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Influence of meso-scale structures on drag in gas–solid fluidized beds

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ABSTRACT

Meso-scale structures lead to heterogeneity of gas–solid flows which cannot be properly modeled by homogeneous drag models. Heterogeneous drag models have been developed, but there are still some problems with these heterogeneous drag models. The present work identifies the key reasons why predictions of the QL-EMMS drag model do not match those of the experimentally based O–S model and then aims to improve the QL-EMMS model. Since the meso-scale structures are the key reason for the heterogeneities in the two-phase flows, the influence of the cluster characteristics on the drag force needs to be further understood. The present work investigates the effects of both the cluster size and the cluster density on the drag function by sensitivity analyses. Both influences are analyzed to show that the cluster density has a greater effect on the drag force. Thus, the inaccuracy of the drag model is due to the inaccuracy of the cluster density model with the essential reasons being the basic concepts in EMMS theory. Then the characteristics of cluster density are further investigated to show that the cluster density curve tends to coincide with the homogeneous 45° line in the extreme dilute and dense extremes, and then tends to the heterogeneous state around a local solid volume fraction of $\varepsilon_s = 0.1$. A mathematical model was then developed to complement EMMS theory.

1. Introduction

In fluidized gas–solid two-phase flows, the drag force represents the strength of the gas–solid interactions and the entrainment of particles into the gas, which is an obviously important force for two-phase flows. If the drag force model is not accurate, the two-phase flow simulations will also not be accurate. The classical Wen-Yu [1], Gidaspow [2], and Ergun [3] drag model and so on are all based on the hypothesis of homogeneous fluidization. Studies have shown that adopting these drag models to simulate the fluidized beds result in that the circulating mass flux is far higher than the experimental data, the particles distribute uniformly, and also cannot show the typical heterogeneous characteristics like “annulus-core” and “up dilute and bottom dense”, especially for the fine particle two-phase flow like Geldart [4] type-A particle. These are as a result of that these drag models are for homogeneous flow without consideration of the drag reduction caused by the heterogeneities.

The solid clusters make the two-phase flow heterogeneous, which results in a large slip velocity and then a large drag reduction between the gas and solid particles. Actually, the clusters are a meso-scale phenomenon, with a scale between the scale of a single particle and the reactor scale macro-flow which are totally different. Hence, the clusters are called meso-scale structures.

The existing drag models can be divided into homogeneous and heterogeneous types. The homogeneous drag models have been shown to not properly simulate the fluidization process, while the heterogeneous drag model can better simulate dense gas–solid two-phase flows.

As a multi-scale analysis method, the Energy Minimization Multi-scale theory (EMMS) [5] focuses on the suspension of particles in the flow and the transport of energy from the gas to the particle phase in the fluidization process, while the Euler–Euler approach (Two-Fluid Model) involves only mass and momentum balances that are incomplete because they do not consider the drag reduction in the heterogeneous flow states. The drag model based on EMMS theory can predict a drag reduction considering the heterogeneity. Therefore, the EMMS drag model that determine the drag function, β, can be theoretically regarded as an additional boundary condition coupled with the Euler–Euler approach to determine the drag force term [6]. After the success of the first modification by Xiao et al. [7], a series of heterogeneous drag models based on the EMMS method have been developed and verified in the past decade to describe to some extent the drag reduction caused by meso-scale structures in the flows [7–11], as shown in Fig. 1.

The O–S model [12] is a heterogeneous drag model developed from experiment data which is an important benchmark to evaluate theoretical drag models [13]. Fig. 1 compares the drag function distributions, β, for several typical heterogeneous drag models [8–10] and the O–S model. The various heterogeneous drag models are indicated by the first author's name. The existing heterogeneous drag curves are quite different from the O–S curve both qualitatively and quantitatively. The

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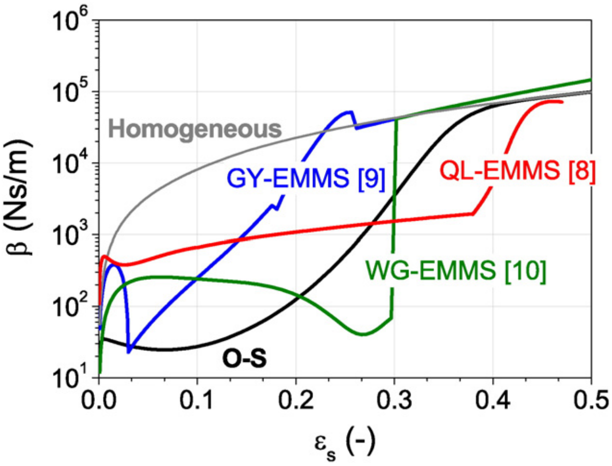

Fig. 1. Comparisons of different EMMS drag models (Parameters: $\rho_g = 1.205$ kg/m^3, $d_p = 100$ μm, $\mu_g = 1.848 \times 10^{-5}$ Pa · s, $\varepsilon_{s,\,mf} = 0.5$, $u_{slip} = 1.0$ m/s).

turning points in the drag function curves cannot be explained physically which indicates the problems in the existing EMMS drag models.

Though the existing heterogeneous drag models can apply well in limited individual cases, they cannot generally applied to other operating conditions. The QL-EMMS [8] drag model is closer to the O–S model than the other models, but still has similar problems. In addition, the QL-EMMS model has little variation at different conditions which is unreasonable, as shown in Fig. 2 where the O–S drag curves are quite different.

The object of the present research is to clarify the essential reasons why the QL-EMMS model disagrees with the O–S model and find a way to improve it. Since the meso-scale structures, the clusters, are the major reason causing the flow heterogeneities and the drag reduction, the effects of the clusters need to be investigated in terms of the cluster size, d_{cl}, and the solid concentration in cluster (short for cluster density), ε_{sc}. The effect of the cluster characteristics on the drag force must be known and then a model must be developed to relate the drag force in heterogeneous flow to the cluster characteristics. Researchers have paid much attention to the effect of cluster size and have thought that the cluster size has a key effect on the drag force. Thus, many researchers have developed many cluster size models to improve the drag model. However, there have been few studies on the effect of cluster density. Thus this study investigates the effects of both the cluster size and the density on the drag function. The effects are compared and to determine which factor has a greater effect on the drag force to develop ways to improve the QL-EMMS drag model.

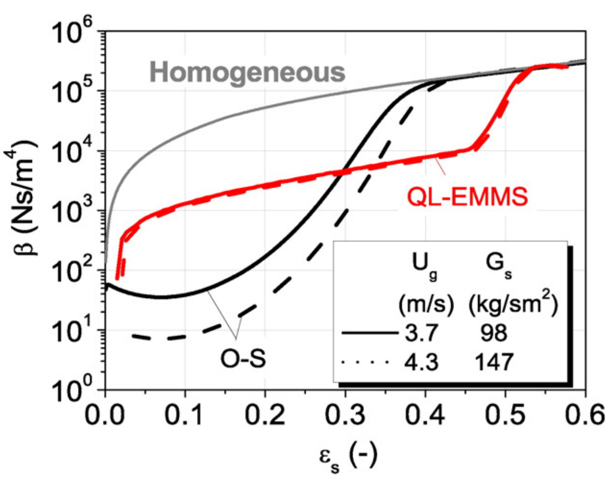

Fig. 2. Comparison of QL-EMMS drag model with the O–S model (Parameters: $\rho_g = 1.144$ kg/m^3, $\mu_g = 1.848 \times 10^{-5}$ Pa · s, $\rho_p = 1714$ kg/m^3, $d_p = 76$ μm, $\varepsilon_{s,\,mf} = 0.6$).

2. QL-EMMS model

According to the multi-scale analysis, a heterogeneous fluidized flow was divided into three phases: the dense phase, dilute phase and interphase in the EMMS theory [5]. Based on the basic EMMS theory, the QL-EMMS model was developed by considering the particle accelerations in dense and dilute phases. The QL-EMMS model [8] includes 10 variables, 7 basic equations and 1 extremal condition, which is a constrained nonlinear programming problem. The 10 variables are: the solid concentration in dense phase (ε_{sc}) and dilute phase (ε_{sf}), the superficial fluid velocity in dense phase (U_{gc}) and dilute phase (U_{gf}), the particle velocity in dense phase (U_{pc}) and dilute phase (U_{pf}), the acceleration of particle in dense phase (a_c) and dilute phase (a_f), the volume fraction of dense phase (f) and the cluster equivalent diameter (d_{cl}).The model equations of the QL-EMMS drag model are summarized in Table 1.

N_{st} represents the mass specific energy consumption for suspending and transporting particles, W/kg, which consists of energy consumption in the three phases. Formulas (1)–(7) are basic or constrained equations, which limit the solution domain. Formula (8) is the stability extremal condition as an objective function which determines the uniqueness of the solution. The stability condition means that the two-phase flow tends to reach a stable state when N_{st} reaches a minimum. The solving process is that first traversal solving the 7 basic equations to obtain a feasible region, then searching the only solution among the feasible domain which satisfies the stability condition.

3. Influence of cluster size, d_{cl}, on drag

In actual fluidized gas–solid flows, the cluster shape varies from hour to hour, including the cluster, streamer/strand, swarms and sheet, as shown in Fig. 3. Thus, the cluster size is not simply the diameter of a spherical cluster and lacks a unified definition (see Fig. 4). The d_{cl} measured in experiments is always the axial size, while in EMMS theory the size is an equivalent size for various cluster patterns. The differences in the cluster size definition result complicate comparisons among clusters with different shapes.

The existing cluster size models include some empirical models based on experiments and the cluster size model based on EMMS theory.

Table 1
Summary of the QL-EMMS model.

(1) Force balance for the clusters in unit volume of the suspension:

$$fn_cF_c + n_iF_i = f\varepsilon_{sc}(\rho_p - \rho_g)(g + a_c)$$

(2) Force balance for the dilute phase in unit volume of the suspension:

$$n_fF_f = \varepsilon_{sf}(\rho_p - \rho_g)(g + a_f)$$

(3) Pressure drop balance between the clusters and the dilute phase:

$$(\Delta p/\Delta h)_f + \frac{(\Delta p/\Delta h)_i}{1-f} = (\Delta p/\Delta h)_c,\; n_f F_f + \frac{n_i F_i}{1-f} = n_c F_c$$

(4) Mass conservation for the fluid:

$$U_g = U_{gf}(1-f) + U_{gc}f$$

(5) Mass conservation for the particles:

$$U_p = U_{pf}(1-f) + U_{pc}f$$

(6) Definition of cluster equivalent diameter:

$$d_{cl} = \frac{\left[\frac{U_p}{1-\varepsilon_{,\max}} - \left(U_{mf} + \frac{\varepsilon_{mf}U_p}{1-\varepsilon_{mf}}\right)\right]g}{N_{st}\frac{\rho_p}{\rho_p-\rho_g} - \left(U_{mf} + \frac{\varepsilon_{mf}U_p}{1-\varepsilon_{mf}}\right)g} d_p$$

(7) Definition of mean voidage

$$\varepsilon_s = f\varepsilon_{sc} + (1-f)\varepsilon_{sf}$$

(8) Stability condition

$N_{st} \rightarrow \min$,

where,
$$N_{st} = (N_{st})_c + (N_{st})_f + (N_{st})_i = \frac{\rho_p - \rho_g}{\rho_p} g\left[U_g - \frac{\varepsilon_{sc}-\varepsilon_{sf}}{1-\varepsilon_g} f^2(1-f)U_f\right]$$