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A generalized drag Law for heterogeneous gas-solid flows in fluidized beds

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ABSTRACT

An accurate drag model is key to simulating the fluidization process in circulating fluidized beds. Existing drag models only apply well to homogeneous gas solid flows or to some heterogeneous flows, but lack generalization. The present work generalizes the heterogeneous QC-EMMS drag model [12]. The particle heterogeneity was represented in the sub-model of the QC-EMMS model by introducing a local heterogeneity factor Ψ so that the meso-scale drag model varies with the operating conditions. The overall macroscopic heterogeneity is characterized by the Reynolds number (Re^*) of the overall gas-solid slip velocity, which represents the fluidization state variations with the operating conditions. The relationship between the local heterogeneity, Ψ, and the overall heterogeneity, Re^*, indirectly relates the local drag force to the operating conditions via the cluster sub-model to generalize the QC-EMMS model. The model is incorporated into the two-fluid method to simulate the gas-solid flow behavior in a riser, with the results for various working modes verifying the model accuracy with relative differences all less than 10%.

1. Introduction

The two-fluid model, the Euler-Euler method, is the main method used to simulate large industrial scale two-phase flows. The simulation accuracy then directly depends on the drag model [1–3]. The drag force model affects the gas-solid interactions and the particle entrainment by the gas. Existing drag models can be divided into homogeneous and heterogeneous types. The homogeneous drag models cannot accurately simulate the entire fluidization process, so the heterogeneous drag models are used to simulate the dense gas-solid two-phase flows. Existing heterogeneous drag models can generally describe individual experiments well, but they often cannot be applied to other operating conditions. Therefore, a heterogeneous drag model is needed which can be generalized to various operating conditions.

Energy Minimization Multi-scale (EMMS) theory [4] is an effective method for developing heterogeneous drag models [5]. EMMS theory has been used to develop several drag models that describe to some extent the drag force reduction characteristics caused by heterogeneous flows [5–9]. In order to distinguish different heterogeneous drag models, they are named here by the first word of the researcher's last name. The O-S model [1] is a heterogeneous drag model developed from experiments which can be used as a benchmark for theoretical drag models [10]. The distributions of the drag function, β, predicted by different drag models are compared in Fig. 1 for several typical heterogeneous drag models [6–8] and the O-S model. The existing heterogeneous drag curves differ greatly from the O-S curve both qualitatively and quantitatively. There all have sudden turning points in the drag function curves, which cannot be explained physically. The essential features of the O-S curve are that it first decreases and then increases concave upward along a smooth curve, with the minimum at a local solid volume fraction, ε_s, of about 0.1. Thus, there are problems in the existing EMMS drag models. The essential reasons lie in the inaccurate modeling of the meso-scale structures, with large differences in the meso-scale structures given by the models and seen in experiments [11].

The existing EMMS drag models have unreasonable assumptions which reduce their simulation accuracy and limit applications of the drag models to various conditions. Chen [12] and Chen & Qi [13,14] developed a new understanding of the relationship between the clusters and the drag force. They then presented a cluster model that gave a much better drag model and good agreement with the O-S curve, as shown in Fig. 1. The improved drag model, the QC-EMMS model, accurately represented the natural characteristics of the O-S model, including that the entire drag curve is smooth, the flow is the most heterogeneous and the drag reduction is the largest around $\varepsilon_s = 0.1$ and the flow becomes homogeneous and the drag curve approaches the homogeneous drag curve for both extremely dilute and dense conditions. Compared to the other heterogeneous drag curves [6–8], there are no sudden turning points in the QC-EMMS curve, and also the QC-EMMS model match the O-S curve the best.

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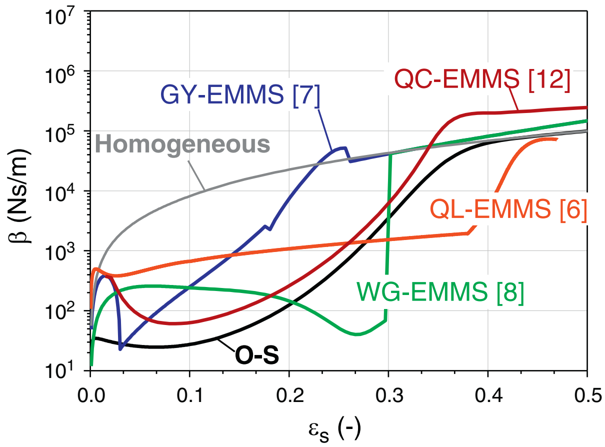

Fig. 1. Drag functions for various heterogeneous drag models (ρ_g = 1.205 kg/m$_3$, d_p = 100 μm, μ_g = 1.848 × 10^{-5} Pa s, u_{slip} = 1.0 m/s, u_g = 3.7 m/s, G_s = 98 kg/m^{2}s).

The QC-EMMS model has notable advantages compared to other heterogeneous drag models. Thus, the QC-EMMS model was generalized in the present work to a heterogeneous drag model that is generally applicable over a wide range of conditions. In order to distinguish with the generalized QC-EMMS model, the QC-EMMS drag model before generalization was called basic QC-EMMS model in the following.

2. Local heterogeneity variation

In the process of developing the basic QC-EMMS model, a sensitivity analysis [12,13] showed that the cluster solid volume fraction (or density), ε_{sc}, is the decisive factor controlling the drag force, not the cluster diameter, d_{cl}. Since the cluster density is the key factor driving the drag force, the cluster density model must first be generalized in order to generalize the drag model.

2.1. Basic cluster density model

There are some defects in the cluster density curve of the QL-EMMS model shown in Fig. 2 that need to be improved, such as there is a sudden turning point in the curve, also the curve present a unreasonable almost linear distribution in a large region. In order to obtain the accurate cluster density curve, two limits have been proposed for the cluster density. The lower limit is a 45° line ($\varepsilon_{sc} = \varepsilon_s$), which represents the homogeneous state where the cluster density is equal to the local particle density. The upper limit is a horizontal line where the cluster density is equal to the minimum fluidization particle density, which is the largest possible solid volume fraction. Then, a new cluster density model of basic QC-EMMS model was developed that combines the cluster density characteristics of a unimodal distribution with the characteristics that the flow becomes homogeneous in the extremely dilute and dense limits to supplement the EMMS theory. This cluster density model is shown in Fig. 2 and is given by [12–14]:

$$\varepsilon_{sc} = \varepsilon_s + \frac{30.35\varepsilon_s^{\,2}}{e^{15.37(\varepsilon_s+0.03)^2} - 0.96}\left(\varepsilon_{s,mf} - \varepsilon_s\right) \qquad (1)$$

This cluster density curve agrees well with the experimental data from the literature [15], which verified the cluster model. The new cluster density curve avoid all the disadvantages in the QL-EMMS curve. This cluster density model was then used in the basic QC-EMMS drag model, which is the core improvement of the drag model, making the basic QC-EMMS model a better agreement with experimental data than all the previous drag models [6–8].

2.2. Generalized cluster density model

A generalized drag model must be related to the operating conditions. Drag models are applied at the mesh or meso-scale to represent the local heterogeneity, while operating conditions are at the macro or reactor scale which represents the overall heterogeneity. Thus, to generalize the drag model, the local heterogeneity must be related to the overall heterogeneity.

The most typical characteristic of heterogeneous gas-solid flows is the appearance of clusters. These meso-scale structures, the clusters, directly represent the heterogeneity of the two-phase flow. The clusters create a large slip velocity, far exceeding the terminal settling velocity of a single particle, which significantly reduces the drag force. Hence, the flow heterogeneity, the meso-scale structures, the gas-solid slip velocity and the drag reduction essentially described the same problem from different perspectives.

The meso-scale clusters and the drag law are closely related to the slip velocity. There have been many experimental investigations of the gas-solid slip velocity. Fig. 3 shows various relationships between the slip velocity and the local solid volume fraction based on experimental data [16,17] where the slip velocity differs for different operating conditions. Thus, the data suggests that both the drag law and the cluster parameters should also differ for different conditions and the cluster density curve should vary with the operating conditions and not be constant as in previous models.

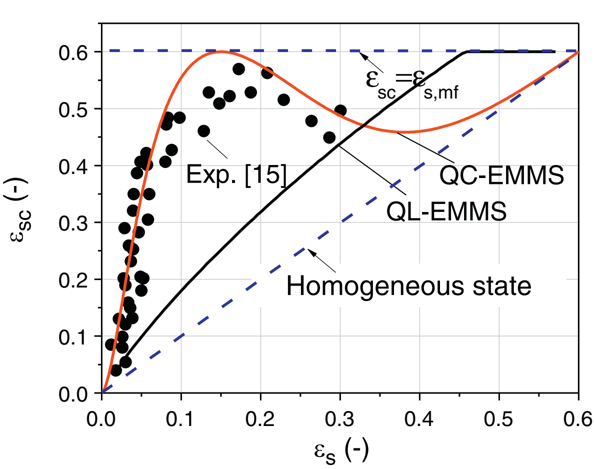

Fig. 2. Cluster density model.

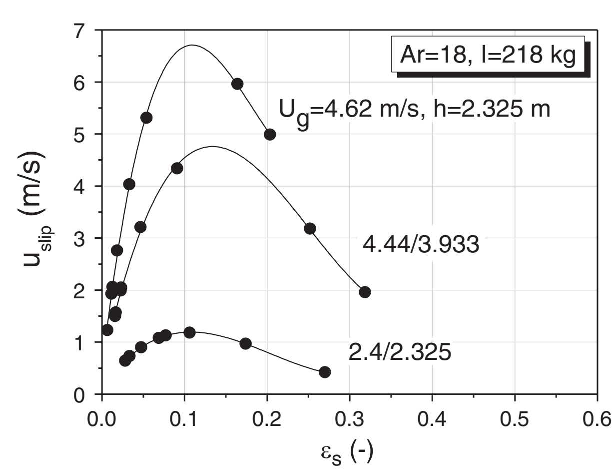

Fig. 3. Experimental results of local slip velocity [17].