Nucl Eng Technol 47 (2015) 513–522

Available online at www.sciencedirect.com

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journal homepage: http://www.journals.elsevier.com/nuclear-engineering-and-technology/

Invited Article

TURBULENCE MODULATION OF THE UPWARD TURBULENT BUBBLY FLOW IN VERTICAL DUCTS

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ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form
10 April 2015
Accepted 23 April 2015
Available online 9 June 2015

Keywords:
Bubble-induced turbulence
Turbulence interaction
Turbulence modeling
Upward turbulent bubbly flow
Wall-induced turbulence

ABSTRACT

The present paper aims at improving the modeling of turbulence for the upward turbulent bubbly flow through the use of experimental databases that contain data on small and large vertical ducts. First, the role of bubble-induced turbulence was analyzed, which indicated the dominant role of the bubble-induced turbulence in the duct center for relatively high void fraction cases. Therefore, the turbulence therein was mainly focused on, which indicated that the stronger turbulence could be induced by bubbles in large ducts with similar void fractions as compared to that in small ducts. Next, the turbulence of upward turbulent bubbly flow near the wall is discussed to understand the interaction between the wall-induced and bubble-induced turbulence. It showed that the existence of a wall could suppress the bubble-induced turbulence given the same void fraction, and the existence of bubbles could also suppress the solely wall-induced turbulence as compared to the single-phase turbulent flow, even though the total turbulence is enhanced. The above characteristics indicated that the current turbulence modeling method needs to be modified, especially when the bubble-induced turbulence plays a dominant role.

1. Introduction

Upward turbulent bubbly flow (UTBF) plays an important role in the optimum design and the safe operation of nuclear facilities, such as light water reactors. Closure of turbulence is one of the key problems in the modeling of turbulent bubbly flow that could affect the other parameters' predictions such as mean flow, bubble distribution, and also rates for bubble breakup and coalescence. Compared to single-phase turbulent flow, the mechanisms of turbulence generation are more complex in the UTBF, which includes the shear-induced turbulence and bubble-induced turbulence as well as the interactions between these two mechanisms. In order to improve the closure of turbulence in UTBF, understanding and modeling of the turbulence modulation by the bubbles are necessary. Several studies have been carried out by comparing the results of the turbulence characteristics in UTBFs to those observed in single-phase turbulent flows. According to the

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http://dx.doi.org/10.1016/j.net.2015.04.006

experimental measurements of the UTBFs in vertical ducts, the presence of bubbles can lead to both turbulence enhancement and reduction as compared to single-phase turbulent flows [1–13] especially near a wall. However, the physical process of turbulence modulation has not yet been clarified, and the predictions for turbulence enhancement and reduction by the bubbles are still difficult. Lance and Bataille [7] studied bubble-induced pseudo-turbulence in uniform bubbly flow and showed that the bubble-induced pseudo-turbulence could be estimated in the potential theory under the critical void fraction, and above the critical void fraction the turbulence was strongly amplified by the hydrodynamic interactions between the bubbles and the background turbulence. However, the relationship between the bubble-induced turbulence and the void fraction was only focused on a very low void fraction of less than 3%. As for the modeling of turbulence, Theofanous and Sullivan [14] and van Wijngaarden [15] discussed on bubble-induced turbulence by comparing the turbulent intensities prior to and after the bubbles' introduction. van Wijngaarden [15] derived the pseudo-turbulent Reynolds stress for the rising bubbles in the laminar and turbulent flows. Theofanous and Sullivan [14] estimated the total turbulence of the bubbly flow in the pipes based on the mean flow velocity and the wall shear stress. With the eddy viscosity assumption, the turbulent shear stress for the turbulent bubbly flow was modeled by a zero or one equation derived from the single-phase turbulence, where the eddy viscosity and the mixing length were focused on [16,17]. More accurate turbulent models for turbulent bubbly flow have also been developed on the basis of the two-equation model or the Reynolds stress model of the single-phase turbulent flow [18–27]. For example, Kataoka and Serizawa [18] derived the transport equations for the turbulent Reynolds stress and dissipation of the two-phase flow. Lahey et al [20,21] and Lopez de Bertodano et al [22,23] developed the $\tau-\varepsilon$ model for the turbulent bubbly flow. Among these models, the attention was mainly paid to source terms induced by bubbles. However, it is notable that most of the previous numerical validations was carried out for a single model and focused on the small ducts and low void fractions. Brief overviews of the existing models of the bubble-induced turbulence were done by Rzehak and Krepper [28,29]. Moreover, Rzehak and Krepper [28,29] carried out a detailed comparison of the different bubble-induced source terms to qualify their validity after selecting the existing experimental databases in the upward vertical circular pipes, in which the experimental databases in large ducts established by Shawkat et al [12] were also considered. Unlike those in small ducts, the predictions of turbulent kinetic energy in large ducts tend to be smaller than the experimental measurements for cases with higher void fractions. However,due to the lack of experimental databases in large ducts, the question as to whether the above models are suitable for analysis of the UTBF in large ducts still needs further investigation. Moreover, only the turbulence enhancement near the wall could be predicted because of the superposition of the wall-induced and bubble-induced turbulence and by neglecting the interaction between these two mechanisms. To improve the turbulence modeling of the turbulent bubbly flow, it is necessary to study the interaction between the wall-induced and bubble-induced turbulence.

The present study aims at understanding the turbulence modulation in the UTBF in vertical ducts. The paper is arranged as follows: in Section 2, the experimental databases of turbulence for the turbulent bubbly flow is first collected and described; Section 3 presents the analytical results including the comparison of the turbulence in different ducts and the interaction between the wall-induced and bubble-induced turbulence. Their interaction is studied by analyzing the bubble effect on solely wall-induced turbulence and the wall effect on solely bubble-induced turbulence. Here, in the UTBF, solely wall-induced turbulence is defined as the strength of the wall-induced turbulence if there is no effect from the bubbles, and solely bubble-induced turbulence is defined as the strength of the bubble-induced turbulence if there is no effect from the wall. Finally, the improvement of turbulence modeling is discussed. The conclusions are given in Section 4.

2. Experimental databases

As mentioned previously, turbulence generation in UTBFs is very complicated and could be affected by many factors such as void fraction, bubble size and bubble deformation, initial turbulence, and liquid phase velocity. To understand turbulence modulation, such as bubble-induced turbulence and its interaction with the wall-induced turbulence, a large number of experimental databases from various ducts will be necessary. In addition, the experimental databases should also include several flow quantities simultaneously, such as turbulent kinetic energy, void fraction, and bubble size, and satisfy certain requirements. However, it is rather difficult to find enough effective experimental databases to conduct a

Table 1 – Experimental databases and flow conditions in different duct geometries.

Duct shape	Researchers	Duct size D_H (mm)	Flow conditions	Bubble size D_B (mm)
Small circular pipe	Serizawa [1]	60	$J_l = 0.37–1.03$ m/s	3–4.5
	Wang et al [5]	57.15	$J_g = 0–0.321$ m/s	
	Liu and Bankoff [6]	57.2		
	Hibiki and Ishii [9]	50.8		
	Hosokawa and Tomiyama [11]	25		
Large circular pipe	Shawkat et al [12]	200	$J_l = 0.45–0.68$ m/s $J_g = 0–0.18$ m/s	3–5.5
Large square duct	Sun [13]	136	$J_l = 0.5–1.25$ m/s $J_g = 0–0.27$ m/s	3–5