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Bubble generated turbulence and direct numerical simulations ☆

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HIGHLIGHTS

- Bubble generated turbulence.
- Measurement of turbulence characteristics in gas–liquid dispersion.
- Direct numerical simulations of gas–liquid dispersions.
- Turbulence and motion of single and dual bubbles.
- Bubble column reactors: turbulence measurement and DNS simulations.

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ABSTRACT

Gas–liquid two phase flows are widely encountered in industry. The design parameters include two phase pressure drop, mixing and axial mixing in both the phases, effective interfacial area, heat and mass transfer coefficients. Currently, there is a high degree of empiricism in the design process of such reactors owing to the complexity of coupled flow and reaction mechanism. Hence, we focus on synthesizing recent advances in computational and experimental techniques that will enable future designs of such reactors in a more rational manner by exploring a large design space with high-fidelity models (computational fluid dynamics) that are validated with high-fidelity measurements (hot film anemometry (HFA), Laser Doppler anemometry (LDA), particle image velocimetry (PIV), etc.) to provide a high degree of rigor. Understanding the spatial distributions of dispersed phases and their interaction during scale up are key challenges that were traditionally addressed through pilot scale experiments, but now can be addressed through advanced modelling.

For practically complete knowledge of the fluid mechanical parameters, it is desirable to implement direct numerical simulations (DNS). However, the current computational power does not permit full DNS for real bubble columns. Therefore, we have been using simplified turbulence models (such as large eddy simulation, Reynolds stress, k–ε, etc.) which need the knowledge of turbulence parameters. For the estimation of these parameters, currently semi-empirical procedures are being used pending the knowledge of turbulence. Further, the formulation of governing equations in all the CFD models (except DNS), the knowledge of interface forces (drag, lift, virtual mass, Basset, etc.) is needed and for their estimations empirical correlations are being employed, again pending the knowledge of fluid mechanics under turbulent conditions in bubble columns.

Abbreviations: 2D, two dimensional; 3D, three dimensional; BC, bubble column; BCR, bubble column reactor; CFD, computational fluid dynamics; CHA, channel flow; CJR, condensation jet reactor; CTA, constant temperature anemometry; CWT, continuous wavelet transform; DNS, direct numerical simulation; DWT, discrete wavelet transform; EIM, eddy identification methodology; EIM-ZC, EIM based on Zero Crossing; FF, flatness factor; FFT, fast fourier transform; HPIV, holographic PIV; II, intermittency index; JLR, jet loop reactor; LDA, laser doppler anemometry; LDV, laser doppler velocimetry; LES, large eddy simulation; LIM, local intermittency measure; MLSE, multipoint linear stochastic estimate; PF, pipe flow; PIV, particle image velocimetry; POD, proper orthogonal decomposition; PTFE, polytetrafluoroethylene; PTS, principal time scales; RSM, Reynolds stress model; RTD, residence time distribution; SGS, subgrid scale; SL, solid liquid; SRLIM, scale relative local intermittency measure; VL, vapour liquid; VOF, volume of fluid; WT, wavelet transform; WTMM, wavelet transform modulus maxima

☆ This article is based on the inaugural address given by J.B. Joshi at the opening of GLS-9 at Montreal in 2009. The contents, however, have been updated till 2015.

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In gas–liquid dispersions, the gas is sparged in the form of bubbles. During the bubble rise, the mechanism of wake detachment creates turbulence which can be called as wake generated turbulence. In addition, energy gets transferred from the gas phase to liquid phase. The quantitative amounts are negligible when bubble motion is not hindered and the gas–liquid dispersion is homogenous. The amounts increase with an increase in the extent of hindrance. However, in the homogenous regime, even under extreme conditions, the extent of energy transfer in the bulk gas–liquid dispersions (volume other than wake volume) is fairly limited. On contrast, in the heterogeneous regime, the rates of energy transfer become sizeable. The energy received by the liquid (in both the regimes) also creates turbulent motion and termed as bulk generated turbulence. In turbulent flows a compendium of eddies (flow structures) of different length and time scales contribute towards improved/enhanced mixing, momentum transfer, heat transfer, and mass transfer (transport phenomena). Hence, a proper understanding of the dynamics of these turbulent flow structures, and their role in the transport phenomena, can bring substantial improvement in the scale-up and design procedures. The present paper brings out the current status of knowledge on bubble generated turbulence. All the published literature in experimental measurements and DNS simulations has been critically analysed and coherently presented.

1. Introduction

Though bubble columns are widely used for a variety of unit processes and unit operations, the design procedures are still closer to an art than the desired state of science. The design parameters are axial mixing in the gas and liquid phases (D_G, D_L) mass and heat transfer coefficients (k_L, h), gas hold-up (ϵ_G), effective interfacial area ($\underline{a}$), etc. For the estimation of these parameters a large number of empirical correlations are available in the published literature (at least 10 each). However, the predictions from the empirical correlations for any design parameter may vary by even 1000% [figures in Gandhi et al. (2009)]. Such a precarious situation is principally because of the lack of the knowledge of fluid mechanics in multiphase systems. The fluid mechanical parameters include (a) three components of mean velocity and turbulent intensity, (b) turbulent kinetic energy and turbulent energy dissipation rate, (c) eddy diffusivity, (d) nine components of mean and turbulent stress, (e) size, shape , velocity and energy distribution of turbulent structures, (f) energy spectra, etc. The last two decide the surface renewal rates and hence mass (k_L) and heat transfer (h) coefficients.

For the elucidation of fluid mechanics, computational fluid dynamics (CFD) is being used and about 100 papers have been published during the past 25 years for bubble columns. For practically complete knowledge of the fluid mechanical parameters, it is desirable to implement direct numerical simulations (DNS). However, the current computational power does not permit full DNS for real bubble columns. Therefore, we have been using simplified turbulence models (such as large eddy simulation, Reynolds stress, k–ε, etc.) which need the knowledge of turbulence parameters. For the estimation of these parameters, currently semi-empirical procedures are being used pending the knowledge of turbulence. Further, the formulation of governing equations in all the CFD models (except DNS), the knowledge of interface forces (drag, lift, virtual mass, Basset, etc.) is needed and for their estimations empirical correlations are being employed, again pending the knowledge of fluid mechanics under turbulent conditions in bubble columns.

In bubble columns, the most important governing parameter is bubble size and its distribution. For the estimation of this, a framework of population balance is available. However, for the reliable estimation of break-up and coalescence rates, the knowledge of fluid mechanical parameters is again needed in particular the dynamics of turbulent structures.

The forgoing discussion brings out the importance of the knowledge of turbulence in gas–liquid dispersions in bubble columns. In such dispersions, the gas is sparged in the form of bubbles. During the bubble rise, the mechanism of wake detachment creates turbulence which can be called as wake generated turbulence. In addition, energy gets transferred from the gas phase to liquid phase. The quantitative amounts are negligible when bubble motion is not hindered and the gas–liquid dispersion is homogenous. The amounts increase with an increase in the extent of hindrance. However, in the homogenous regime, even under extreme conditions, the extent of energy transfer in the bulk gas–liquid dispersions (volume other than wake volume) is fairly limited. On contrast, in the heterogeneous regime, the rates of energy transfer become sizeable. The energy received by the liquid (in both the regimes) also creates turbulent motion and termed as bulk generated turbulence. In turbulent flows a compendium of eddies (flow structures) of different length and time scales contribute towards improved/enhanced mixing, momentum transfer, heat transfer, and mass transfer (transport phenomena). Hence, a proper understanding of the dynamics of these turbulent flow structures, and their role in the transport phenomena, can bring substantial improvement in the scale-up and design procedures.

The present paper brings out the current status of knowledge on bubble generated turbulence. All the published literature in experimental measurements and DNS simulations has been critically analysed and coherently presented. The second section is concerned with the motion of single/dual bubbles. The third section consists of two parts. The first part describes the experimental efforts (about 40 papers) on the quantitative measurement of turbulence parameters. The second part presents the past efforts on identification and the dynamics (size, velocity and energy distribution) of turbulent structures in bubble columns. These two parts also bring out the current status on (a) meaning of pseudo turbulence in gas–liquid dispersions, (b) characteristic features of turbulence in homogeneous and heterogeneous regimes in terms of homogeneity, isotropy, intensity etc. and their dependence on bubble diameter, column diameter, superficial gas and liquid velocities, their directions of flow and the physical parameters of gas–liquid systems, (c) relationships between turbulence intensity and gas hold-up (d) possible modulation of turbulence by bubbles under some conditions, (e) behaviour of energy spectra in gas–liquid dispersions as compared with single phase flows, (f) dependence between turbulence parameters (length and velocity scales) and eddy viscosity, eddy conductivity, eddy diffusivity, etc. and the respective experimental validation.

The fourth section presents a review of published literature on direct numerical simulations and, as a result, the current understanding of bubble generated turbulence. The fifth section summarises the current status of knowledge and clearly brings out the need for future research work in this area.