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Structure-dependent analysis of energy dissipation in gas-solid flows: Beyond nonequilibrium thermodynamics

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HIGHLIGHTS

- Structure-dependent analysis of energy dissipation rate is presented for fluidization.
- Minimum energy dissipation rate applies to homogeneous flow state.
- EMMS predicts the choking transition but minimum energy dissipation rate fails.

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ABSTRACT

Gas-solid fluidized bed is a typical dissipative system, featuring meso-scale structures with bimodal distribution of parameters. The energy-minimization multi-scale (EMMS) model focuses on such dissipative characteristics and has shown many successful applications. In previous work, through structure-dependent analysis of mass, momentum and energy conservation, we have discussed the consistency between the hydrodynamic equations of two-fluid model (TFM) and those of the EMMS model. In this work, we extend this structure-dependent analysis to the extremum behavior of dissipation processes, revealing that the solution based on the minimum energy dissipation rate applies only to homogeneous, dilute flow states, but fails in the particle-fluid compromising fluidization regime, in particular, fails to predict choking transition. By comparison, the EMMS variational stability condition that is based on the principle of compromise in competition between dominant mechanisms well describes the flow regimes of fluidization. This work unfolds a fresh viewpoint to understand the EMMS stability condition that is beyond the analysis of extremum of energy dissipation. And it is expected to boost the development of EMMS-based meso-scale modeling in broader realm of multiphase flow systems.

1. Introduction

Gas-solid fluidized beds are normally operated at dissipative states, featuring heterogeneous, meso-scale structures with non-Maxwellian distribution of solid velocity (Li and Kwauk, 1994; Wang and Chen, 2015). It was revealed that such complex behavior can be approximated with a locally dilute-dense, two-phase structure with bimodal velocity and density distributions (Bhusarapu et al., 2006; Chen et al., 2013; Li and Kwauk, 1994; Wang and Chen, 2015; Zhang et al., 2003; Mei et al., 2016; Pandey et al., 2004; Lin et al., 2001; Bai et al., 1999; Cui et al., 2000).

The traditional two-fluid model (TFM), which was prevalent in coarse-grid simulation of fluidized beds (Agrawal et al., 2001; Gidaspow, 1994; Nieuwland et al., 1996), was established on the presumption of local equilibrium with nearly Maxwellian and homogeneous distribution of particles. As a result, it failed to predict certain fluidization characteristics, e.g., S-shaped profile of voidage together with high superficial relative velocity in circulating fluidized bed with Geldart A particles (Geldart, 1973), where these fine particles are alternately aggregated and dispersed, staying far from local equilibrium states (Hong et al., 2016; Jiradilok et al., 2006; Wang and Chen, 2015; Wang et al., 2010; Yang et al., 2003). For coarse particles belonging to Geldart B, the effect of meso-scale structure is not as strong as in the case of fine particles, the clustering phenomenon can hence be captured using the traditional TFM approach (Tsuo and Gidaspow, 1990), though the solid flux is still hard to predict (Lu et al., 2011).

To take into account the effects of meso-scale structures in fluidized beds, some approaches have been proposed (Agrawal et al., 2001; Li and Kwauk, 1994; Parmentier et al., 2012; Schneiderbauer and Pirker, 2014), among which the energy-minimization

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Nomenclature

a_{jk} interfacial area concentration of interface A_{jk}, m^{-1}
A_k surface of phase k
A_{jk} interface between phases j and k
B any scalar, vector or tensor variable
$\bar{B}$ volume averaging of B
$\bar{\bar{B}}$ phase averaging of B
$\hat{B}$ phase density-weighted averaging of B
B' fluctuating component of B
C_d drag coefficient of homogeneous group of particles
e virtual internal energy per unit mass, J kg^{-1}
E interfacial total energy source term, J m^{-3} s^{-1}
E_d energy dissipation or energy dissipation rate, J s^{-1}
f volume fraction of dense phase
$\mathbf{F}_{k,jk}$ interfacial force density of phase k at interface A_{jk}, N m^{-3}
$\mathbf{F}_{jk}$ interfacial force density at interface A_{jk}, N m^{-3}
$\mathbf{g}$ body force field, m s^{-2}
$\mathbf{G}_s$ solid flux, kg m^{-2} s^{-1}
I general interfacial source term
$\mathbf{J}$ flux
$\mathbf{M}$ interfacial momentum source term, kg m^2 s^{-2}
$\boldsymbol{n}_k$ unit normal exterior to phase k
N_{st} power for suspending and transporting particles per unit mass of particles, J kg^{-1} s^{-1}
p pressure, Pa
$\overline{\overline{q_{k,jk}}}$ average heat transfer of phase k at interface A_{jk} per interfacial area, J m^{-2} s^{-1}
$\mathbf{q}$ heat flux, J m^{-2} s^{-1}
s entropy per unit mass, J kg^{-1} K^{-1}
T temperature, K
t time, s
u internal energy per unit mass, J kg^{-1}
$\mathbf{U}_g$ superficial gas velocity, m s^{-1}
$\mathbf{U}_p$ superficial solid velocity, m s^{-1}
$\mathbf{v}_k$ velocity of phase k, m s^{-1}
$\mathbf{v}_{k,jk}$ velocity of phase k adjacent to interface A_{jk}, m s^{-1}
$\mathbf{v}_{jk}$ velocity of interface A_{jk}, m s^{-1}
V_k volume of phase k, m^3
$W'_{k,jk}$ work due to fluctuations in interfacial force density, J m^{-3} s^{-1}

Greek letters
α volume fraction
Λ_k interfacial internal energy source of phase k, J m^{-3} s^{-1}
Δ_k entropy production of phase k per unit volume, J m^{-3} s^{-1} K^{-1}
ρ_g density of gas phase, kg m^{-3}
ρ_p density of solid phase, kg m^{-3}
$\boldsymbol{\tau}$ viscous stress tensor, Pa
$\boldsymbol{\sigma}$ stress tensor, Pa
ψ property of extensive characteristics
φ source term
δ_k phase indicator
ε_g bed-averaged volume fraction of gas phase
ε_s bed-averaged volume fraction of solid phase
ε_{gf} voidage of dilute phase
ε_{gc} voidage of dense phase
ε_{min} lower boundary of voidage
ε_{max} upper boundary of voidage

Subscripts
k phase indicator number, $k = 1, 2, 3, 4$
j phase indicator number, $j = k - 1$
l phase indicator number, $l = k + 1$
jk interface A_{jk}
kl interface A_{kl}
1 dense-phase gas (gc)
2 dense-phase solid (pc)
3 dilute-phase gas (gf)
4 dilute-phase solid (pf)

multi-scale (EMMS) model (Li and Kwauk, 1994) considered the bimodal distribution by decomposing the meso-scale structures into the dilute and dense phases. In the dilute phase, the particles were assumed homogeneously dispersed, whereas in the dense phase, particles were assumed to take the form of clusters. The cluster diameter was assumed inversely proportional to the power for suspending and transporting particles per unit mass of particles, N_{st}, which tends to minimum according to the principle of compromise in competition (Li et al., 2013). To integrate with computational fluid dynamics (CFD), the EMMS model was extended to the sub-grid level by taking into account the inertial effects of gas and particles within computational cells, thereby constructing a structure-dependent EMMS drag (Yang et al., 2003; Lu et al., 2009; Wang and Li, 2007). Later, the EMMS model was further extended from a model for gas-solid fluidized beds to a general method, which has been successfully applied to more multiphase flow systems (Ge et al., 2007, 2011; Li et al., 2013).

Meanwhile, to reveal the relationship between the EMMS model and the TFM, Hong et al. (2012) and Hong et al. (2013) proposed the structure-dependent multi-fluid model (SFM) and proved its steady-state version is consistent with the hydrodynamic balance equations of the EMMS model. Thus, the rapidly growing practice of CFD simulation with EMMS drag is actually based on the SFM conservation equations. Song et al. (2014) further unified the EMMS and TFM through SFM analysis of mass, momentum and energy balance. The SFM facilitates understanding of the structure-dependent nature of conservation laws for fluidization. However, how to analyze the variational feature of N_{st} remains to be a hard issue since the EMMS model is totally different from those used in other seemingly relevant and well-known theories, e.g., nonequilibrium thermodynamics.

Indeed, besides deterministic description on the dynamics, attempts never cease to find certain universal function, whose extremum would determine the development of a system as a whole (Prigogine, 1967; Onsager, 1931; Ziegler, 1983; Martyushev and Seleznev, 2006). For example, Prigogine (1967) proposed that the minimum entropy production is satisfied, when a linear nonequilibrium system is stationary. Gidaspow (1978) derived a relative velocity equation by minimizing the rate of entropy production. And this relative velocity was further used as a constitutive relation for a mixture model (Arastoopour and Gidaspow, 1979). The minimum entropy generation method (Bejan, 1982; Lucia, 2013), which was based on system integral of the entropy production, has received engineering application in heat transfer systems. Paltridge (1978) proposed a steady-state earth climate model, in which entropy production was maximized subject to the sole constraint of global energy balance. It should be noted, however, that both the minimum and maximum entropy production principles were proposed based on local equilibrium assumption. Thus they may not be suitable for analyzing