Pergamon

Int. Comm. Heat Mass Transfer, Vol. 26, No. 4, pp. 467–475, 1999

0735-1933/99/\$–see front matter

PII S0735-1933(99)00032-9

FLOW REGIME TRANSITION IN BUBBLE COLUMNS

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(Communicated by J.W. Rose and A. Briggs)

ABSTRACT

The various factors influencing the regime transition point in gas-liquid bubble columns are examined. Increasing gas density delays regime transition. This phenomenon is described in a qualitative way by the correlations of Reilly [1] and Wilkinson [2] of which the Reilly correlation is found to be more accurate. However, both correlations are unable to account for the influence of the addition of small quantities of surface tension reducing agents. The Reilly and Wilkinson correlations are also not adequate to describe the influence of the addition of catalyst particles on the transition point for a bubble column slurry reactor.

Flow Regimes and Regime Transitions

If one sparges gas into a column filled with a liquid (see Figure 1 (a)), the bed of liquid begins to expand "homogeneously" and the bed height increases almost linearly with the superficial gas velocity U. This regime of operation of a bubble column is called the *homogeneous bubbly flow regime*. The bubble size distribution is narrow and a roughly uniform bubble size, in the range 2 - 7 mm, is found. As the gas velocity is increased the gas holdup, ε, increases and at a certain gas velocity U_{trans} coalescence of the bubbles takes place to produce the first fast-rising "large" bubble. The appearance of the first large bubble changes the hydrodynamic picture dramatically. The regime of operation for superficial gas velocities exceeding U_{trans} is commonly referred to as *heterogeneous* or *churn-turbulent regime*; this regime is of importance in industrial reactor operation. An analogous picture exists for a gas-solid fluid bed. When a gaseous phase is introduced uniformly through the bottom of a packed bed of particles (see Figure 1 (b)) the bed begins to expand for gas velocities exceeding the minimum fluidization velocity U_{mf}. For fine particles, say smaller than 200 μm, the bed expands uniformly; this is the regime of *homogeneous fluidization*. This regime of homogeneous fluidization prevails till a certain velocity is reached at which bubbles are first observed; the velocity at this point, U_{mb}, is usually called the *minimum bubbling velocity*. For the purposes of drawing analogies with gas liquid systems, we shall denote this velocity as the transition velocity, U_{trans}. The operating gas velocity window between U_{mf} and U_{trans} is usually very narrow and it is usually not possible to operate commercial reactors in a stable manner in this regime. On the other hand in gas-solid beds of large particles, say larger than 1 mm, bubbles appear as soon as the gas velocity exceeds U_{mf} and hence $U_{trans} \approx U_{mf}$. Beyond the gas velocity corresponding to U_{trans}, we have the regime of *heterogeneous fluidization*. In the heterogeneous fluidization regime, a small portion of the entering gas is used to keep the solids in suspension, while the major portion of the gas flows through the reactor in the form of bubbles. Commercial reactors usually operate in the heterogeneous or bubbling fluidization regime at gas velocities U exceeding 0.1 m/s, a few orders of magnitude higher than U_{trans}. Analogous parameters affect the transition point in gas-solid fluid beds and gas-liquid bubble columns.

The prediction of the regime transition point for conditions of high pressure and high solids concentration is one of the key issues in the design and scale up of the bubble column reactors, e.g. for Fischer Tropsch synthesis of hydrocarbons [3]. It is for this reason we test the predictive capability of existing literature correlations.

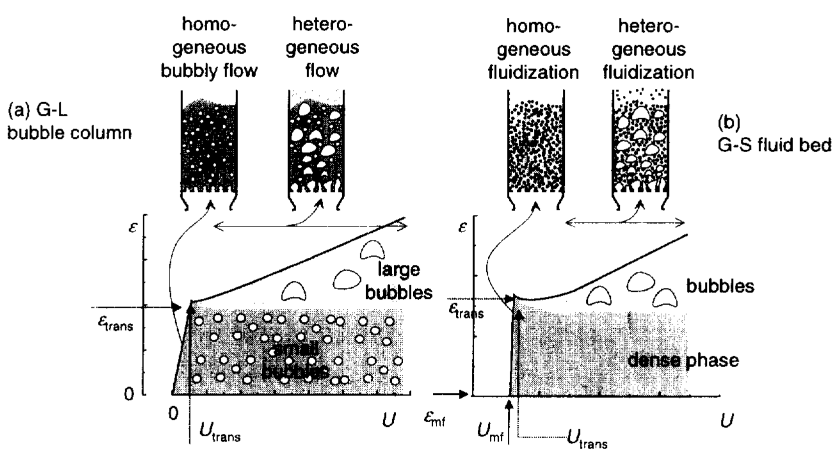

FIG. 1.
Flow regimes and flow regime transitions in (a) bubble columns and (b) fluid beds.

Reilly [1] and Wilkinson [2] Correlations for Regime Transition

In the published literature there are two correlations for estimation of the regime transition point in bubble columns; these have been summarised below.

Reilly et al. [1] Correlation:

The gas holdup at regime transition is $\varepsilon_{\rm trans} = 0.59B^{1.5}\sqrt{\frac{\rho_G^{0.96}}{\rho_L}\sigma^{0.12}}$ where the parameter B = 3.85. The superficial gas velocity at regime transition is $U_{\rm trans} = V_{\rm small}\varepsilon_{\rm trans}(1-\varepsilon_{\rm trans})$ where the "small" bubble rise velocity is $V_{\rm small} = \frac{1}{2.84}\frac{1}{\rho_G^{0.04}}\sigma^{0.12}$.

Wilkinson et al. [2] Correlation:

The gas holdup at regime transition is $\varepsilon_{\rm trans} = 0.5\exp\left(-193\rho_G^{-0.61}\mu_L^{0.5}\sigma^{0.11}\right)$. The superficial gas velocity at regime transition: $U_{\rm trans} = \varepsilon_{\rm trans}V_{\rm small}$ where the "small" bubble rise velocity is $\frac{V_{\rm small}\mu_L}{\sigma} = 2.25\left(\frac{\sigma^3\rho_L}{g\mu_L^4}\right)^{-0.273}\left(\frac{\rho_L}{\rho_G}\right)^{0.03}$.

In Figures 2 (a) and 2 (b) the Reilly and Wilkinson correlations are compared with the experimental data of Letzel et al. [4] obtained in a column of 0.15 m diameter operating with the system air-water. Letzel et al. [4] used chaos techniques for determination of the regime transiton parameters. From Figure 2 it can be concluded that the Reilly correlation provides a resonably good prediction of $\varepsilon_{\rm trans}$ and $U_{\rm trans}$. The Wilkinson correlation tends to underpredict both $\varepsilon_{\rm trans}$ and $U_{\rm trans}$ for all gas densities; see Figure 2 (a).

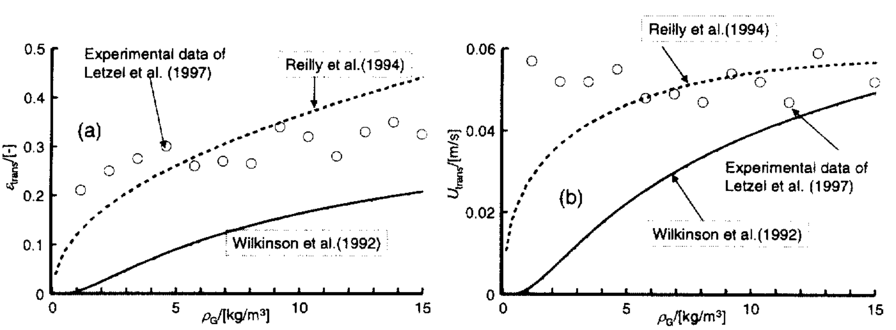

FIG. 2.
Influence of gas density on (a) holdup at transition and (b) gas velocity at transition.

Influence of Surface Tension Reducing Agents

We made gas holdup measurements with the system air-water, water + 0.1% ethanol and water + 1% ethanol in a 0.05 m diameter bubble column fitted with a glass sintered plate with a pore size in the range 20-40 µm. Small additions of alcohol increase the holdup dramatically; see Figure 3 (a). The regime transition points can be determined from a Wallis plot [5] (see Figure 3 (b)).

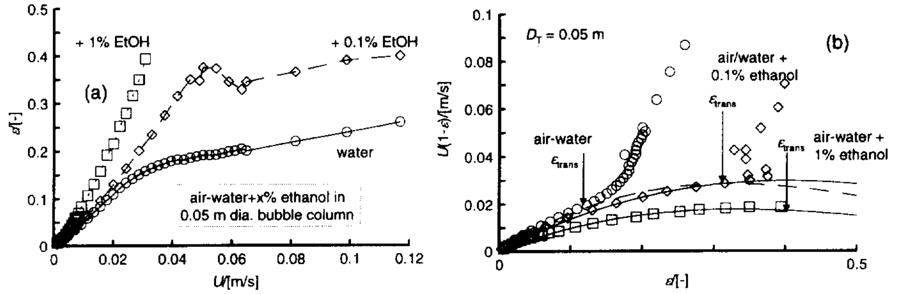

FIG. 3.
(a) Influence of alcohol addition on gas holdup. (b) Wallis plots to show influence of alcohol addition on regime transition

In the Wallis plot the "drift flux", U (1 - ε), is plotted against the gas holdup, ε. The smooth curve in Figure 3 (b) are drawn using the Richardson-Zaki formulation [6], i.e. drift flux $= v_\infty \varepsilon(1-\varepsilon)^n$ where n is the Richardson-Zaki index (with a value about 2) and v_∞ is the rise velocity of a single gas bubble (with a value around 0.23 m/s). The Richardson-Zaki formulation is valid for the homogeneous regime. The point of deviation of the experimental values from the Richardson-Zaki curve is taken to indicate the regime transition point. The Wallis plot shows that addition of 0.1 % ethanol delays the transition holdup ε_{trans} from 0.12 to a value of 0.32 ! Experiments with 1 % ethanol in water show that homogeneous bubbly flow can be made to prevail to the point of flooding without experiencing transition to the heterogeneous flow regime.

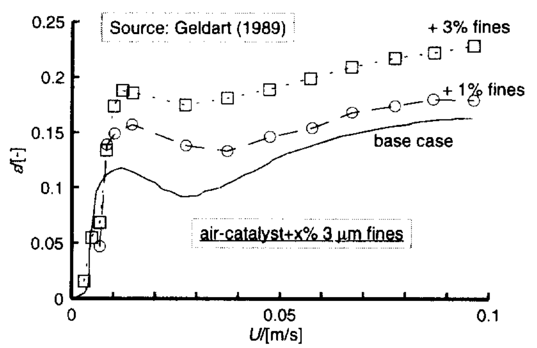

FIG. 4.
Influence of fines addition on bed voidage in gas-solids fluidized beds.

The experiments with varying ethanol concentrations demonstrate the strong influence of surface effects on the bubble coalescence phenomena. It also demonstrates the difficulty of attempting to predict the transition gas velocity and gas holdup to any degree of accuracy in commercial operation; these transition parameters will be very sensitive to surface phenomena. Presence of impurities such as dirt, etc., will also have an effect on the regime transition point. Such effects are not accounted for in the Reilly and Wilkinson correlations. It is noteworthy that an analogous influence exists for gas-solid fluid beds where small quantities of "fines" increase the bed expansions dramatically (Geldart [7]); see Figure 4.

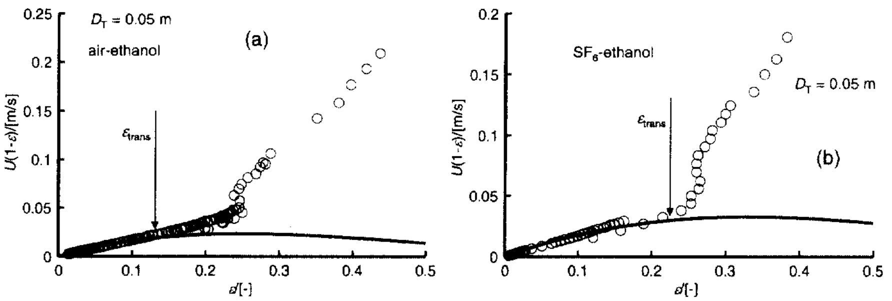

FIG. 5.
(a) Wallis plot for air-ethanol. (b) Wallis plot for SF_6 – ethanol.

Figure 5 (a) is the Wallis plot for measurements with pure ethanol in the 0.05 m diameter column. The gas holdup at transition is determined ε_{trans} to be 0.14. Collecting all the transition data from Figures 3 (b) and 5 (a) we find the values in Table 1.

TABLE 1.

Transition gas holdup data

System	ε_{trans}
Air – water	0.12
Air – water + 0.1% ethanol	0.32
Air – water + 1 % ethanol	0.4
Air – ethanol	0.14

Clearly the bulk liquid properties alone cannot be used to predict the values of the regime transition point. The influence of addition of small amounts of "impurities" has an enormous effect on regime transitions in bubble columns and fluid beds . This effect is not catered for in the available theories for regime transition and regime stability (Batchelor [8]; Biesheuvel and Gorissen [9]; Foscolo and Gibilaro [10]; Hoefsloot and Krishna [11]; Krishna et al. [12]; Lammers and Biesheuvel [13]; Letzel et al. [4]). There is a clear need to develop improved theories to describe the effect of "impurities".

Influence of Bulk Liquid Properties

In order to test the accuracy of the Wilkinson and Reilly correlations for non-aqueous systems we performed measurements of the transition gas velocity with air-ethanol and SF_6-ethanol. The Wallis plots for these two sets of measurements are seen in Fig. 5 (a) and Fig. 5 (b). Switching from air (ρ_G =1.29 kg/m^3) to SF_6 (ρ_G =6.07 kg/m^3) as the gas phase has the effect of shifting the transition from ε_{trans} = 0.14 for air to ε_{trans} = 0.22 for SF_6. The predictions of ε_{trans} and U_{trans} using the Reilly and Wilkinson correlations for the air-ethanol and SF_6 - ethanol are compared with experimental data in Figures 6 (a) and 6 (b). The shift in the regime transition point is adequately predicted by the Reilly correlation. The Wilkinson correlation appears to be less successful in this regard. The Wilkinson correlation significantly underpredicts both the transition gas holdup and the transition gas velocity whereas the Reilly correlation appears to provide reasonable estimates of these parameters. Apparently the influence of increased gas density and bulk liquid properties on the regime transition point are better represented by the Reilly correlation.

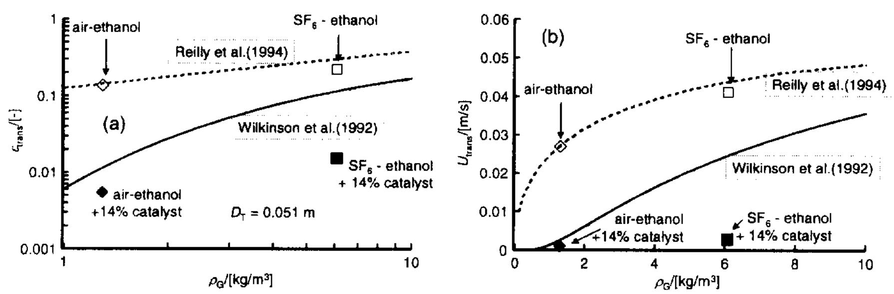

FIG. 6.
(a) Influence of gas density on (a) holdup at regime transition and (b) superficial gas velocity at regime transition. Liquid phase is ethanol. The open points refer to measurements with pure ethanol as the liquid phase. The filled symbols refer to measurements with addition of silica catalyst (14 % by volume).

Influence of Addition of Silica Catalyst Particles to the Liquid Phase

Measurements were also made with the ethanol containing 14 volume % of silica catalyst particles (of mean diameter 40 μm); the gas phase used was both air and SF_6. The transition gas holdup is significantly reduced (see the filled black points in Figure 6 (a)). The significant influence of addition of catalyst particles on the regime transition point is not accounted for in either the Reilly or the Wilkinson correlations, whose estimations are hardly changed when the appropriate slurry viscosity and slurry density are used for estimations of the regime transition points for the 14 % ethanol-slurry system.

Addition of catalyst particles tends to promote the coalescence of bubbles. This enhanced coalescence leads to an earlier regime transition.

Conclusions

In this work we have tested the accuracy of the Reilly and Wilkinson correlations to predict the regime transition for various systems.

Air-water System using the Experimental Data of Letzel et al. (1997) as Basis

- The influence of increased gas density on the regime transition point is correctly predicted, qualitatively, by both the Reilly and Wilkinson correlations.
- The Wilkinson correlation generally tends to underpredict both ε_{trans} and U_{trans}.
- The Reilly correlation provides a reasonably good prediction of ε_{trans} and U_{trans}.

Influence of Addition of Small Amounts of Ethanol to Water in an Air-Water Bubble Column

- Small addition of "impurities" such as surface tension reducing has a pronounced effect on regime transition in bubble columns and fluid beds.
- The strong influence of addition of surface tension reducing agents on the transition point is not accounted for in either the Reilly or Wilkinson correlations.
- There is a need to develop reliable theories to describe the influence of "impurities" on regime stability and transition.

Influence of Bulk Liquid Properties

- Changing the bulk liquid properties has an effect on the regime transition. This effect is adequately taken account of in the Reilly correlation.

Influence of Addition of Catalyst Particles

- Addition of catalyst particles tends to promote regime transition. This effect is due to enhanced coalescence of bubbles.
- The strong influence of addition of catalyst particles to the liquid phase on the transition point is not accounted for in either the Reilly or Wilkinson correlations.

Nomenclature

B	constant in Reilly correlation
g	gravitational acceleration, m s^{-2}
n	Richardson-Zaki index, -

U	superficial gas velocity, m s^{-1}
U_{mb}	superficial velocity at which the first "bubbles" are formed, m s^{-1}
U_{mf}	minimum fluidization velocity (corresponds to U_{trans},), m s^{-1}
U_{trans}	superficial gas velocity at regime transition, m s^{-1}
v_{∞}	rise velocity of "small" bubbles in a swarm, m s^{-1}
V_{small}	rise velocity of "small" bubbles in a swarm, m s^{-1}
ε	total gas voidage of G-S or G-L system
ε_{mf}	voidage of G-S fluidized bed at minimum fluidization conditions
ε_{trans}	gas hold-up at the regime transition point
μ_L	viscosity of liquid phase, Pa s
ρ_G, ρ_L	density of gaseous and liquid phases, kg m^{-3}
σ	surface tension of liquid phase, N m^{-1}

Subscripts

G	referring to gas
L	referring to liquid
mf	referring to minimum fluidization conditions
small	referring to "small" bubbles
trans	referring to the transition point

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Received December 10, 1998