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Enhancement of channel wall vibration due to acoustic excitation of an internal bubbly flow

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Abstract

The effect of an internal turbulent bubbly flow on vibrations of a channel wall is investigated experimentally and theoretically. Our objective is to determine the spectrum and attenuation rate of sound propagating through a bubbly liquid flow in a channel, and connect these features with the vibrations of the channel wall and associated pressure fluctuations. Vibrations of an isolated channel wall and associated wall pressure fluctuations are measured using several accelerometers and pressure transducers at various gas void fractions and characteristic bubble diameters. A waveguide-theory-based model, consisting of a solution to the three-dimensional Helmholtz equation in an infinitely long channel with the effective physical properties of a bubbly liquid is developed to predict the spectral frequencies of the wall vibrations and pressure fluctuations, the corresponding attenuation coefficients and propagation phase speeds. Results show that the presence of bubbles substantially enhances the power spectral density of the channel wall vibrations and wall pressure fluctuations in the 250–1200 Hz range by up to 27 and 26 dB, respectively, and increases their overall rms values by up to 14.1 and 12.7 times, respectively. In the same frequency range, both vibrations and spectral frequencies increase substantially with increasing void fraction and slightly with increasing bubble diameter. Several weaker spectral peaks above that range are also observed. Trends of the frequency and attenuation coefficients of spectral peaks, as well as the phase velocities are well predicted by the model. This agreement confirms that the origin of enhanced vibrations and pressure fluctuations is the excitation of streamwise propagating pressure waves, which are created by the initial acoustic energy generated during bubble formation.

Keywords: Internal bubbly flow; Channel wall vibration; Void fraction; Bubble diameter; Acoustic normal mode; Waveguide theory

1. Introduction

Bubbly-flow-induced pipe vibrations often exist in industrial heat exchangers, such as condensers, evaporators, nuclear steam generators, boilers and reboilers (Pettigrew and Taylor, 1994). Under certain conditions, these vibrations may become excessive, and may cause serious pipe failure by fatigue, fretting wear and cracking, leading to costly maintenance and loss of production. Therefore, measuring and understanding these vibrations has attracted considerable research interest in the past.

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Previous studies of this problem may be divided into two groups: one dealing with flows with vapor bubbles and another with flows with gas bubbles. The studies in the first group are more numerous as the situation here is closer to that of many practical applications. Representative studies are those by Pettigrew and Gorman (1981), Feenstra et al. (1995), Mann and Mayinger (1995) and Nakamura et al. (2002) who introduced tube bundles into steam bubbly cross-flows to approximate the situation encountered in heat exchangers. These experiments are expensive and difficult and require complex experimental facilities. For these reasons, and also in view of their inherent interest, other researchers have studied similar arrangements in which the bubbles consist of an incondensable gas rather than vapor (see, e.g., Gorman, 1971; Joo and Dhir, 1994; Iijima et al., 1995; Uchiyama, 2003; Heilker and Vincent, 1981; Pettigrew et al., 1985, 2001, 2005). The two situations are physically different, although they exhibit some similarities, such as the excitation of pipe vibrations, as shown by Weaver and Fitzpatrick (1988) and Pettigrew et al. (2002). All these investigations, with both vapor and gas bubbles, show that bubbly flows cause a substantial increase in the amplitude of pipe vibrations. Two main mechanisms, as summarized by Weaver et al. (2000), are responsible for the enhanced vibrations. The first is fluidelastic instability, which occurs beyond a critical flow rate, when interactions among individual tubes generate excitation forces on the surrounding tubes. These forces, which vary with the void fraction, reduced velocity and flow pattern, are both proportional to tube displacements and in-phase with tube velocities, leading to great enhancement in the vibration amplitudes. The second mechanism is random turbulence excitation. The resultant excitation force by the presence of bubbles, dependent on flow conditions and void fraction, increases broadband pressure fluctuations near the tubes and consequently tube vibrations.

It is worth mentioning that the previous studies only focused on the channel vibrations caused by external bubbly flow. To the best of our knowledge, channel vibrations induced by internal bubbly flow have never been investigated before. However, according to the Heat Transfer and Fluid Flow Service of Canada (HTFS; Pettigrew and Taylor, 1994), more than half of the process heat exchangers operate in an environment of two-phase bubbly flow, which inherently involves also internal bubbly flows. Thus, it is of engineering significance to investigate the role and contribution of internal bubbly flow on the vibrations as, our group has done in recent years. In a first stage of this research program, the gas bubble case is studied by introducing CO_2 gas bubbles into a channel flow, and examining the channel vibrations. Following two conference papers with preliminary results (Pelletier et al., 2006; Zhang and Katz, 2007), this paper provides both data and analysis of the observed substantial increase in channel wall vibrations and wall pressure fluctuations after introducing bubbles into the flow. We first show that vibration and pressure fluctuation spectra vary with void fraction, characteristic bubble size, and location within the channel. Subsequent analysis then focuses on the observed spectral peaks and their variations along the channel. We show that a mathematical model of sound propagation and attenuation in a bubby medium using waveguide theory, based on earlier work of Commander and Prosperetti (1989) and Lu (1990), predicts and elucidates the observed trends. We start with a description of the test facility and data acquisition procedure in the following section.

2. Experimental set-up and procedures

The experiments have been performed in a closed-loop water channel facility, which was used in previous studies of flow-induced vibrations (Gopalan et al., 2004), and then substantially modified for generating flows with controlled bubble sizes and spatial distributions for the present work. Fig. 1(a) shows a schematic of the facility. The water is driven by two 11 kW centrifugal pumps, located in the basement below the facility to prevent any pump cavitation issues, and connected to the facility by flexible hoses. Three strategies are implemented to isolate the test channel from external excitations. First, the settling chamber is mounted on vibration-isolated supports, and the test channel is supported by vibration-isolated padding. Second, long flexible hoses with varying lengths are used for connecting components of the test loop to reduce the effect of pump-induced vibrations or other facility resonances on the channel flow. Third, water is introduced into the settling chamber (see, Fig. 1(a)), through perforated plates covering three of the chamber's walls, while the remaining wall has a port through which the bubble injector is inserted. By doing so, the primary extraneous unsteady loading, namely the signatures of non-uniformities generated by upstream pipe flows and pumps are greatly reduced. The channel is also supported by a heavy structure that does not vibrate at any meaningful level when there is flow, with or without bubbles, in the facility. The bubbles are introduced in the settling chamber, and the bubbly water passes through a honeycomb and a streamlined nozzle before entering a 0.15 m × 0.15 m cross-section, 2 m long channel. Suction of the boundary layer on the channel wall, followed by tripping using a series of grooves, reduces the effects of upstream disturbances, and generates a classical, fully turbulent boundary layer profile (Gopalan et al., 2004). The test channel is aligned vertically to prevent gravity-induced streamwise variations in bubble distribution. It is essential to remove and reintroduce bubbles continuously so that their size and spatial distribution can