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Influence of elevated pressure on the stability of bubbly flows

H. M. Letzel,*†‡ J. C. Schouten,* C. M. van den Bleek* and R. Krishna†

*Faculty of Chemical Technology, Delft University of Technology, Julianalaan 136, 2628 BL Delft, The Netherlands; †Department of Chemical Engineering, University of Amsterdam, Nieuwe Achtergracht 166, 1018 WV Amsterdam, The Netherlands

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Abstract—The effect of elevated pressure on the stability of the homogeneous bubbly flow regime in a gas–liquid bubble column is examined. Experiments were performed in a 0.15 m diameter bubble column operated at pressures in the range 0.1–1.3 MPa with nitrogen as the gas phase and water as the liquid phase. The transition from homogeneous to heterogeneous flow regime was determined by two procedures. The first procedure involved visual examination of the swarm velocity vs gas velocity curve to determine the transition point. In the second procedure the transient pressure signals were monitored by high-frequency pressure transducers and the instability point determined by analysis of the chaotic features. The two major findings of the work were: (a) increased system pressure reduces the bubble swarm velocity of the homogeneous dispersion, (b) increased system pressure results in a significant increase in the gas holdup at the instability point. The stability theory of Batchelor (1988, *J. Fluid Mech.* **193**, 75–110) and Lammers and Biesheuvel (1996, *J. Fluid Mech.* **328**, 67–93) has been used to provide theoretical support to these observations. © 1997 Elsevier Science Ltd

Keywords: Bubble column; elevated pressure; stability; flow regime transition; pressure sensing; chaos analysis.

INTRODUCTION

Several industrial bubble column reactors are operated at high pressures and it is important to understand its influence on the hydrodynamics and mass transfer. Available experimental data suggest that the influence of increased system pressure is to delay the transition from homogeneous bubbly flow to the heterogeneous churn-turbulent flow regime (Hoefsloot and Krishna, 1993; Krishna *et al.*, 1991, 1994; Reilly *et al.*, 1994; Tarmy *et al.* 1984; Wilkinson, 1991). Correlations of Reilly *et al.* (1994) and Wilkinson (1991) predict a significant increase in gas holdup at the regime transition point with increased system pressure.

Different authors however do not agree on the positions of the transition point at different pressures. Furthermore, it is not yet understood why the regime transition shifts to higher gas fractions with increasing pressure.

The objectives of the present work are: (a) to obtain improved estimations of the regime transition point by analyzing chaotic features of pressure fluctuation signals, and (b) to use the stability theories of Batchelor (1988) and Lammers and Biesheuvel (1996) to provide a theoretical support of the observed pressure effect. We start by a short summary of the stability analysis.

STABILITY THEORY OF BATCHELOR (1988)/ LAMMERS AND BIESHEUVEL (1996)

The theory of Batchelor (1988) and Lammers and Biesheuvel (1996) yields the following criterion for instability in homogeneous bubbly flow:

$$\left[\frac{\mathrm{d}(\phi H U^2)}{\mathrm{d}\phi} + \frac{\gamma(\rho_l - \rho_g)/(\rho_g) g}{U} D\right] < \phi^2 \frac{\rho_l}{\rho_g}\left(\frac{\mathrm{d}U}{\mathrm{d}\phi}\right)\left(\frac{\mathrm{d}CU}{\mathrm{d}\phi}\right). \tag{1}$$

The first term on the left-hand side of eq. (1) arises from a pressure force due to the random movement of the dispersed phase and is negligible in case of gas liquid flow. Bubbles do barely touch each other in the homogeneous regime, and only diffusional effects [second term on the left hand-side of eq. (1)] play a role. Furthermore, the liquid density is usually much

‡Corresponding author. Fax: 00 31 15 2784452. E-mail: letzel@stm.tudelft.nl.

larger than the gas density, so the instability criterion can be written as

$$\frac{\gamma g D}{U} < \phi^2 \left(\frac{\mathrm{d}U}{\mathrm{d}\phi}\right)\left(\frac{\mathrm{d}(CU)}{\mathrm{d}\phi}\right). \quad (2)$$

Drag on a bubble is proportional to bubble velocity to the power γ. Therefore, γ is a constant between 1 and 2. For the diffusivity D, Batchelor (1988) suggests on dimensional grounds

$$D = \alpha a U \quad (3)$$

where a is the bubble diameter and α is an unknown constant. For the system nitrogen–water as used in our work, the bubble diameter is estimated to be 0.004 m. The velocity U is the bubble swarm velocity with respect to the zero volume flux frame. It is related to U_{swarm}, the swarm velocity with respect to the laboratory frame, as follows:

$$U = U_{\text{swarm}} - \phi U_{\text{swarm}} = U_{\text{swarm}}(1 - \phi). \quad (4)$$

Using the Richardson and Zaki (1954) relationship

$$U_{\text{swarm}} = v_\infty (1 - \phi)^n. \quad (5)$$

The first derivative on the right-hand side of eq. (2) can be written:

$$\frac{\mathrm{d}U}{\mathrm{d}\phi} = \frac{\mathrm{d}(v_\infty(1-\phi)^{n+1})}{\mathrm{d}\phi} = -(n+1)v_\infty(1-\phi)^n$$
$$= -(n+1)U_{\text{swarm}}. \quad (6)$$

The added mass coefficient C for a sphere in an infinite medium equals 0.5; this means that the added mass of the bubble should be close to 0.5 times the mass of the displaced fluid. In a gas–liquid dispersion, where the gas density is negligible in comparison with the liquid density, the mass of the displaced dispersion is $(1 - \phi)$ times the mass that would be displaced in a pure liquid. Therefore, it seems a reasonable estimate to take: $C = 0.5(1 - \phi)$. We therefore find

$$\frac{\mathrm{d}CU}{\mathrm{d}\phi} = \frac{\mathrm{d}(0.5 \cdot v_\infty(1-\phi)^{n+2})}{\mathrm{d}\phi}$$
$$= -0.5(n+2)v_\infty(1-\phi)^{n+1}$$
$$= -0.5(n+2)(1-\phi)U_{\text{swarm}}. \quad (7)$$

Combining the above relations we obtain the following working form of the condition of instability defined in terms of an instability parameter N:

$$N = \frac{0.5\phi^2(1-\phi)(n+1)(n+2)U_{\text{swarm}}^2}{\gamma g \alpha a} > 1. \quad (8)$$

To understand the mechanism by which increased gas density stabilizes the flow, the influence of gas density on n, v_∞ and U_{swarm} needs to be known. It will be shown that it is not possible to estimate n and v_∞ unambiguously from the gas fraction data obtained in this work. Equation (8) could, however, be written explicitly in terms of U_{swarm}. In this work, detailed gas fraction measurements were done in a nitrogen–water bubble column in order to determine U_{swarm} accurately, and to find the influence of the gas density on gas fraction and swarm velocity. The gas density could be varied by changing the system pressure of the bubble column. In this way it was possible to obtain detailed data at different gas densities without changing the gas type.

EXPERIMENTAL SETUP

Figure (1) shows the experimental setup. A glass bubble column, 0.15 m in diameter and 1.2 m high, was placed in a steel vessel. The liquid phase was demineralized water. Nitrogen was sparged into the

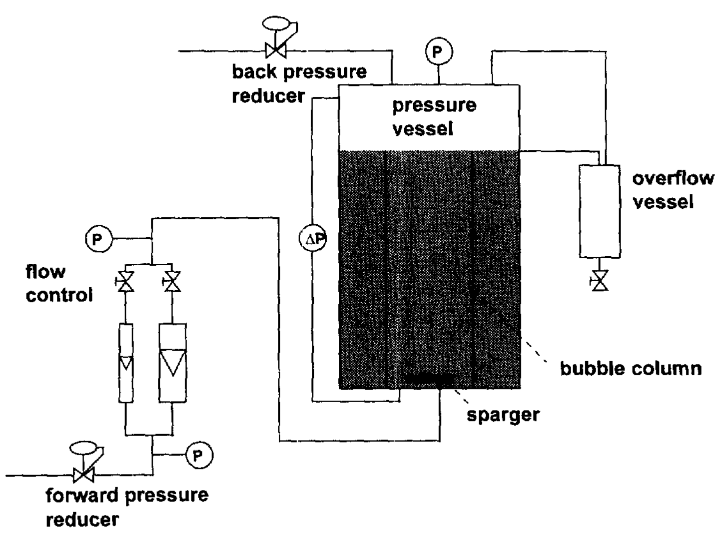

Fig. 1. Experimental setup.

reactor through a 0.1 m diameter perforated plate, with 200 evenly distributed orifices, 0.5 mm in diameter. This ensured equal distribution of the gas over the distributor area. The pressure in the vessel could be regulated with a back-pressure reducer. In the vessel, windows of quartz-glass were placed. By filling the room between the column and the vessel glass with water, visual observation without breaking of the light was possible.

Gas fractions were measured by means of an overflow vessel. Pressure fluctuation signals were measured by means by a Valydine DP15 pressure sensor.

GAS FRACTIONS AND SWARM VELOCITIES

Figure 2 shows gas fraction data measured at different system pressures. A significant influence of system pressure on total gas fraction is observed. The bubble swarm velocity, determined from

$$U_{\text{swarm}} = U_g/\phi \tag{9}$$

has been plotted against the superficial gas velocity in Fig. 3. The minimum in this curve may be taken to represent the transition point. If we plot the bubble swarm velocity at the transition point against the gas density (Fig. 4) we note a strong decrease in U_{swarm} with increasing gas density. None of the published correlations (Reilly *et al.*, 1994; Wilkinson, 1991) predict such a significant decrease in the swarm velocity as found in Fig. 4.

At very low gas velocities ($< 0.01\ \text{m s}^{-1}$) it is impossible to obtain a precise measurement, since here the relative error of the gas flow meters is the largest. Furthermore, one might expect that an error in the holdup measurement has the largest impact at these low values. These arguments might explain that the swarm velocities in Fig. (3) do not converge to the terminal rise velocity in an infinite medium. A slight overestimation of the gas velocity or underestimation of the gas fraction can be the cause of this. The data should be more reliable at velocities above $0.02\ \text{m s}^{-1}$, since the relative errors in both the gas flow and the gas fraction are expected to be much smaller in this case. The realistic values of the swarm velocity at these gas velocities in Figure (3) confirm this.

Figure 5 shows $-\ln(U_g/\phi)$ as a function of $-\ln(1-\phi)$. According to the Richardson and Zaki

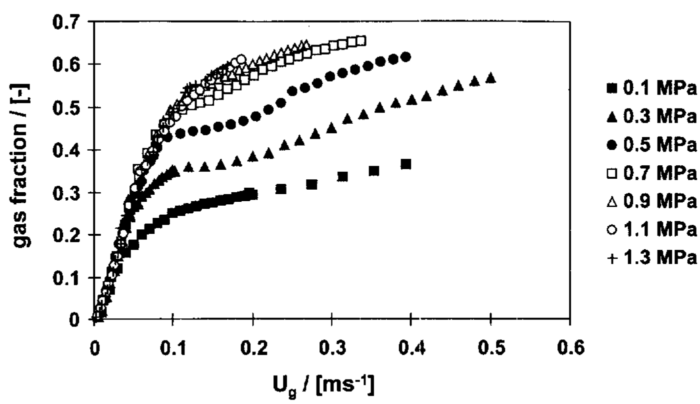

Fig. 2. Gas fraction data as function of superficial gas velocity for different system pressures.

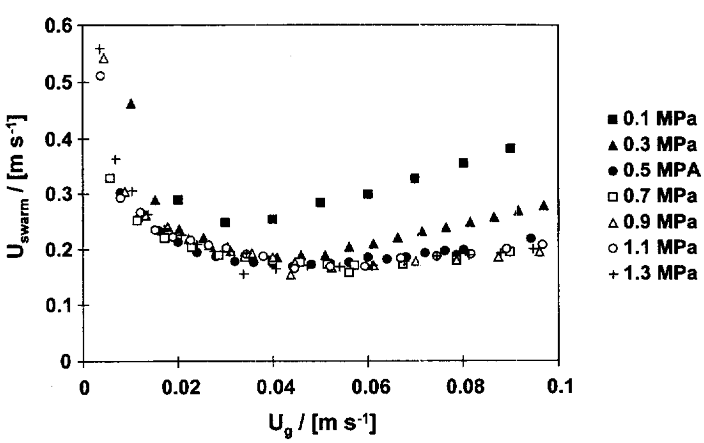

Fig. 3. Swarm velocity as function of superficial gas velocity for different system pressures.

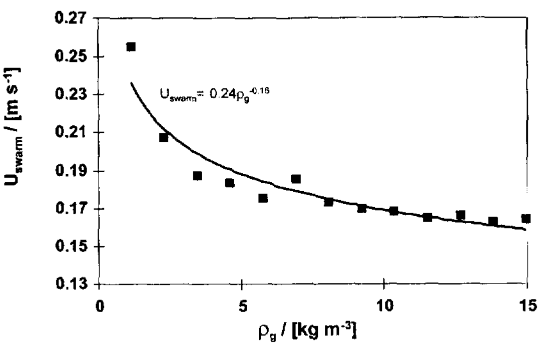

Fig. 4. Minimum values of U_{swarm} as function of gas density.

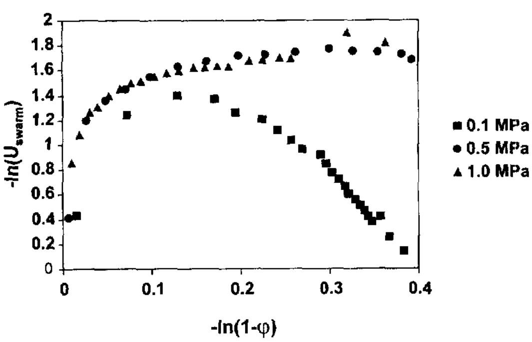

Fig. 5. $-\ln(U_{\mathrm{swarm}})$ as function of $-\ln(1-\varepsilon)$ for different system pressures.

(1954) model, a straight line should be obtained with a slope equal to the Richardson–Zaki exponent. Since the measurement errors are expected to be too large at gas velocities smaller than $0.02\ \mathrm{m\,s^{-1}}$ as was argued above, exact estimation of the Richardson and Zaki exponent is not possible. The fact that the Richardson–Zaki exponent cannot be determined accurately from experiments is not a major issue because in the instability criterion, eq. (8), the proportionality constant α is also not known. We may therefore rewrite eq. (8) in the form

$$N = \frac{0.5\phi^2(1-\phi)U_{\mathrm{swarm}}^2}{\gamma g \beta a} > 1 \qquad (10)$$

where the unknown constant

$$\beta = \alpha/(n+1)(n+2). \qquad (11)$$

The value of β can be chosen to match the experimental values of the instability parameter N.

STABILITY CALCULATIONS

Figure 6 shows the term N as a function of gas fraction, for seven values of the gas density. The unknown constant β was taken equal to 0.0125; γ was taken equal to 2; according to eq. (8), an instability occurs in the flow when N becomes bigger than unity. One can observe that increased gas density has a stabilizing effect on the flow.

The values for ϕ_{ins} can be calculated by assuming for the bubble diameter $a = 0.004$ m. The drawn lines in Fig. 7 show, for three values of β, the *theoretical* values for ϕ_{ins}, using the empirically determined dependence of U_{swarm} on gas density. We see that the gas fraction at instability increases with increasing gas density.

The gas velocity at the instability point, U_{ins}, is simply the swarm velocity times the gas fraction, or

$$U_{\mathrm{ins}} = U_{\mathrm{swarm}}\phi_{\mathrm{ins}}. \qquad (12)$$

The drawn lines in Fig. 8 show the values for U_{ins} calculated according to eq. (12). This Fig. 8 shows that only a very slight increase with gas density is predicted. The reason for this is that the decrease in U_{swarm} with increasing gas density [see Fig. (4)] almost nullifies the increase of ϕ_{ins} with increasing gas density, leaving a small, residual effect.

DETERMINATION OF THE INSTABILITY POINT BY CHAOS ANALYSIS

The determination of the instability point by looking for a minimum in the bubble swarm velocity

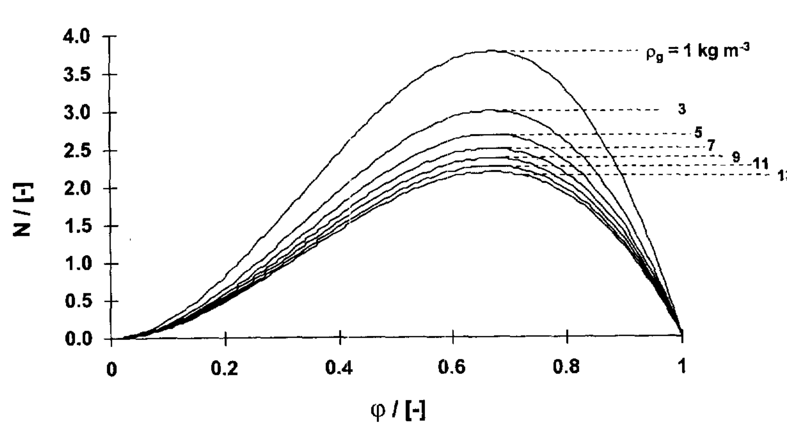

Fig. 6. Stability parameter N as function of gas fraction for different gas densities.

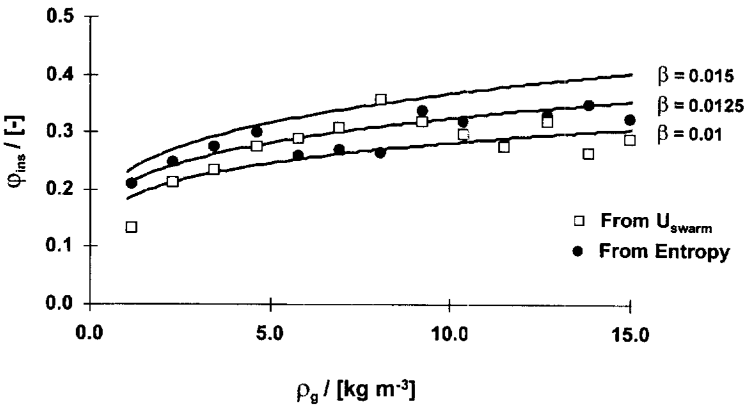

Fig. 7. Theoretical gas fraction at instability as function of gas density compared with experimentally determined values from swarm velocity and entropy plots.

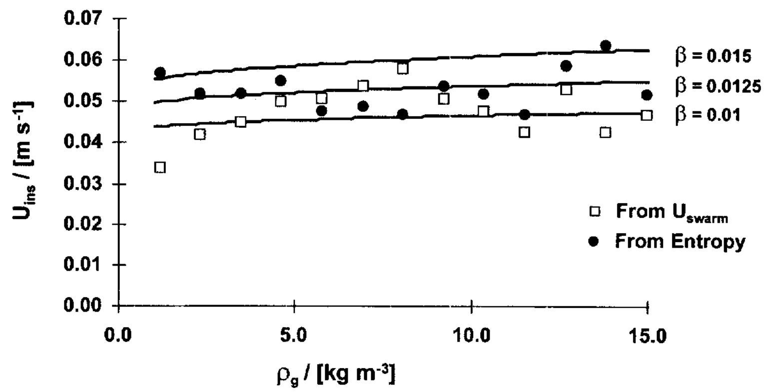

Fig. 8. Theoretical gas velocity at instability as function of gas density compared with experimentally determined values from swarm velocity and entropy plots.

(cf. Fig. 3) is fraught with uncertainty. In order to get a more accurate determination of the flow regimes and the transition points between flow regimes, the hydrodynamics were monitored directly by measuring pressure fluctuations. It was shown by Letzel *et al.* (in press) that chaotic features of pressure fluctuation signals measured in bubble columns change significantly with changing flow regime, giving a powerful tool to analyze hydrodynamics at elevated pressures. The technique of chaos analysis of pressure signals was developed by Van den Bleek and Schouten (1993) to analyze hydrodynamics in gas–solid fluidized beds. Letzel *et al.* (in press) showed that analyzing chaotic features of pressure signals yielded more information about the flow regime in bubble columns than for example the standard deviation of the signal.

Pressure fluctuation series were acquired and processed as described in Letzel *et al.* (in press) to estimate entropy values. A Validyne DP15 differential pressure sensor was used. Figure 9 shows entropy values and gas fractions, measured at several gas velocities, at system pressures of 0.1, 0.5, 0.7 and 0.9 MPa. The typical shape of the entropy profile, that was also encountered in Letzel *et al.* (in press), is observed. At a certain gas velocity, entropy suddenly decreases; at a certain (higher) gas velocity, entropy rises again. It was suggested that the first point, the decrease in entropy, is the point where vortices appear. Swarms of small bubbles move in swirls through the column. The pressure fluctuation signal, that results from passing bubbles and bubble swarms, appears to get more structure compared to the situation where bubbles rise in straight lines; in this situation a more complex signal is measured, possibly because the (small) bubbles in the "stable" regime contribute less to the signal than the vortices in the "unstable" regime do. The increased structure of the signal in the "unstable" regime results in a lower entropy.

From the entropy profiles, the superficial gas velocity at the instability point, U_{ins}, is estimated, as well as the gas fraction at the instability point, ϕ_{ins}. The experimental values obtained in this way are plotted in Figs (7–8).

Both the stability theory and the experiments show that elevated pressure has a small influence on the

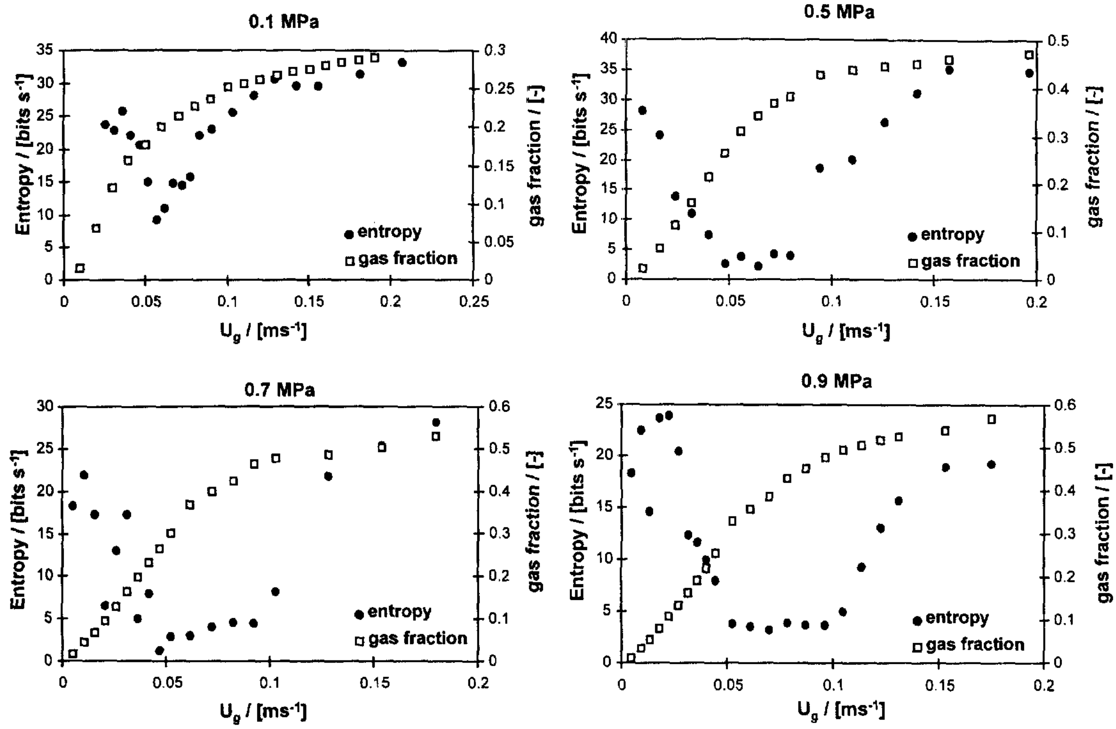

Fig. 9. Kolmogorov entropy estimate, calculated from pressure signal, and gas fraction as function of superficial gas velocity for system pressures of 0.1, 0.5, 0.7 and 0.9 MPa.

superficial gas velocity at instability. Values for gas fractions at instability, ϕ_{ins}, are found to increase with increasing pressure. Both theory and experiments show the same trend. Comparing the change in ϕ_{ins} with the change in total gas fraction at gas velocities above U_{ins}, it becomes clear that the effect of pressure on stability cannot explain the entire effect of elevated pressure. Other mechanisms influencing hydrodynamics at elevated pressure are the subject of further study.

CONCLUDING REMARKS

The influence of increased system pressure on the hydrodynamics of a bubble column has been studied. In particular, the focus in this work has been the determination of the point of instability of the homogeneous bubbly flow regime and transition to the heterogeneous or churn-turbulent flow regime. A novel feature of this work has been the analysis of the chaotic features of the transient pressure signals in order to determine the instability point. The major findings of this study are the following:

(a) The gas fraction at the instability point, ϕ_{ins}, increases with increasing system pressure. This increase can be rationalized on the basis of the stability theory of Batchelor (1988) and Lammers and Biesheuvel (1996).

(b) The velocity of the bubble swarm at the instability point, U_{swarm}, is found to decrease significantly with increasing system pressure. This effect has not been earlier reported in the literature.

(c) The superficial gas velocity at the instability point, U_{ins}, which is the product ϕ_{ins} U_{swarm}, is found to be practically independent of the system pressure.

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NOTATION

a bubble diameter, m
C added mass coefficient, dimensionless
D bubble diffusivity, given by eq. (3), $m^2 s^{-1}$
g gravity acceleration constant, $m s^{-2}$
H a constant of proportionality relating the mean square fluctuation velocity of bubbles to the squared bubble swarm velocity, dimensionless
n Richardson and Zaki exponent, dimensionless
N stability parameter, dimensionless
U bubble swarm velocity relative to zero flux frame, $m s^{-1}$
U_g superficial gas velocity, $m s^{-1}$

U_{swarm} bubble swarm velocity relative to laboratory fixed frame, $m\,s^{-1}$

v_{∞} terminal bubble velocity in infinite medium, $m\,s^{-1}$

Greek letters

α constant of proportionality in the bubble diffusivity relation, eq. (3), dimensionless

β parameter defined by eq. (11), dimensionless

γ exponent in dependence of drag on bubble velocity, dimensionless

ϕ volume fraction of gas phase, dimensionless

μ_l liquid viscosity, Pa s

ρ_g gas density, $kg\,m^{-3}$

ρ_l liquid density, $kg\,m^{-3}$

ϕ_{ins} gas fraction at instability point, dimensionless

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