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Experimental study of internal two-phase flow induced fluctuating force on a 90° elbow

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ABSTRACT

Experiments were performed with a 52.5 mm I.D., 90° elbow to study the internal two-phase flow induced fluctuating forces on pipe bends. The dynamic force signals were obtained directly from force sensors by separating the natural frequency of test section from the predominant frequency of excitation forces. A total of 36 tests were carried out to cover bubbly, slug, churn and annular flows. The results showed that for a fixed liquid flow rate, the predominant frequency of force peaked at slug flow regime. The root mean square value of force fluctuations continuously increased with gas flow rate and reached its maximum in annular flow regime. The excitation force presented a strong dependence on the momentum flux of two-phase flows. The integral of local pressure measurements could predict the time averaged momentum flux change reasonably well. However, the root mean square values of fluctuating forces were quite different due to the additional effect caused by the impact of liquid slugs on the elbow. The impact force, which has not been emphasized in the literature for the internal two-phase flow induced vibration analysis, is found to be significant in determining the force fluctuations in the slug flow regime. A two-phase flow induced excitation force model was developed based on the local instant formulation of two-fluid model. Analyses showed that the high frequency fluctuating components of centrifugal forces could be damped by the integral effect of the elbow.

1. Introduction

Internal two-phase flow induced vibration on piping elements has been given increasing attention in recent years (Urthaler et al., 2011; Pontaza and Menon, 2011; Cargnelutti et al., 2010; Riverin and Pettigrew, 2007), due to its importance in many industrial applications especially in nuclear power generation and petroleum production and transportation. The two-phase flow is intrinsically unstable in terms of local fluctuations of phase, density, velocity, pressure, and momentum flux among other hydrodynamic parameters. These fluctuations in turn may impose periodic forces on the piping elements which convey the fluids, such as elbows and tees. Resonance may happen when the frequency of the excitation force is close to piping natural frequency. This can deteriorate the performance of designed system and even damage the structural integrity in certain circumstances. Therefore, understanding two-phase internal flow induced vibration mechanism is indispensable for safe design and operation of piping system in the related industries.

The pioneering work of momentum flux fluctuation in two-phase flow was done by Yih and Griffith (1968). They measured the response of a beam structure under the impact of the two-phase upflow coming out of vertical ducts. The momentum flux fluctuation was then obtained by taking the inverse transform of the beam response. The tests covered a wide range of velocities (15–75 m/s), volumetric qualities (50–100%), and pipe inner diameters (I.D. 6.35 mm, 15.9 mm and 25.4 mm). Their results showed that the maximum momentum fluctuation appears in either high void slug or low void annular flow regime for a given total volumetric flow rate. The unsteadiness of momentum fluxes in small pipes was found to be enhanced compared to large pipes. The authors attributed this trend to the better mixing of two-phases in large pipes. They also found that the system pressure, duct size and shape did not have significant effect on the predominant fluctuation frequencies, which were generally less than 30 Hz in their tests.

In order to study the two-phase slug flow induced forces acting on pipe bends, Tay and Thorpe (2004) performed experiment on a 90° horizontal elbow with 70 mm I.D. and 105 mm elbow radius. Their major concern was the effect of liquid viscosity and surface tension on the maximum forces acting on the elbows in oil pipelines, where these two physical properties

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vary under different conditions. Isopropanol and glycerol solutions were used to alter liquid viscosity and surface tension up to -32% and $+162\%$, respectively, compared to those in air–water flows. Their experimental data showed that there was no significant effect on the maximum forces with the change of either property. The authors also compared the data with their "piston flow model" developed for slug flows. The model could predict the maximum force acting on the elbow with reasonable accuracy.

Riverin and Pettigrew (2007) preformed experiments to study the vibration of U-shaped piping elements under internal two-phase flow excitations. They used 20.6 mm I.D. PVC piping with non-dimensional bending radius, R/d, ranging from 0.5 to 7.2. Severe in-plane vibrations were observed which were caused by resonance due to the similar frequency range of excitation force and piping natural frequency. The root mean square (RMS) value and predominant frequency of measured force fluctuation increased with velocity for a constant volumetric quality. Given a fixed velocity, the RMS peaked at 50–60% volumetric quality range which fell into churn flow regime. These results seemed to be consistent with Yih and Griffith's (1968) study even though tests were performed in different ways. Riverin et al. (2006) carried out additional experiments on PVC tees with the same I.D. (20.6 mm). They correlated the available RMS force data using Weber number and obtained good agreement for a wide range of geometric and hydrodynamic conditions.

Zhang et al. (2008) studied the drag and lift forces of a 3×6 triangular rod bundle subjected to two-phase cross flows. They simulated the flow channel with the combination of a series of 60° elbows connected to each other. By integrating the one-dimensional momentum equation along the elbow, the force fluctuations were obtained as a function of void fraction. Their experimental results and modeling attempt showed that the quasi-periodic drag forces were mainly caused by two-phase momentum flux fluctuations.

A recent study on this topic was reported by Cargnelutti et al. (2009). They performed air–water experiments on 6 mm I.D. elbows with 16.2 mm and 25 mm radii. The highest force level was found in the slug flow regime which was similar to the other experiments preformed in much larger pipes. However, the obtained data could not be correlated by Weber number alone. Cargnelutti et al. (2010) further performed similar studies using 25.4 mm elbows and tees in a horizontal configuration. Their data showed that the force fluctuating amplitude in the annular flow regime was as high as that in the slug flow regime, both being several orders of magnitude higher than the single phase flows with similar velocities. Their results from three different elbows showed that the elbow radius did not play an important role in the two-phase flow induced excitation force. However, the tee showed significantly lower force as compared to the elbows.

In spite of the aforementioned progresses, the phenomenon has not been thoroughly understood because of the complicated two-phase flow behavior and limited number of experiments. Most of the previous experiments were conducted with considerable vibration of piping elements. Even though this is beneficial to study the flow and structure interactions, the two-phase flow induced forces may not be accurately extracted due to overlapping with the natural frequency of piping structure. In industrial applications, the natural frequencies of piping structures vary greatly with their material, size, support method and other factors. It is not practical to perform experiments to cover the entire ranges of these parameters. On the other hand, the vibration of ducts may also influence the two-phase flow structures (Hibiki and Ishii, 1998). Therefore, it is essential to minimize the structure vibration to understand the fundamental mechanisms of two-phase flow induced fluctuating force.

The available data on the void fraction fluctuations were obtained using either local point (optical probe by Riverin and Pettigrew, 2007; Zhang et al., 2008; Cargnelutti, et al., 2009), or line averaged (parallel-wire probe by Tay and Thorpe, 2004) measurement techniques. The information from these measurements may not be enough to develop a model based on area-averaged one-dimensional parameters, such as superficial gas and liquid velocities. In order to understand the forces imposed by fluids, it is important to know the detailed local pressure distribution around the piping element. Such experiment has been conducted in single phase flows (Nakamura et al., 2005). However, it is not seen for two-phase flows.

In view of the above, experimental study on the two-phase flow induced fluctuating force on a 90° elbow was conducted in this research. The structural response was minimized by separating the piping natural frequency from the excitation force frequency. Thus, the scope of the current study is focused on the force itself without involving the flow induced vibration phenomenon. The force and related flow parameters such as volumetric fluxes, void fraction fluctuation and local pressure distribution around the elbow were obtained to provide useful database for model development and engineering design needs. An excitation force model was developed from the local instant formulation of two-fluid model and control volume analysis. Important terms which caused the fluid force and fluctuations were identified in the newly developed model. An important effect which has not been emphasized in the literature, namely, the impact force due to the liquid slugs on the elbow was found to have considerable contribution to the force fluctuations.

2. Experimental facility and instrumentation

The flow induced vibration phenomenon usually involves the following three engineering aspects: (1) two-phase flow characteristics, such as mean and fluctuating behaviors of void fraction, phase velocity, momentum flux and pressure, etc. (2) Excitation force acting on the structure which also defines the boundary pressure and shear conditions for the fluid. (3) Response of the structure which is subjected to both static and dynamic fluid induced forces. The second aspect acts as a bridge to connect two-phase flow and structural vibration problems. As mentioned in the previous section, the objective of this study is to investigate the fundamental mechanisms of two-phase flow induced fluctuation forces. The response of the structure was decoupled from the current study. With this in mind, experimental facility and instrumentation were designed to focus on the first two aspects. More specifically, two-phase flow characteristics were measured by using gas and liquid flow meters, impedance void meters, and pressure transmitters. The excitation forces were measured by pressure transmitters and force sensors. The details of the test facility and instrumentation are given in the following.

2.1. Test loop

The schematic of the test loop is shown in Fig. 1. It was designed to operate adiabatic air–water two-phase flows at room temperature and atmospheric pressure condition. The air flow is supplied from a 14.4 m^3 compressed air tank which was maintained at 10 bar by an air compressor. The volumetric flux of air flow was measured by Venturi meter and rotameter, for high ($>0.55\ m^3/min$) and low ($<0.55\ m^3/min$) flow rates, respectively. A 1.5 m^3 stainless steel tank was used for water storage and two-phase separation. The water flow was divided into primary and secondary lines after passing through a 75 hp centrifugal pump and a magnetic flowmeter (Honeywell MagneW 3000). The secondary water flow was used to shear off the air bubbles generated on the porous metal surface in the two-phase