Chemical Engineering Science 157 (2017) 76–87

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Instabilities due to turbulence through inlet jet in plunging jet bubble column

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HIGHLIGHTS

- Analyzed instabilities occurring in plunging jet bubble column.
- CFD simulations predicted the phase fluctuations.
- Applied stability criteria based on the linear stability analysis.
- Significance of each of the roots that constitute the stability criteria.
- Good agreement with published experimental results.

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form
7 May 2016
Accepted 11 May 2016
Available online 17 May 2016

Keywords:
Bubble column
Regime transition
Instability
Turbulence
Drift flux analysis

ABSTRACT

Bubble columns, where the liquid is in the continuous phase and the gas phase is on the form of dispersed bubbles, are widely utilised in many industrial applications. When designing these bubble columns it is important to be able to predict the conditions that mark the transition from homogeneous (bubbly) to heterogeneous (churn-turbulent) flow. The transition is a function of many variables, including: liquid and gas superficial velocities, bubble diameter, and liquid and gas physical properties. Linear stability analysis (LSA) has been successfully applied by many researchers to determine the gas volume fraction at which the instability takes place; and correspondingly a one dimensional stability factor, f_1, has been proposed (see for example Joshi et al. (2001)). Briefly, the LSA analysis utilises the velocity fluctuations of both the dispersed and continuous phases associated with the specific energy dissipation rate of the two phase mixture. Typically, the specific energy dissipation rate is correlated with the density of the bed. The previous analysis, however, does not consider the energy input which associated with the turbulence intensity (velocity fluctuations) of the incoming liquid stream. Usually, this component can be ignored in sparged bubble columns because its magnitude is relatively small and it also decays in the axial direction. In plunging liquid jet bubble columns the liquid is introduced as a high speed jet that entrains gas which is then broken into fine bubbles in the Mixing Zone. The bubby mixture then passes into the Two Phase Flow Zone where instabilities can be generated. The Mixing Zone is a region of high energy dissipation resulting in relatively large liquid velocity fluctuations, which can directly influence the instability of the Two Phase Flow Zone.

In this study the existing linear stability analysis is modified to include the influence of inlet liquid velocity fluctuations on the stability parameter, f_1. The modified theory is applied to the previous work of Evans (1990) for a plunging liquid jet bubble column to determine the critical gas volume fraction at which transition takes place in the Two Phase Flow Zone. In order to apply the model, drift-flux analysis has been used to obtain bubble diameter as a function of gas and liquid superficial velocities, and computational fluid dynamics has been utilised to quantify the velocity fluctuations of the liquid exiting the Mixing Zone.

1. Introduction

Efficient phase interactions are central to all multiphase reactors, especially for gas–liquid operations carried out in bubble

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http://dx.doi.org/10.1016/j.ces.2016.05.019
0009-2509/

Nomenclature

A	parameter for stability criterion (–)
B	parameter for stability criterion (m/s)
C	parameter for stability criterion (m^2/s^2)
C_{V0}	virtual mass volume coefficient (–)
D	column diameter (m)
$\boldsymbol{D}_G$	gas phase dispersion coefficient (m^2/s)
$\boldsymbol{D}_G$	liquid phase dispersion coefficient (m^2/s)
D_N	jet nozzle diameter (m)
d_B	bubble diameter (m)
F	parameter for stability criterion (1/s)
$\vec{F}_{int.}$	interphase force exchange term (per unit volume) ($kg/m^2\,s^2$)
f_1	stability function defined by Eq. (2) (–)
$(f_1)_D$	stability function denominator ($kg^9/m^{20}\,s^9$)
$(f_1)_N$	stability function numerator ($kg^9/m^{20}\,s^9$)
G	parameter for stability criterion (m/s)
g_z	gravity (has negative sign since acting in downward (negative) z direction) (m/s^2)
k	turbulent kinetic energy (m^2/s^2)
$K_{0,1,2}$	constant used in stability criterion (–)
K_3	parameter used in stability criterion, defined in Eq. (26) (–)
Mo	Morton number $\left(g\mu_L^4\Delta\rho\big/(\rho L^2\sigma^3)\right)$ (–)
L	length (m)
P	pressure ($kg/m\,s^2$)
Re	Reynolds number ($\rho_L V_{B\infty} d_B/\mu_L$) (–)
r_B	bubble radius (m)
t	time (s)
Ta	Tadaki number ($ReMo^{0.23}$) (–)
U_L	liquid superficial velocity (m/s)
u	liquid interstitial velocity (m/s)
u'	liquid fluctuating velocity in the liquid surrounding the bubbles (m/s)
u'_{inlet}	liquid fluctuating velocity of the inlet liquid (m/s)
V_G	gas superficial velocity (m/s)
V_G'	gas drift-flux velocity (m/s)
V_j	jet velocity exiting the nozzle (m/s)
$V_{B\infty}$	gas (bubble) terminal velocity in an infinite liquid (m/s)
V_S	slip velocity ($v-u$) (m/s)
v	gas interstitial velocity (m/s)
v'	gas fluctuating velocity (m/s)
Z	parameter of the stability criterion (m^2/s^2)
z	axial (vertical) position (m)

Greek letters

α, β	fitted parameters in Eq. (35) (–)
Φ_1, Φ_2	fitted parameters in Eq. (37) (–)
ϵ_G	gas (dispersed phase) volume fraction (–)
ε	specific energy dissipation rate (m^2/s^3)
ρ_G	gas (dispersed phase) density (kg/m^3)
ρ_L	liquid (continuous phase) density (kg/m^3)
μ_L	liquid (continuous phase) dynamic viscosity (kg/ms)
σ	liquid surface tension (kg/s^2)

Subscripts

G	gas (dispersed) phase
$inlet$	inlet to Two Phase Flow Zone
L	liquid (continuous) phase
D	denominator
MZ	mixing zone
N	numerator

columns, stirred tanks, etc. Bubble columns are often favoured over other gas–liquid multiphase equipment due to their high efficiency and simplicity of construction. Typically, bubble columns have an upflowing gas phase whilst the liquid phase is either stationary or downflowing. Numerous variations exist, however, depending on the operation being performed. For example, plunging liquid jet bubble columns are used for mineral flotation processes as they produce very fine bubbles and have high gas volume fractions—where both of these characteristics are beneficial for the recovery of the valuable mineral product.

In the plunging jet bubble column the gas and liquid phases enter through the top of the column. The liquid phase is injected through the centre in the form of a jet, which entrains the gas as bubbles. The bubbles travel in a downward direction against gravity due to the drag force exerted by the liquid. Two zones with different flow patterns are generated within the column. The Mixing Zone is at the top of the column where the liquid jet plunges into the fluid below and creates a highly circulating two-phase flow with a high rate of energy dissipation. The Mixing Zone performs two important tasks, namely: (a) entrainment of gas into the liquid, and (b) breakup of larger bubbles into finer bubbles, thus generating the gas–liquid dispersion. The dispersion exits the Mixing Zone and into the Pipe Flow Zone before being discharged from the outlet located at the bottom of the column. As the name implies the Pipe Flow Zone has the typical characteristics of two phase flow inside a pipe, i.e. uniform pressure drop in the axial direction.

The exchange of momentum between the gas and liquid phases in plunging jet column is a complex phenomenon. Bubble columns can operate in either homogeneous or heterogeneous regime. In the homogeneous regime, the gas volume fraction and liquid velocity are deemed to be uniform over the cross-section of the column. Typically, either no or very little bubble breakup or coalescence takes place. In the heterogeneous regime, both the gas volume fraction and velocity profile of the liquid phase become non-uniform and the bubble size usually increases significantly due to coalescence. Heterogeneous flow is associated with higher turbulence and generally provides better heat, mass and momentum transfer rates. Conversely, it can be detrimental to the efficiency of some processes such as flotation due to the disruption of bubble surfaces (interfacial area) onto which the recovered minerals have become attached to. The preference for either homogeneous or heterogeneous regimes will depend on the particular application, and in order to optimise the system it is important to know the operating ranges for each of these regimes and the point at which the transition takes place. For a plunging liquid jet bubble column with a given geometry and liquid jet velocity regime transition is tied closely to the gas superficial velocity. At very low gas superficial velocities the operation regime is almost always homogeneous, whilst at much higher gas superficial velocities the operation regime will be heterogeneous. The homogeneous to heterogeneous regime transition occurs at some gas superficial velocity between these two limits.

The regime transition for the plunging liquid jet bubble column is determined by the balance between stabilising and disturbing forces. In the homogeneous regime the stabilising forces dominate, suppressing the instability caused by perturbations such as