

Stability-driven Structure Evolution: Exploring the Intrinsic Similarity Between Gas-Solid and Gas-Liquid Systems*

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Abstract As the core of the Energy-Minimization Multi-Scale (EMMS) approach, the so-called stability condition has been proposed to reflect the compromise between different dominant mechanisms and believed to be indispensable for understanding the complex nature of gas-solid fluidization systems. This approach was recently extended to the study of gas-liquid bubble columns. In this article, we try to analyze the intrinsic similarity between gas-solid and gas-liquid systems by using the EMMS approach. First, the model solution spaces for the two systems are depicted through a unified numerical solution strategy, so that we are able to find three structural hierarchies in the EMMS model for gas-solid systems. This may help to understand the roles of cluster diameter correlation and stability condition. Second, a common characteristic of gas-solid and gas-liquid systems can be found by comparing the model solutions for the two systems, albeit structural parameters and stability criteria are specific in each system: two local minima of the micro-scale energy dissipation emerges simultaneously in the solution space of structure parameters, reflecting the compromise of two different dominant mechanisms. They may share an equal value at a critical condition of operating conditions, and the global minimum may shift from one to the other when the operating condition changes. As a result, structure parameters such as voidage or gas hold-up exhibit a jump change due to this shift, leading to dramatic structure variation and hence regime transition of these systems. This demonstrates that it is the stability condition that drives the structure variation and system evolution, which may be the intrinsic similarity of gas-solid and gas-liquid systems.

Keywords multi-scale, fluidized bed, bubble column, regime transition, stability condition

1 INTRODUCTION

Regime transition is always an important issue in the study of two-phase flow systems. In the earlier studies of fluidization systems, the terminologies of “particulate fluidization” and “aggregative fluidization” were proposed to demarcate two distinct two-phase structures of fluidization states [1, 2]. Mainly due to the density ratio between the continuous phase and dispersed phase, liquid-solid systems are generally considered particulate while gas-solid and gas-liquid systems are aggregative. Compared to the particulate fluidization, more heterogeneous structure emerges in the aggregative fluidization, such as emulsion phase surrounding bubbles (bubbling fluidization) or particle-rich clusters and gas-rich dilute broth (fast fluidization). Similarly, more complex structure appears in the heterogeneous (churn) regime of gas-liquid bubbly flow, such as bubble wakes, liquid vortices and coalescence or breakup of bubbles in contrast to the homogeneous regime.

The similarity between gas-solid and gas-liquid flow has been recognized by many researchers [3–6]. With increasing gas velocities, gas-solid systems evolve sequentially from uniform expansion, bubbling and turbulent fluidization to fast fluidization and finally dilute transport [7]. These regimes can find their counterpart in gas-liquid systems: dispersed bubbly, coalescing bubbly, churn-turbulent, annular and mist [6],

as shown in Fig. 1. If the diameter of apparatus is relatively small, slug flow may be observed between bubbling and turbulent flow. Since design parameters such as pressure drop, heat and mass transfer coefficients are dependent on different flow patterns, a large number of regime maps have been proposed based on experiments and theoretical analysis [8–10]. Bi and Grace [6] found that some empirical approaches or correlations developed for gas-solid fluidization could be used to predict the corresponding transitions between different regimes in gas-liquid bubbly flows. Ellenberger and Krishna [5] proposed a unified approach to scale-up gas-solid fluidized bed or gas-liquid bubble column reactors by analyzing the analogy between these two systems. Analogous to the distinction of dense and dilute phases in bubbling fluidization, the fast-rising bubbles in bubble columns were identified as the dilute phase whereas the liquid phase containing entrained small bubbles as the dense phase. However, these studies have to rely on some empirical correlations, and a more fundamental explanation behind these similarities is still lacking.

Li *et al.* [11, 12] proposed that the gas-solid fluidized systems belong to a typical dissipative system wherein the two-phase heterogeneous structure is characterized by the so-called dissipative structure. Energy is likely to dissipate in the self-organized and yet heterogeneous ordered structure when the system is far from the equilibrium state. The transition from bubbling

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to turbulent fluidization can be characterized as a non-equilibrium phase transition, *i.e.*, the first bifurcation point of the gas-solid fluidized system [7]. When the system operates at fast fluidization, global heterogeneous structure may exist, accompanied by the top-dilute phase and bottom-dense phase. The transition from fast fluidization to dilute transport is marked by a jump change (choking), signifying the second bifurcation point of the system. Generally each regime of two-phase flow may correspond to some non-equilibrium steady state, thus the regime transition is essentially a non-equilibrium phase transition.

Hence Li and Kwauk [7] proposed the Energy-Minimization Multi-Scale (EMMS) model which is then extensively developed and applied for gas-solid fluidization in theoretical analysis of regime transition and CFD modeling of gas-solid flow structure [13]. The methodology was also extended to other complex systems, in particular, the gas-liquid bubbly flow systems recently [14, 15]. In the EMMS approach, each dominant mechanism was identified and mathematically expressed with an extremum tendency of energy dissipation, and the mutually constrained extremum tendency constitutes a stability condition of the system,

reflecting the compromise of different dominant mechanisms. The stability condition can then be used for closing the model in addition to mass and force balance equations. Though the formula of stability condition is system-dependent, it could be used to explore the underlying physics of structure variation with a unified approach.

In this work, we compared the EMMS models for gas-solid and gas-liquid systems to explore the intrinsic similarity of these two systems. The latter is denoted as GL-EMMS model. We confine our discussion in gas-solid fast fluidization and gas-liquid bubbly flow rather than the whole regime expansion. Within the framework of the EMMS model, the solution space of the model is further clarified to help understanding the structure variation during regime transitions.

2 GAS-SOLID FAST FLUIDIZATION

The original EMMS model proposed by Li and Kwauk [7] can be represented in a reduced form in Table 1 [16]. The equations define a non-linear problem for calculating the eight structure parameters to

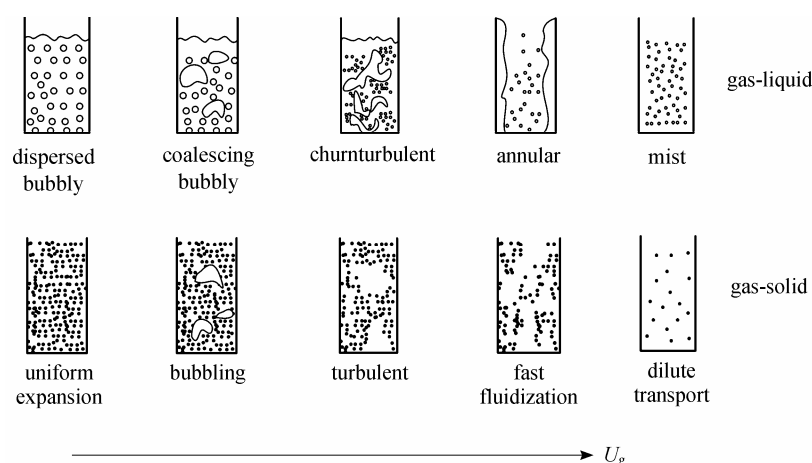


Figure 1 Schematic diagram of regime transition in gas-solid and gas-liquid systems

Table 1 The EMMS model for gas-solid systems (Variables: ε_f , ε_c , U_f , U_c , U_{pf} , U_{pc} , d_{cl} , f)

Conservation equations	
continuity of fluid:	$U_g = fU_c + (1-f)U_f \quad (1)$
continuity of solid:	$U_p = fU_{pc} + (1-f)U_{pf} \quad (2)$
force balance of dilute phase:	$\frac{3}{4}C_{Df} \frac{\rho_g U_{sf}^2}{d_p} = (\rho_p - \rho_g)g \quad (3)$
force balance of dense phase:	$\frac{3}{4}C_{Dc} \frac{\rho_g U_{sc}^2}{d_p} = \frac{1-\varepsilon}{1-\varepsilon_c} (\rho_p - \rho_g)g \quad (4)$
force balance of interphase:	$\frac{3}{4}C_{Di} \frac{\rho_g U_{si}^2}{d_{cl}} = (\varepsilon - \varepsilon_c)(\rho_p - \rho_g)g \quad (5)$
cluster diameter:	$d_{cl} = \frac{(\rho_p - \rho_g)g U_p / \rho_p (1 - \varepsilon_{max}) - N_{st, mf}}{N_{st} - N_{st, mf}} d_p \quad (6)$

Table 1 (Continued)

Energy resolution	$N_T = N_{st} + N_d = \frac{(\rho_p - \rho_g)}{\rho_p} g U_g$	(7)
Stability criterion	$N_{st} = \left[U_g - \frac{\varepsilon_f - \varepsilon}{1 - \varepsilon} f(1 - f) U_f \right] \frac{(\rho_p - \rho_g) g}{\rho_p} = \min$	(8)
Definitions and correlations		
Superficial slip velocity of dilute phase	$U_{sf} = U_f - \frac{\varepsilon_f U_{pf}}{1 - \varepsilon_f}$	(9)
Superficial slip velocity of dense phase	$U_{sc} = U_c - \frac{\varepsilon_c U_{pc}}{1 - \varepsilon_c}$	(10)
Superficial slip velocity of interphase	$U_{si} = \left(U_f - \frac{\varepsilon_f U_{pc}}{1 - \varepsilon_c} \right) (1 - f)$	(11)
Mean voidage	$\varepsilon = f \varepsilon_c + (1 - f) \varepsilon_f$	(12)
	$N_{st,mf} = \frac{(\rho_p - \rho_g) g}{\rho_p} \left(U_{mf} + \frac{U_p \varepsilon_{mf}}{1 - \varepsilon_{mf}} \right)$	(13)
	$(\beta / \varepsilon_{mf}) (U_{mf} / \varepsilon_{mf}) = (1 - \varepsilon_{mf}) (\rho_p - \rho_g) g$	(14)
	$\beta = 150 \frac{(1 - \varepsilon_{mf})^2 \mu_g}{\varepsilon_{mf} d_p^2} + 1.75 \frac{(1 - \varepsilon_{mf}) \rho_g}{d_p} \frac{U_{mf}}{\varepsilon_{mf}}$	(15)
	$Re_c = \frac{\rho_g d_p U_{sc}}{\mu} \quad Re_f = \frac{\rho_g d_p U_{sf}}{\mu} \quad Re_i = \frac{\rho_g d_{cl} U_{si}}{\mu}$	(16)
	$C_{Dc0} = \frac{24}{Re_c} + \frac{3.6}{Re_c^{0.313}} \quad C_{Df0} = \frac{24}{Re_f} + \frac{3.6}{Re_f^{0.313}} \quad C_{Di0} = \frac{24}{Re_i} + \frac{3.6}{Re_i^{0.313}}$	(17)
	$C_{Dc} = C_{Dc0} \varepsilon_c^{-4.7} \quad C_{Df} = C_{Df0} \varepsilon_f^{-4.7} \quad C_{Di} = C_{Di0} (1 - f)^{-4.7}$	(18)

describe the heterogeneous structure of the particle-rich dense phase and the gas-rich dilute phase. Ge and Li [16] implemented a rigorous analysis of the model and identified choking as a jump change between two stable solutions as $N_{st}(\varepsilon_{mf}) = N_{st}(\varepsilon_o)$. This work follows this scheme [16] but more analysis is given on the structure hierarchy of the model to ascertain the complete solution space. The starting point of the present work is the feature of the solution space of the EMMS model. In other words, to what extent the stability condition acts and how the formulation of the meso-scale structure parameters, *e.g.* the cluster diameter equation, determines the final solution.

We noticed two points in the new exploration of the EMMS model. First, the energy dissipation term of N_{st} at each grid node within the space defined by two structure parameters (ε_c and f) is independent of d_{cl} , as can be seen from Eq. (8). Hence we are able to temporarily isolate the variable d_{cl} and Eqs. (5), (6) from the whole set of model equations. In other words, with given value of ε_c , ε_f and f , we can immediately obtain the four structure parameters (U_c , U_f , U_{pc} , U_{pf}) from Eqs. (1)–(4). The new algorithm is illustrated in Fig. 2, traversing ε_c and f over all possible values by small steps. The domain of ε_c – f is discretized into 1000×3000 cells, and N_{st} can be calculated without the need to

solve Eqs. (5, 6). Note that U_{si} could be obtained from Eqs. (11) and then d_{cl} could also be calculated as an associated variable from Eq. (5) at this moment, but we leave this to the next step. In addition, Eqs. (14) and (15) are used to calculate the parameter U_{mf} .

When searching the whole space of (ε_c, f), no local minimum of N_{st} can be found except at the boundary (see Fig. 3). Hence the second point is to evaluate the effect of the cluster diameter equation on the model solution. It can be seen from Eq. (6) that d_{cl} is a function of N_{st} and U_p , so that the parameter U_{si} can be either determined by Eq. (5) with d_{cl} calculated from Eq. (6), or obtained from its definition formula, *i.e.*, Eq. (11), without d_{cl} being known in advance. From this viewpoint, Eqs. (5) and (6) provide extra constraints $\Delta U_{si} = 0$ to ensure the model equations converged.

Figure 3 reveals the elaborate structure of the solution space for the EMMS model. The grid nodes (combination of ε_c and f), each of which has a valid value of $N_{st}(\varepsilon_c, f)$ and $\Delta U_{si}(\varepsilon_c, f)$, constitutes a curved surface. The structure parameters at each grid node satisfy the mass and momentum conservative equations for the dilute and dense phases [Eqs. (1)–(4)], but most of them do not obey the cluster diameter correlation of Eq. (6). To let the structure parameters also meeting the force balance equation for interphase

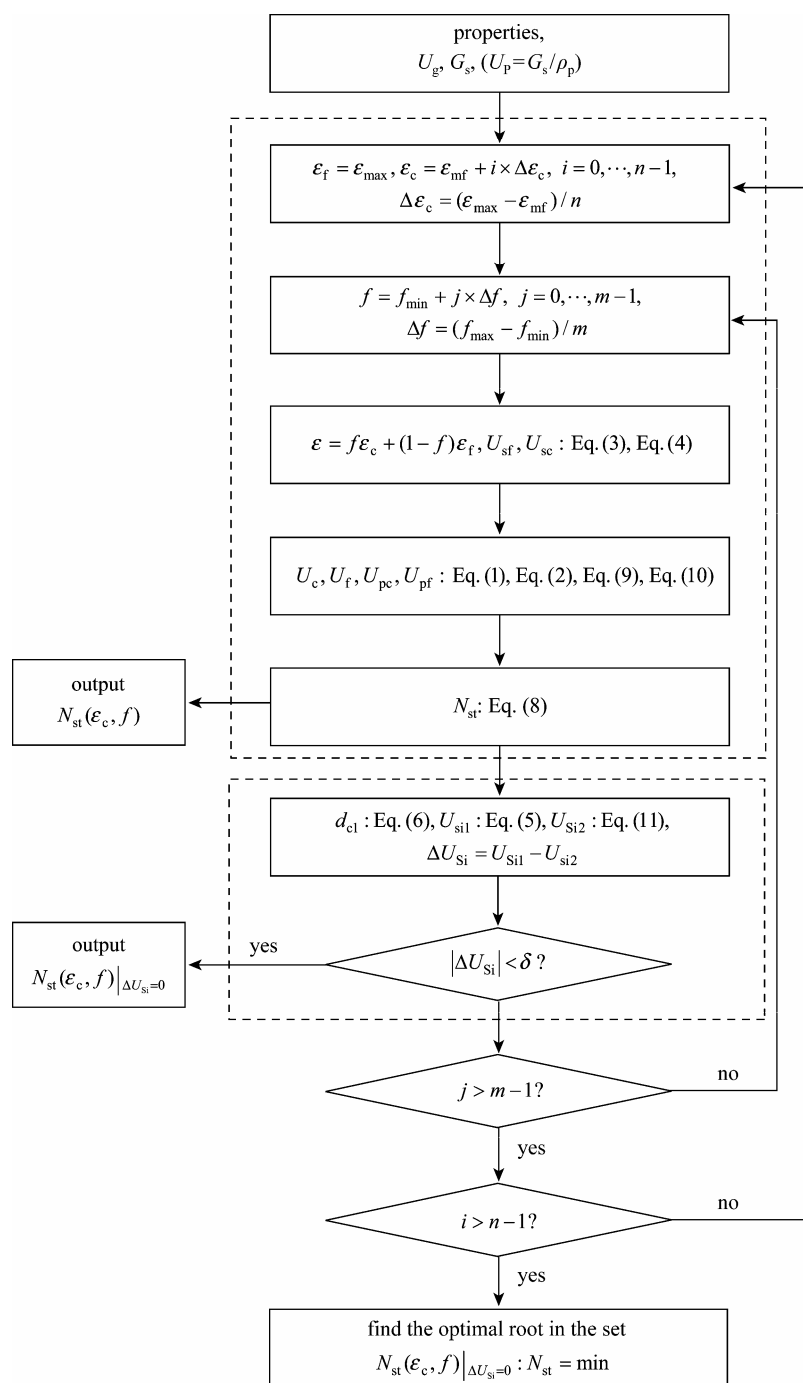


Figure 2 Solution scheme of the EMMS model for gas-solid flow (model equations are in Table 1, $m = 3000$, $n = 1000$)

(the “phase” between dilute and dense phases) of Eq. (5), the cluster diameter d_{cl} has to be correspondingly adjusted to fit with Eqs. (1)–(4).

In this case, the cluster diameter equation, Eq. (6), applies to avoid the adjustment. The characteristic of Eq. (6) lies in that d_{cl} is a function of U_p and N_{st} in contrast to other cluster diameter correlations in literature which is only related to average voidage. N_{st} is again a combination of other structure parameters. Combination of Eqs. (5), (6) and (11) leads to an extra

constraint $\Delta U_{si}(\epsilon_c, f) = 0$. Physically this constraint means that the meso-scale parameters ϵ_c and f are closely correlated. This extra constraint further compresses the solution space of a curved surface into a curve $\zeta(\epsilon_c, f)|_{\Delta U_{si}=0}$. Finally the optimization is performed on the curve of $\zeta(\epsilon_c, f)|_{\Delta U_{si}=0}$. The stability criterion ($N_{st} = \min$) is used to capture the points of final solution satisfying all of the physical constraints. Evidently there are three structure hierarchies in seeking the final solution, from a curved surface only

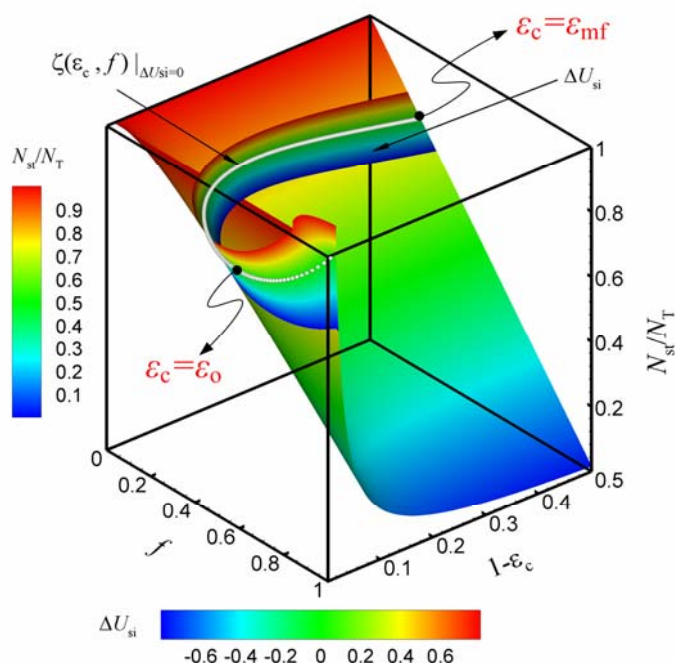


Figure 3 The numerical topology of solution space of the EMMS model (air-FCC system, $\rho_p = 929.5 \text{ kg}\cdot\text{m}^{-3}$, $d_p = 54 \text{ }\mu\text{m}$, $\rho_g = 1.1795 \text{ kg}\cdot\text{m}^{-3}$, $\mu_g = 1.8875 \times 10^{-5} \text{ Pa}\cdot\text{s}$, $U_g = 3.4 \text{ m}\cdot\text{s}^{-1}$, $G_s = 50 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). The N_{st}/N_T surface is monotonous *versus* either f or ε_c , and hence no local minimum can be found without the constraint of $\Delta U_{st} = 0$. Note that d_{cl} is a function of N_{st} [see Eq. (6)], so ΔU_{st} becomes an implicit function of N_{st} . The solution space of curve $\zeta(\varepsilon_c, f)|_{\Delta U_{st}=0}$ is obtained by embedding $\Delta U_{st} = 0$ into the N_{st}/N_T surface. Finally the stability criterion ($N_{st}/N_T = \min$) is used to identify the final solution on the curve $\zeta(\varepsilon_c, f)|_{\Delta U_{st}=0}$

obeying the conservative equations of dense and dilute phases [Eqs. (1)–(4)], to a curve also satisfying the cluster diameter correlation and the force balance equation for the interphase [Eqs. (5), (6)], and finally shrinking into the points with the minimum of N_{st} .

Figure 4 illustrates the solution curves of different U_g at a constant solid flow rate $G_s = 50 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. There are one or two points of the minimum of N_{st} for each curve. This can be more clearly identified from Fig. 5 in which the solution space is projected on the $N_{st}-\varepsilon_c$ plane. The boundary of $\varepsilon_c = \varepsilon_{mf}$ is considered as a local minimum if $N_{st}(\varepsilon_{mf}) < N_{st}(\varepsilon_{mf} + \Delta\varepsilon_c)$. Another local minimum of N_{st} may appear at a high ε_c denoted as ε_o . With decreasing U_g , a state of $N_{st}(\varepsilon_{mf}) = N_{st}(\varepsilon_o)$ can be achieved, signifying the regime transition from dilute transport to fast fluidization [16, 17]. This transition is well known as the “C type” choking [18]. More details about choking can be found in the references [18, 19]. Before choking $N_{st}(\varepsilon_o)$ is always smaller than $N_{st}(\varepsilon_{mf})$ and the former is the real solution of the system, as shown in Fig. 5. After choking $N_{st}(\varepsilon_{mf})$ becomes the smaller one. The global minimum point shifts between the two local minima when choking happens. There is a large difference for dense phase structure parameter ε_c before and after choking, which agrees with the experimental evidence that choking is a collapse of suspension with decreasing U_g or increasing G_s [20].

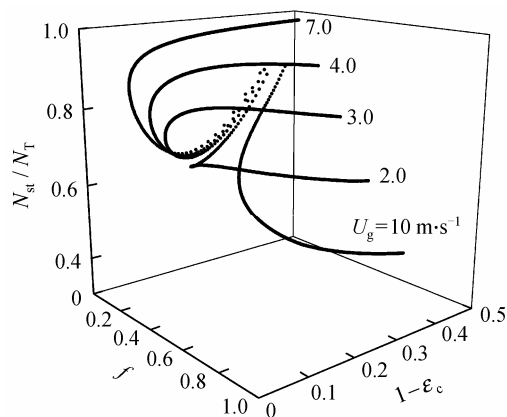


Figure 4 The solution spaces of different U_g at constant solid flow rate ($G_s = 50 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)

The bifurcation phenomena can be understood from Fig. 6. With increasing U_g , the two local minima of N_{st} generate two branches, and one of them should be a pseudo solution. The branch 1-1 in Fig. 6 (a) corresponds to the local minimum of N_{st} when $\varepsilon_c = \varepsilon_{mf}$ and the branch 1'-1' in Fig. 6 (b) is an associated curve of branch 1-1 because all the structure parameters are determined by the stability criterion. The branches 2-2 and 2'-2' correspond to the other local minimum with $\varepsilon_c = \varepsilon_o$. The stability criterion requires

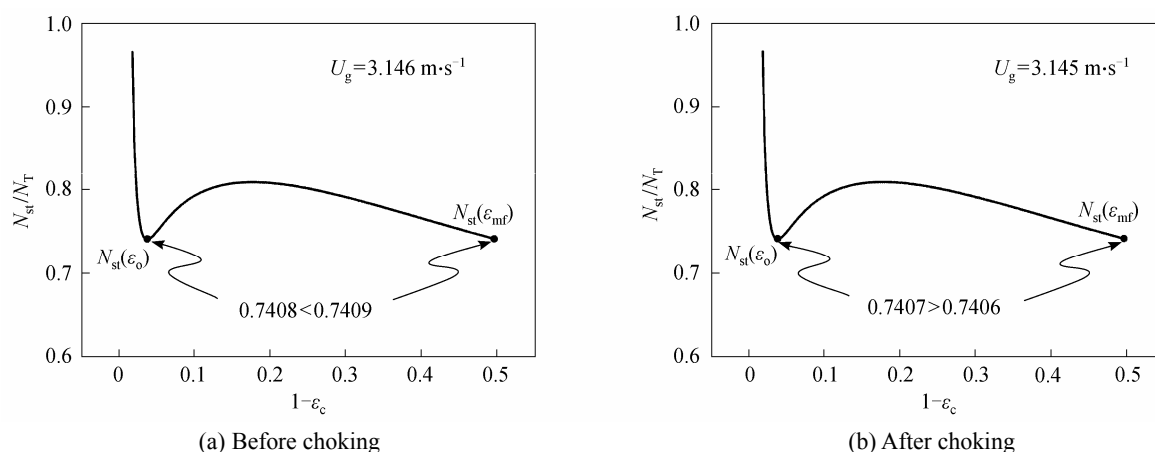


Figure 5 The two local minima of N_{st}/N_T [16] ($G_s = 50 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)

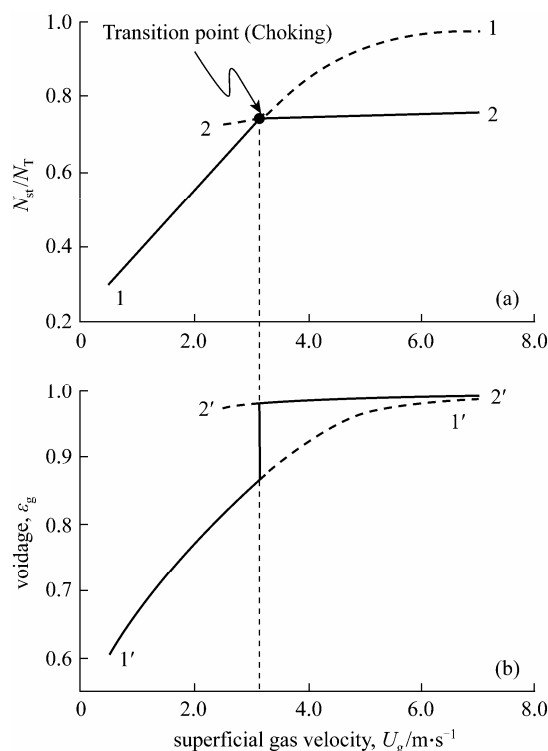


Figure 6 Relationship between structure bifurcation and energy dissipation in gas-solid system

the global minimization of N_{st} , so the real solution shifts from branch 1-1 to branch 2-2 at the transition point. Correspondingly the voidage curve shifts from 1'-1' to 2'-2' and this jump change reflects the abrupt change in the phase structure. As a result, the solid line in Fig. 6 shows the real solution and the broken line represents the pseudo solution.

Li *et al.* [17, 21] recognized that the bifurcation phenomena should relate the structure variation of the system to the stability condition which physically reflects the compromise of two different mechanisms: the tendency of gas passing through particle layer with

the least resistance ($W_{st} = \min$) and the tendency of particles maintaining least gravitational potential ($\varepsilon = \min$). But in general neither the gas nor the particles dominate the system, and the former gas-dominated and the latter particle-dominated mechanisms coexists in the system and jointly leads to the stability condition $\{N_{st} = W_{st}/[\rho_p(1-\varepsilon)]\}$.

The new findings in this study on the hierarchy of solution structure and the description of the structure evolution using the two branches of voidage and N_{st} would further reinforce the understanding of the essence of the EMMS model. In recent years there is some work in the literature on the modification of cluster diameter correlations of the EMMS model [22]. This work also suggests that the cluster diameter correlation be physically related to the meso-scale energy dissipation reflecting the compromise between different dominant mechanisms, and be mathematically of a curve with two local minima when intersecting with the curved surface of Fig. 3. The latter guarantees the co-existence of the bi-stable states of the system when regime transition occurs.

3 GAS-LIQUID BUBBLY FLOW

Our previous work [23–25] established the Dual-Bubble-Size (DBS) model, extending the EMMS method to gas-liquid bubbly flow. The system structure is resolved into a liquid phase, a small bubble phase and a large bubble phase. Six structure parameters are used to describe the system, *i.e.*, bubble diameter d_s and d_L , gas volume fraction f_s and f_L , superficial gas velocity $U_{g,s}$ and $U_{g,L}$. The total energy dissipation rate per unit mass is resolved to three parts: energy dissipation due to bubble oscillation N_{surf} , viscous dissipation in liquid phase N_{turb} and energy dissipation due to bubble breakage N_{break} . The stability criterion is proposed as the minimization of micro-scale energy dissipation terms ($\Sigma N_{surf,i} + N_{turb}$). The model equations are summarized in Table 2.

There are six structure parameters and only three

Table 2 The EMMS model equations for gas-liquid flow (GL-EMMS) (Variables: $U_{g,S}$, $U_{g,L}$, d_S , d_L , f_S , f_L)**Conservation equations**

$$\text{continuity of gas:} \quad U_g = U_{g,S} + U_{g,L} \quad (19)$$

$$\text{force balance of small bubble phase:} \quad \frac{3}{4} C_{D,S} \left(\frac{U_{g,S}}{f_S} - \frac{U_L}{1-f_b} \right)^2 = \frac{(\rho_l - \rho_g) g d_S}{\rho_l} \quad (20)$$

$$\text{force balance of large bubble phase:} \quad \frac{3}{4} C_{D,L} \left(\frac{U_{g,L}}{f_L} - \frac{U_L}{1-f_b} \right)^2 = \frac{(\rho_l - \rho_g) g d_L}{\rho_l} \quad (21)$$

Energy resolution

$$N_T = \sum_i N_{\text{surf},i} + N_{\text{turb}} + \sum_i N_{\text{break},i} = g U_g \quad (22)$$

Stability criterion

$$\sum_i N_{\text{surf},i} + N_{\text{turb}} = \min \quad (23)$$

Definitions and correlations

$$C_{D,S} = C_{D0,S} (1-f_b)^4 \quad C_{D,L} = C_{D0,L} (1-f_b)^4 \quad (24)$$

$$C_{D0,i} = \frac{4}{3} \frac{g d_i}{U_T^2} \frac{\rho_l - \rho_g}{\rho_l} \quad U_T = \frac{\mu}{\rho_l d_i} M^{-0.149} (J - 0.857) \quad (25)$$

$$M = \frac{\mu_i^4 g (\rho_l - \rho_g)}{\rho_l^2 \sigma^3} \quad J = \begin{cases} 0.94 H^{0.757} & (2 < H \leq 59.3) \\ 3.42 H^{0.441} & (H > 59.3) \end{cases} \quad (26)$$

$$H = \frac{4}{3} Eo \cdot M^{-0.149} \left(\frac{\mu_l}{\mu_{\text{ref}}} \right)^{-0.14} \quad Eo = \frac{g (\rho_l - \rho_g) d_b^2}{\sigma} \quad (27)$$

$$N_{\text{surf},i} = U_{g,i} g \frac{C_{D0,i} - C_{D,p}}{C_{D0,i}} \quad (28)$$

$$\begin{cases} C_{D,p} = \frac{24}{Re} (1 + 0.15 Re^{0.687}) & (Re < 1000) \\ C_{D,p} = 0.44 & (Re > 1000) \end{cases} \quad (29)$$

$$N_{\text{break},i} = \int_{\lambda_{\min}}^{d_i} \int_0^{0.5} \frac{\omega(d_i, f_i, \lambda)}{(1-f_b) \rho_l + f_b \rho_g} \cdot P_b(d_i, \lambda, f_{BV}) \cdot c_f \pi d_i^2 \sigma \cdot d f_{BV} d \lambda \quad (30)$$

$$\omega(d_i, f_i, \lambda) = 0.923 (1-f_i) n_i N_{\text{turb}}^{1/3} \frac{(\lambda + d_i)^2}{\lambda^{11/3}} \quad (31)$$

$$P_b(d_i, \lambda, f_{BV}) = \exp \left[- \frac{\max \{ c_f \pi d_i^2 \sigma, \pi \sigma \lambda^3 / (3 d_i f_{BV}^{1/3}) \}}{\rho_l (\pi/6) \lambda^3 \cdot (\lambda N_{\text{turb}})^{2/3}} \right] \quad (32)$$

$$\lambda_{\min} = 11.4 \left[\frac{(\mu_l / \rho_l)^3}{N_{\text{turb}}} \right]^{0.25} \quad (33)$$

conservation equations in the model, thus three variables are open. Each conservation equation can be considered as a constraint. Analogous to the solution strategy of the EMMS model for gas-solid systems, the non-linear optimization problem is solved by searching the space of open structure parameters to locate the minimum points of the microscale energy dissipation ($\sum N_{\text{surf},i} + N_{\text{turb}}$). Fig. 7 shows the solution scheme of the GL-EMMS model in the air-water system. d_S , d_L and $U_{g,S}$ are selected as three open variables to construct the solution space. In this work, the minimum bubble diameter is set as 0.5 mm and the maximum bubble diameter as 60 mm. Since the global minimum of ($\sum N_{\text{surf},i} + N_{\text{turb}}$) is always attained in the medium value of bubble diameters, the real solution is

independent on the minimum and maximum bubble diameters. The logarithmic steps for d_S and d_L are used to capture sufficient information of structure variation at small bubble region. The grid partition of $m \times n \times l$ is performed as $55 \times 55 \times 100$ considering the balance between computation load and numerical precision.

The GL-EMMS model is capable of predicting the regime transition from homogeneous and transitional flows to heterogeneous flow between $0.128 \text{ m} \cdot \text{s}^{-1}$ and $0.129 \text{ m} \cdot \text{s}^{-1}$ for air-water system, as found by many experiments [26–28]. Fig. 8 shows the solution space for these two gas velocities. Two troughs can be clearly seen in the solution space. In other words, there are also two local minima of the stability

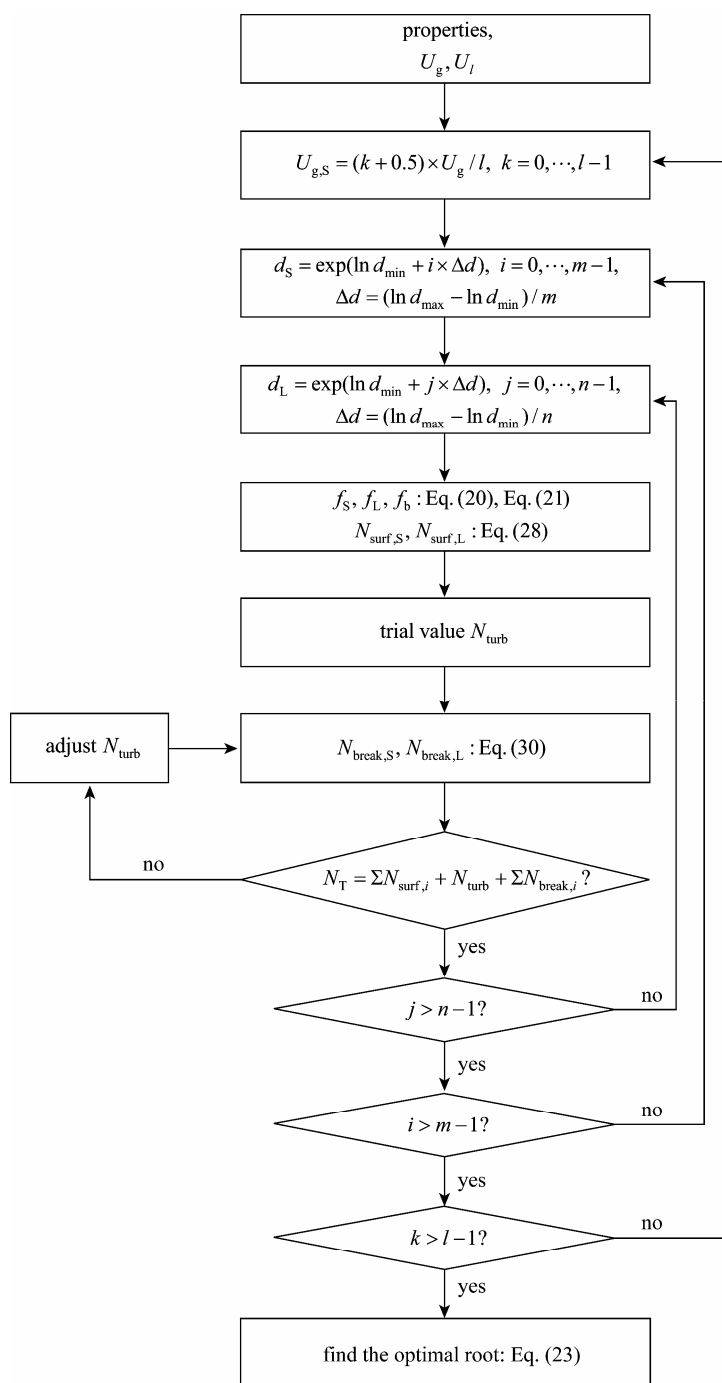


Figure 7 Solution scheme of the GL-EMMS model for gas-liquid systems

condition, which is analogous to the case in the gas-solid systems (see Fig. 5). When regime transition occurs, the global minimum point shifts from $d_s = 1.42$ mm to $d_s = 2.86$ mm while the large bubble diameter remains to be 8.85 mm. Fig. 9 depicts the stability criterion against d_s only and the red points mark all possible solutions with respect to U_g . There is only one local minimum at lower gas velocities. When the second local minimum appears the system may fall into a bi-stable state as that in gas-solid systems. Note

that the jump change point could be more accurately captured by fining the grid resolution and optimizing the solution algorithm [29].

The bifurcation is related to the compromise between two dominant mechanisms in gas-liquid systems: the ability of gas playing the leading role in pattern formation through the minimization of energy dissipation *via* liquid viscosity N_{turb} , and the ability of liquid through the minimization of energy dissipation due to the response of bubble surface to liquid N_{surf} .

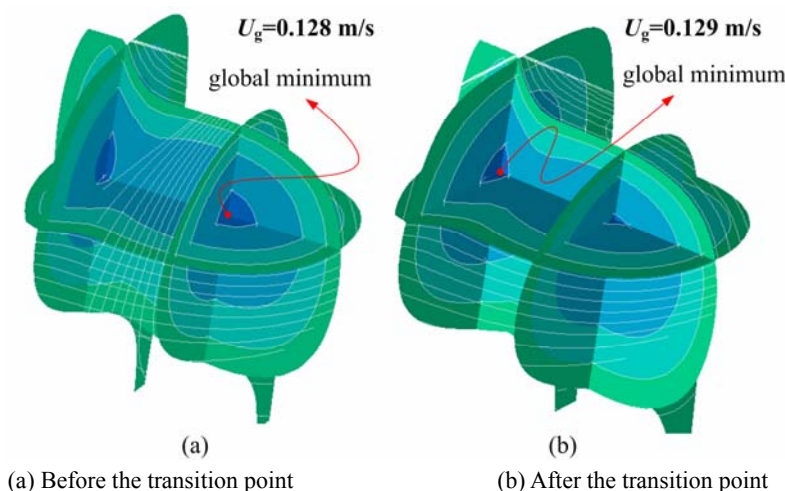


Figure 8 The numerical landscape of solution space of the GL-EMMS model [25] (air-water system, $\rho_l = 998 \text{ kg}\cdot\text{m}^{-3}$, $\rho_g = 1.225 \text{ kg}\cdot\text{m}^{-3}$, $\mu_l = 1.0 \times 10^{-3} \text{ Pa}\cdot\text{s}$, $\mu_g = 1.8875 \times 10^{-5} \text{ Pa}\cdot\text{s}$). The two panels illustrate the existence of two local minimum of micro-scale energy dissipation $[(\Sigma N_{\text{surf},i} + N_{\text{turb}})/N_T]$ at two adjacent gas flow rates. The left panel indicates that the global minimum of N_{st}/N_T lies at the right potential trough at $0.128 \text{ m}\cdot\text{s}^{-1}$ of gas velocity but shifts to the left at $0.129 \text{ m}\cdot\text{s}^{-1}$ at the right panel. This jump causes the dramatic variation of structure parameters, and hence drives the macro-scale regime transition

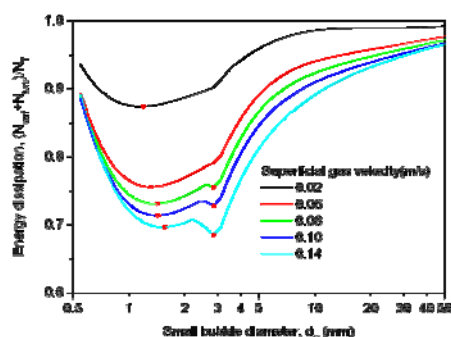


Figure 9 Variation of energy dissipation against small diameter with increasing gas velocity (the points mark the local minima)
superficial gas velocity/ $\text{m}\cdot\text{s}^{-1}$: — 0.02; --- 0.06; 0.08; -.-.- 0.10; 0.14

Analogous to the bifurcation for gas-solid systems, two branches can also be found for gas-liquid systems, as illustrated in Fig. 10. They are determined by the local minima of micro-scale energy dissipation within the solution space of structure parameters for each gas velocity. The solid line denotes the real solution and the broken line denotes the pseudo solution. The two branches in Fig. 10 (a) are continuous, even at the crossing point; but discontinuity occurs on the gas hold-up curve. This characteristic is coincident more or less with first-order phase transition in equilibrium thermodynamics which obeys the principle of minimization of the Gibbs free energy. When the first-order phase transition happens, the Gibbs free energy exhibits continuity but its first derivative such as the specific volume exhibits discontinuity. Note that the regime transition in two-phase flow and the first-order phase transition in thermodynamics are of dif-

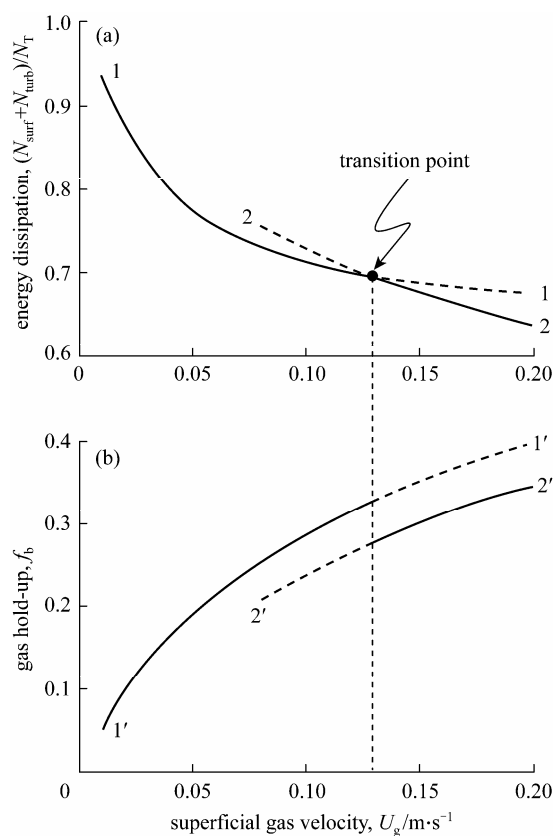


Figure 10 Relationship between structure bifurcation and energy dissipation in bubble columns [14]

ferent physical implications, because the former belongs to a non-linear non-equilibrium thermodynamics problem; whereas the latter is always regarded as an equilibrium system. The analogy discussed herein is

purely from the view of numerical characteristics.

4 CONCLUSIONS

This work attempts to analyze the intrinsic similarity between gas-solid and gas-liquid two-phase flow systems within the framework of the EMMS approach. The models solution spaces for the two systems are exhaustively analyzed, and thus regime transitions in gas-solid fluidization and gas-liquid bubbly flows can be theoretically predicted under an unified modeling strategy. For gas-solid systems, the cluster diameter is found to provide an extra constraint on the final solution, and hence critical to capturing the bi-metastable states and the regime transition. The bifurcation of minimized energy dissipation rate can be clearly observed by recording all local minima of stability criterion in the solution space, reflecting the compromise between two different mechanisms. Regime transition is therefore attributed to the existence of the multiple stable states captured in the numerical solution. The relationship between the bifurcations of stability conditions and of structure parameters is found to exist in both gas-solid and gas-liquid two-phase flow systems, indicating that the stability conditions, though system-dependent in expression, is the drive for the structure evolution of the systems. The new findings on the three hierarchies of solution structure in the model and the similar bifurcations in gas-solid and gas-liquid systems would further reinforce the understanding of the essence of the EMMS approach.

NOMENCLATURE

C_D	drag coefficient for a bubble swarm
C_{D0}	drag coefficient for a bubble in quiescent liquid
c_f	coefficient of surface area increase [$c_f = (f_{BV})^{2/3} + (1 - f_{BV})^{2/3} - 1$]
d_b	bubble diameter, m
d_{cl}	cluster diameter, m
d_L	large bubble diameter, m
d_p	particle diameter, m
d_S	small bubble diameter, m
Eo	Eötvös number
f	volume fraction of dense phase
f_{BV}	breakup ratio of daughter bubble to its mother bubble
f_b	volume fraction of gas phase
f_L	volume fraction of large bubbles
f_S	volume fraction of small bubbles
G_s	solid flow rate, $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
g	gravity acceleration, $\text{m}\cdot\text{s}^{-2}$
M	Morton number
N_{break}	energy dissipation rate due to bubble breakage and coalescence per unit mass, $\text{m}^2\cdot\text{s}^{-3}$
N_d	energy dissipation due to collision and friction per unit mass, $\text{m}^2\cdot\text{s}^{-3}$
N_{st}	energy dissipation rate for suspending and transporting particles per unit mass, $\text{m}^2\cdot\text{s}^{-3}$
N_{surf}	energy dissipation rate due to bubble oscillation per unit mass, $\text{m}^2\cdot\text{s}^{-3}$
N_T	total energy dissipation rate per unit mass, $\text{m}^2\cdot\text{s}^{-3}$
N_{turb}	energy dissipation rate in turbulent liquid phase per unit mass,

	$\text{m}^2\cdot\text{s}^{-3}$
n_i	number density of bubbles, m^{-3}
P_b	bubble breakup probability
U_c	superficial gas velocity in dense phase, $\text{m}\cdot\text{s}^{-1}$
U_f	superficial gas velocity in dilute phase, $\text{m}\cdot\text{s}^{-1}$
U_g	superficial gas velocity, $\text{m}\cdot\text{s}^{-1}$
$U_{g,L}$	superficial gas velocity for large bubble phase, $\text{m}\cdot\text{s}^{-1}$
$U_{g,S}$	superficial gas velocity for small bubble phase, $\text{m}\cdot\text{s}^{-1}$
U_l	superficial liquid velocity, $\text{m}\cdot\text{s}^{-1}$
U_p	superficial solid velocity, $\text{m}\cdot\text{s}^{-1}$
U_{pc}	superficial solid velocity in dense phase, $\text{m}\cdot\text{s}^{-1}$
U_{pf}	superficial solid velocity in dilute phase, $\text{m}\cdot\text{s}^{-1}$
U_s	slip velocity, $\text{m}\cdot\text{s}^{-1}$
W_{st}	volume specific energy consumption for suspension and transportation of particles, $\text{W}\cdot\text{m}^{-3}$
β	drag coefficient for a control volume, $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$
ε	local average voidage
λ	character size of eddy, m
μ	viscosity, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$
ρ	density, $\text{kg}\cdot\text{m}^{-3}$
σ	surface tension, $\text{N}\cdot\text{m}^{-1}$
ω	collision frequency, s^{-1}

Subscripts

b	bubble
c	dense phase
f	dilute phase
g	gas
i	interphase
i	represents "S" and "L" for small, and large bubble phase, respectively
L	large bubble phase
l	liquid
min	minimum
mf	minimum fluidization
max	maximum
p	particle
S	small bubble phase

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