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Development of models correlating vibration excitation forces to dynamic characteristics of two-phase flow in a tube bundle

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ABSTRACT

Recent experiments revealed significant quasi-periodic forces in both the drag and lift directions in a rotated triangular tube bundle subjected to two-phase cross-flow. The quasi-periodic drag forces were found to be related to the momentum flux fluctuations in the main flow path between the cylinders. The quasi-periodic lift forces, on the other hand, are mostly correlated to the oscillation in the wake of the cylinders. In this paper, we develop semi-analytical models for correlating vibration excitation forces to dynamic characteristics of two-phase flow in a rotated triangular tube bundle for a better understanding of the nature of vibration excitation forces. The relationships between the lift or drag forces and the dynamic characteristics of two-phase flow are established through fluid mechanics momentum equations. A model has been developed to correlate the void fraction fluctuation in the main flow path and the dynamic drag forces. A second model has been developed for correlating the oscillation in the wake of the cylinders and the dynamic lift forces. Although still preliminary, each model can predict the corresponding forces relatively well.

1. Introduction

Two-phase cross-flow exists in many shell-and-tube heat exchangers, for instance, in the U-tube region of nuclear steam generators. Flow-induced vibration excitation forces can cause excessive vibration that may result in long-term fretting-wear or fatigue. To prevent such tube failures in heat exchangers, designers and troubleshooters must have guidelines that incorporate flow-induced vibration excitation forces.

In single-phase flow, these forces have been extensively measured and analyzed. They are related to periodic wake shedding and to turbulence generated within the bundle. Experimental data obtained for different kinds of fluids and tube bundles have been satisfactorily compared through the use of adequate data-reduction procedures (Axisa et al., 1990; Blevins, 1991).

In the case of two-phase flows, such extensive studies have not been undertaken, though it is known that there are significant differences between single- and two-phase flows. In particular, the relationship between the two phases must be considered in addition to another parameter which is the void fraction. This results in different flow regimes or patterns of two-phase flow. A few sets of experimental results have been obtained recently, e.g., Axisa et al. (1990), Pettigrew and Taylor (1994), Pettigrew et al. (2005), Nakamura et al. (1995), and Zhang et al. (2006, 2007, 2008). However many questions remain such as the effects of viscosity, surface tension, density ratio and flow regimes. Indeed the main problem is the understanding of the physical mechanism that induces these forces. Detailed flow and vibration excitation force measurements in tube bundles subjected to two-phase cross-flow are required to understand the underlying vibration excitation mechanisms. Some of this work has already been done by Pettigrew et al. (2005) and Zhang et al. (2006, 2007, 2008). The distributions of both void fraction and bubble velocity in rotated triangular tube bundles were obtained (Pettigrew et al., 2005). Significant quasi-periodic forces in both the drag and lift directions were measured (Zhang et al., 2007). The quasi-periodic drag forces appear to be related to the momentum flux fluctuations in the main flow path between the cylinders. The quasi-periodic lift forces, on the other hand, are mostly correlated to the oscillation in the cylinder wakes (Zhang et al., 2008).

The objective of this work is to develop semi-analytical models for correlating these vibration excitation forces to dynamic characteristics of two-phase flow in a rotated triangular tube bundle and understanding the nature of vibration excitation forces. The relationships between the lift or drag forces and the dynamic characteristics of two-phase flow are established through fluid mechanics momentum equations. A model has been developed to correlate the void fraction fluctuation in the main flow path and the dynamic drag forces. A second model has been developed for correlating the oscillation in the wake of the cylinders and the dynamic lift forces.

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2. Experiment

2.1. Experimental set-up

The experiments were done in an air–water loop to simulate two-phase flows. The loop comprised a 25 L/s variable speed pump, a magnetic flow meter, a 2500 L tank, a 250 L/s compressed air supply system and connecting piping as shown in Fig. 1. The water flow was measured via the magnetic flow meter with an overall accuracy of ±0.5% of the reading. The compressed air was injected below a suitably designed mixer to homogenize and distribute the two-phase mixture uniformly below the test-section. The air flow was measured with orifice plates connected to a differential pressure transducer and electronic readout system. The possible measurement error of the orifice plate system is ±1.5% of the nominal value. The loop was operated at room temperature and the pressure in the test-section was slightly above atmospheric.

The test-section, which has essentially a rectangular cross-section (99 × 191 mm), is shown in Fig. 2. It consists of a column of six 38-mm diameter cylinders flanked on either side by half cylinders to simulate essentially the flow path in a large array of cylinders in a rotated triangular configuration. The pitch-to-diameter ratio, P/D, was 1.5 resulting in an inter-cylinder gap of 19 mm which allowed sufficient space for detailed flow measurements. The test-section length-to-gap width ratio is 10, thus, adequate to maintain essentially two-dimensional flow. The measurements were taken at several positions with fiber-optic probes assembled within a traversing mechanism. The tip of the probes could be positioned accurately with a micrometer head.

The probe assemblies were installed at four principal positions in the array as shown in Fig. 2. These positions are henceforth called lower and upper 60° (L60° and U60°) for the narrow gaps between cylinders and lower and upper 90° (L90° and U90°) for the larger flow areas between upstream and downstream cylinders. One cylinder was instrumented with strain gauges to measure the dynamic drag and lift forces due to the two-phase flow.

Each fiber-optic probe has a conical tip and is made of an optical fiber of 170-μm diameter. It acts as a fluid phase sensor based on the different level of light reflection between air and water (Fig. 3). Four probes were used to measure simultaneously the dynamic characteristics of two-phase flow surrounding the instrumented cylinder. Several different probe locations as shown in Fig. 4 were selected for two-phase flow measurements, i.e., LLLL, CCCC, RRRR, etc. Here L, C and R represent the left, center and right positions of probe L60°, L90°, U60° and U90° in the main flow path, respectively. Additionally L_0 is a point on the centerline of the test-section at the U90° probe position. L_1 is about 5 mm from L_0.

Both the dynamic lift and drag forces were measured with a strain gage instrumented cylinder located in the fifth position from the upstream end of the test-section (Fig. 2). The instrumented cyl-

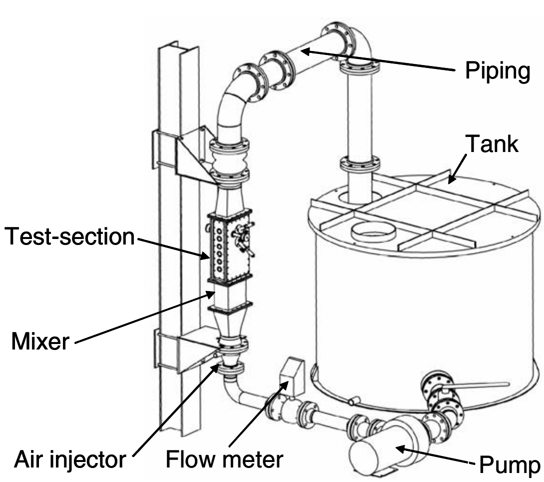

Fig. 1. Test loop.

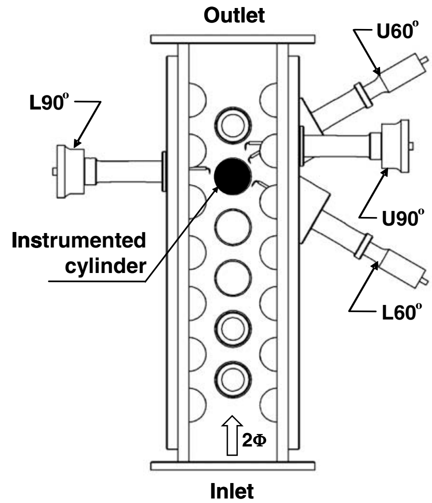

Fig. 2. Test-section.

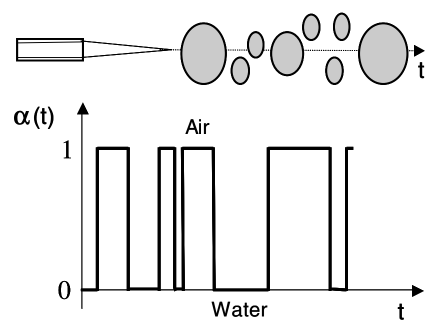

Fig. 3. Ideal two-phase flow signal.

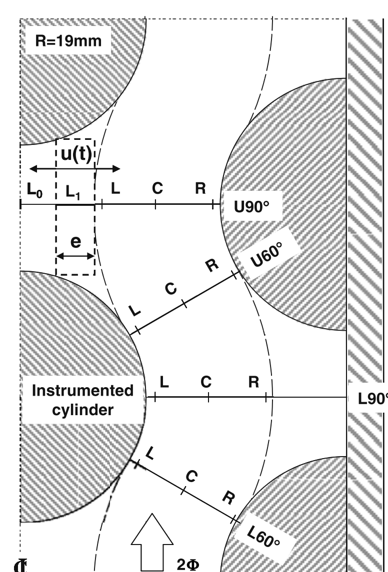

Fig. 4. The main flow path and probe positions for flow measurements.