i. \tag{2}$$

Continuity equation for the dilute-phase gas:

$$\frac{\partial}{\partial t}[(1-f)\varepsilon_f\rho_g]+\nabla\cdot[(1-f)\varepsilon_f\rho_g\mathbf{u}_f]=-\Gamma_g. \tag{3}$$

Momentum equation for the dilute-phase gas:

$$\frac{\partial}{\partial t}[(1-f)\varepsilon_f\rho_g\mathbf{u}_f]+\nabla\cdot[(1-f)\varepsilon_f\rho_g\mathbf{u}_f\mathbf{u}_f]=-(1-f)\varepsilon_f\nabla p+\nabla\cdot[(1-f)\boldsymbol{\tau}_f]$$
$$+(1-f)\varepsilon_f\rho_g\mathbf{g}-(1-f)\mathbf{F}_f-\mathbf{F}_i-\Gamma_g\mathbf{u}_g^i. \tag{4}$$

where, ρ_g, f, ε_c, ε_f, $\mathbf{u}_c$ and $\mathbf{u}_f$ stand for the gas density, the volume fraction of the dense phase, the void fraction in the dense phase, the void fraction in the dilute phase, gas velocity in the dense phase and gas velocity in the dilute phase, respectively; $\mathbf{F}_c$, $\mathbf{F}_f$ and $\mathbf{F}_i$ represent the gas–solid drag per unit volume of the corresponding phase; $\mathbf{u}_g^i$ and Γ_g represent the interfacial gas velocity and the rate of mass exchange between the dilute and dense phases per unit volume. The gas pressures in the dense and dilute phases are assumed equal to each other. Detailed definitions and expressions can be found in Hong et al. (2012).

As a definition, the acceleration of phase k reads

$$\mathbf{a}_k\equiv\frac{D\mathbf{u}_k}{Dt}=\frac{\partial\mathbf{u}_k}{\partial t}+\mathbf{u}_k\cdot\nabla\mathbf{u}_k. \tag{5}$$

So combining Eqs. (1), (3) and (5), the left hand side (LHS) of Eqs. (2) and (4) can be rewritten as

$$\frac{\partial}{\partial t}(f\varepsilon_c\rho_g\mathbf{u}_c)+\nabla\cdot(f\varepsilon_c\rho_g\mathbf{u}_c\mathbf{u}_c)=f\varepsilon_c\rho_g\mathbf{a}_c+\Gamma_g\mathbf{u}_c, \tag{6}$$

$$\frac{\partial}{\partial t}[(1-f)\varepsilon_f\rho_g\mathbf{u}_f]+\nabla\cdot[(1-f)\varepsilon_f\rho_g\mathbf{u}_f\mathbf{u}_f]=(1-f)\varepsilon_f\rho_g\mathbf{a}_f-\Gamma_g\mathbf{u}_f. \tag{7}$$

Substituting Eqs. (6) and (7) into Eqs. (2) and (4), we get

$$f\varepsilon_c\rho_g\mathbf{a}_c=-f\varepsilon_c\nabla p+\nabla\cdot(f\boldsymbol{\tau}_c)+f\varepsilon_c\rho_g\mathbf{g}-f\mathbf{F}_c+\Gamma_g(\mathbf{u}_g^i-\mathbf{u}_c) \tag{8}$$

$$(1-f)\varepsilon_f\rho_g\mathbf{a}_f=-(1-f)\varepsilon_f\nabla p+\nabla\cdot[(1-f)\boldsymbol{\tau}_f]+(1-f)\varepsilon_f\rho_g\mathbf{g}$$
$$-(1-f)\mathbf{F}_f-\mathbf{F}_i-\Gamma_g(\mathbf{u}_g^i-\mathbf{u}_f) \tag{9}$$

The energy conservation of the entire gas phase can be obtained as a dot product of the momentum equations and relevant velocities. Then, Eq. (8)$\cdot\mathbf{u}_c$+Eq. (9)$\cdot\mathbf{u}_f$ gives

$$\begin{aligned}&f\varepsilon_c\rho_g\mathbf{u}_c\cdot\mathbf{a}_c+(1-f)\varepsilon_f\rho_g\mathbf{u}_f\cdot\mathbf{a}_f\\&=-[f\varepsilon_c\mathbf{u}_c+(1-f)\varepsilon_f\mathbf{u}_f]\cdot\nabla p\\&\quad+\rho_g[f\varepsilon_c\mathbf{u}_c+(1-f)\varepsilon_f\mathbf{u}_f]\cdot\mathbf{g}\\&\quad+\{\nabla\cdot(f\boldsymbol{\tau}_c)\cdot\mathbf{u}_c+\nabla\cdot[(1-f)\boldsymbol{\tau}_f]\cdot\mathbf{u}_f\}\\&\quad-[f\mathbf{F}_c\cdot\mathbf{u}_c+(1-f)\mathbf{F}_f\cdot\mathbf{u}_f+\mathbf{F}_i\cdot\mathbf{u}_f]\\&\quad+[\Gamma_g(\mathbf{u}_g^i-\mathbf{u}_c)\cdot\mathbf{u}_c-\Gamma_g(\mathbf{u}_g^i-\mathbf{u}_f)\cdot\mathbf{u}_f].\end{aligned} \tag{10}$$

If we define the kinetic energy of the gas phase per unit volume as follows:

$$E_{kg}=\frac{1}{2}f\varepsilon_c\rho_g\mathbf{u}_c\cdot\mathbf{u}_c+\frac{1}{2}(1-f)\varepsilon_f\rho_g\mathbf{u}_f\cdot\mathbf{u}_f. \tag{11}$$