Chemical Engineering Science 141 (2016) 46–62

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Budget analysis of the turbulent kinetic energy for bubbly flow in a vertical channel

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HIGHLIGHTS

- Own data sets from DNS of bubbles in turbulent channel flow are analysed.
- Budget of the turbulent kinetic energy for bubbly flows evaluated.
- New data constitute a reference for model evaluation and development.
- Dedicated flow visualizations address the local contribution to the TKE budget.
- Existing closures for interfacial term assessed and an improved variant proposed.

ARTICLE INFO

Article history:
Received 15 July 2015
Received in revised form
25 September 2015
Accepted 4 October 2015
Available online 24 October 2015

Keywords:
Direct Numerical Simulation
Bubbly flow
Vertical channel flow
Turbulent kinetic energy
Budget equation

ABSTRACT

This paper analyses the turbulent kinetic energy budget for bubble swarms in a turbulent channel flow configuration with realistic density difference. The data employed result from Euler–Lagrange Direct Numerical Simulations of vertical turbulent channel flow laden with finite-size bubbles and enable the individual evaluation of each term of the budget equation. Two monodisperse swarms are addressed with the same bubble diameter but with different total void fraction. For the parameter range investigated bubbles enhance the liquid turbulence, and this is quantified in the terms of the budget. The turbulence enhancement is generated by the interfacial term which is balanced by the dissipation term in the core region. In the near-wall region, also the production term and the transport term contribute to the budget in a significant manner. Furthermore, the local turbulence modification induced by the bubbles is investigated by means of the transport equation of the local instantaneous kinetic energy and its contributions. Finally, existing closures for the modelling of the interfacial term are assessed and an improvement of these closures is proposed. The data provided may constitute a reference for model development in the framework of Euler–Euler approaches to bubbly flows.

1. Introduction

Bubbly flows represent a main feature of many industrial and environmental applications as encountered in process engineering, waste-water cleaning, bubble curtains for caustic attenuation, etc. When bubbles are present, they interact with the carrier phase and strongly modify the flow features. If the flow is turbulent two cases can be observed, as reported by Hosokawa and Tomiyama (2010). In the first case, the turbulence level of the fluid decreases with the introduction of bubbles, since they disrupt the turbulent eddies and hamper the energy transfer. This is usually observed for small bubbles of the size of the smallest turbulence length scale. In the second case, fluid turbulence is enhanced due to the dominance of production of vorticity at the phase boundary. The different flow behaviours depend on several factors such as bubble size, background turbulence level, geometry, etc.

The turbulent kinetic energy (TKE) is a pivotal quantity for the analysis of turbulence and of the turbulence modification induced by the bubbles. It provides statistical information and is commonly employed in turbulence modelling, as in the two-phase Euler–Euler approach, where two sets of equations are solved separately for the two phases but coupled by some interface terms. Crowe (2005) provides an overview of the topic of turbulence modelling in two-phase flows.

An analysis of the mechanisms involved in the turbulence modification in bubbly flows can be obtained from the transport equation of the TKE which was proposed by Kataoka (1986) and Kataoka and Serizawa (1989). This formulation is based on a

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http://dx.doi.org/10.1016/j.ces.2015.10.013
0009-2509/

Reynolds-like decomposition of the flow field, i.e. either it implies the existence of averaging directions, such as time for a statistically steady state, homogeneous directions over which averaging is performed, or ensemble averaging. The formulation employs a single-phase flow representation but includes the effects of the bubbles by means of additional terms in the basic equations. The conservation equations of instantaneous and averaged quantities were presented in what may be considered as one of the fundamental studies of two-phase turbulence. In particular, the resulting budget of the TKE allows statistical quantification of the mechanisms involved, hence yielding information about their relative importance in a particular flow considered. Since then, this formulation has gained much attention and has been employed in many studies. In the following, some of these studies are recalled, focusing on those investigating similar configurations as addressed below.

Fujiwara et al. (2004) performed experiments in an upward-directed pipe flow configuration and investigated the influence of bubbles on the fluid turbulence. These authors evaluated the budget terms of the TKE, studying the influence of the total void fraction and the role of surfactants on the TKE budget. Only two terms of the budget equation were reported: the production term which is related to the shear rate of the mean flow and the dissipation term which accounts for the transformation of kinetic energy into thermal energy at the smallest flow scales. These authors found that for the investigated configuration the two terms were not balanced, independently of the bubble size. Hence, additional mechanisms were supposed to play a role in the budget analysis, represented by the interfacial terms which account for the effects of the bubble interface on the liquid phase turbulence. Later on, Shawkat and Ching (2011) investigated a similar configuration. To address the influence of bubbles, these authors proposed a simplified formulation of the budget equation where the quantities not accessible via experimental measurements were approximated with single-phase models. The dissipation was evaluated as the sum of the fluid-related dissipation and the bubble-related dissipation, the latter being negligible in the investigated parameter range. The interfacial terms were modelled with available flow quantities by means of a force balance in the streamwise direction. In this study, the budget analysis reduced to the balance between interfacial term and fluid-related dissipation for the investigated regime. Additional information was provided by the analysis of the TKE spectra, where an increase of the energy was observed for length scales comparable to the bubble diameter. Hosokawa et al. (2012) performed experimental measurements of bubbly flow characteristics in vertical square ducts and evaluated the TKE budget with the measured data. For the investigated regime the production of TKE was compensated in the whole channel by the dissipation, except in the near-wall regions. Due to the lack of appropriate measurement techniques, the pressure-related terms and the interfacial terms were neglected and, as a consequence of the incomplete evaluation, an error of around 20% of the TKE budget was found, computed as the ratio between the residual of the budget and the maximum values of the production and the dissipation terms. The interfacial terms were modelled as the product of the drag force and the relative velocity, as proposed by Morel (1997) and Troshko and Hassan (2001). Additionally, these two terms were compared to the formulations employed in usual Reynolds-Averaged Navier–Stokes Equations (RANSE) of bubbly flows, using the K–ϵ model, for example, to assess whether such models are able to correctly represent the terms evaluated. The models tested were found to be able to capture the general trend but, as stated in this reference, improvements and additional validations are needed to develop trustworthy numerical simulations. Lelouvetel et al. (2011) and Lelouvetel et al. (2014) experimentally investigated the mechanisms determining the TKE modification induced by the bubbles in pipes for both up-flow and down-flow configurations, keeping the bulk Reynolds number and the bubble diameter constant among the two experiments. Strong differences were found between upward and downward flows: Under the same conditions, in the upward case the liquid turbulence was reduced by the presence of the bubbles, while it was increased in the downward case. As in Hosokawa et al. (2012), some terms of the TKE budget were neglected due to the available measurement techniques which did not provide access to all flow quantities. In Lelouvetel et al. (2014), for example, the interfacial term was evaluated as the difference between the production term and the dissipation term using a simplified budget equation consisting solely of production, dissipation and interfacial terms.

This brief overview highlights the efforts of experimental investigations to study the turbulence modification induced by bubbles. Although many issues could be clarified with this approach, experiments have proven delicate for a detailed evaluation of each individual term involved in the budget equation, often relying on models whose validity may be questioned.

Direct Numerical Simulations (DNS) of bubbly flows, on the other hand, provide access to every flow quantity and are hence more appropriate for the evaluation of the terms in the budget equation. To the knowledge of the authors, only the group of Martin Wörner in Karlsruhe, Germany, so far has employed DNS data for the evaluation of the budget terms. The DNS performed by Ilic et al. (2004), Ilic (2006), Wörner and Erdogan (2013), and Erdogan and Wörner (2014) address the rise of bubbles in quiescent fluid with the flow being confined between two vertical walls in a relatively small domain. Bubble-wall collision events were avoided by reducing the body force in the Navier–Stokes Equations (NSE) in the vicinity of the walls. The bubble Reynolds numbers were between 1 and 60, depending on the chosen parameter set, e.g. the Eötvös number. For the simulation with nearly spherical bubbles the mean bubble Reynolds number was around 1. The authors evaluated each term in the TKE budget and were able to determine the relative importance of such terms under different conditions. Additionally, the correctness of the available turbulence models in the framework of the RANSE for bubbly flows was investigated. For this analysis, the agreement between the evaluated terms and the corresponding models was not always satisfactory. The reason may be that such models are developed for highly turbulent flows while in Ilic (2006) the flow exhibits only a very low level of turbulence. Nevertheless, the work presented by Ilic (2006) is, to the knowledge of the authors, the most complete, if not the only, attempt to evaluate the TKE budget in bubbly flows from DNS data.

The motivation for the present analysis is the evaluation of each term of the TKE budget by means of the particle-resolving DNS presented in Santarelli and Fröhlich (2015a), labelled SF15 in the following. Some important differences with respect to the work of Ilic (2006) and the related ones cited above need to be stressed here. First of all, in the cited simulations the rise of bubbles in a quiescent fluid was investigated, while the DNS in SF15 address the dynamics of bubbles in a channel flow with background turbulence. Additionally, a free slip condition at the phase boundary was applied in Ilic (2006), hence addressing bubbles in purified water. In the present work, instead, a no slip condition is employed to simulate the rise of bubbles in contaminated water. In Ilic (2006), the density ratio between the bubbles and the liquid is $\rho_p/\rho = 1/2$ to guarantee the stability of the numerical code employed. Here, instead, the ratio is $\rho_p/\rho = 1/1000$, which is in the real range of air–water mixtures. Furthermore, in Ilic (2006) the mean fluid velocity does not feature any gradient while a mean shear of the carrier phase due to the channel walls is present in SF15. The bubble Reynolds number is much lower in the cited reference than in SF15, around 60