FLOW PATTERN RECOGNITION AND DYNAMIC CHARACTERISTICS OF TWO-PHASE CROSS FLOW IN STEAM GENERATOR TUBE BUNDLES

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Abstract

The U-tube region in steam generators is prone to excessive vibration due to two-phase cross flow. Two-phase flow-induced vibrations depend not only on the velocity of the flow but also strongly on void fraction and flow pattern. Thus, it is necessary to understand the dynamic characteristics of two-phase flow and to be able to predict flow patterns. Currently a limited amount of data on flow patterns and void fraction exists due to the complexity of the flow and the difficulties in taking useful measurements.
A research program was undertaken to help this understanding. The program involves the development of fiber optic probes and capacitance sensors to measure the detailed characteristics of the flow such as local void fraction, gas flow velocity, void size and void passage frequency. The measurement of these characteristics provides the necessary information to define and identify objectively two-phase flow patterns.
The measurement of void fraction is a useful technique to identify flow patterns. This paper describes the development of capacitance sensors to measure two-phase cross flow void fraction in a tube bundle.

INTRODUCTION

Several researchers [1, 2, 3, 4] have shown the strong relationship between flow-induced vibration and two-phase flow patterns. Pettigrew et al. [4] deduced the power spectral density of turbulence excitation forces from tube response at its resonant frequency. Figure 1 shows the relationship between vibration and flow pattern. The turbulence-induced vibration excitation forces are much stronger for bubbly-plug flow than for churn flow.

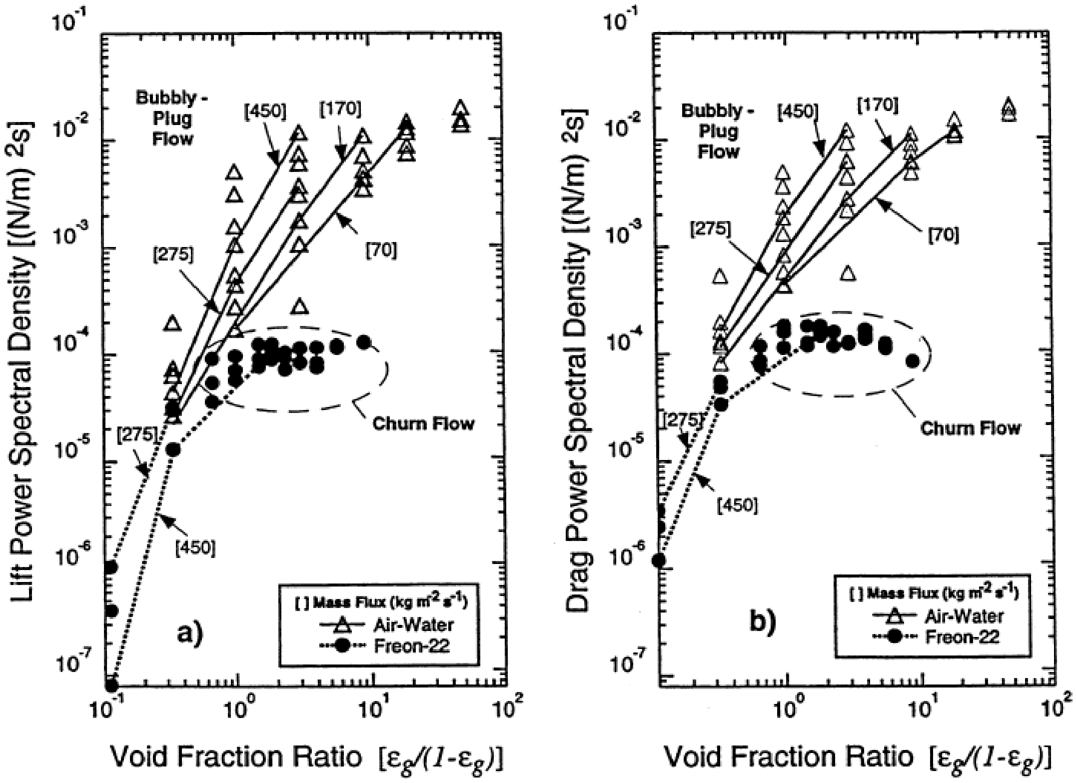

Figure 1: Spectral density of random excitation induced by turbulence (Freon 22 vs. air-water) left: lift direction; Right: drag direction [4].

To develop a model to predict two-phase flow-induced vibration, it is essential to understand the flow patterns and to develop a reliable method to classify them. Flow patterns are reasonably well understood for two-phase internal flow. Flow pattern maps supported by both theory and empirical correlations may be found in [5].

TWO-PHASE CROSS FLOW REGIME

Much less work has been done to understand and classify two-phase cross flow patterns. Grant et al. [6] conducted the first study on two-phase cross flow pattern. A few other studies as described in [7, 8, 9, 10, 11] followed.
Most of the authors distinguish three flow patterns: bubbly flow, slug or intermittent flow, and annular flow as illustrated in figure 2.

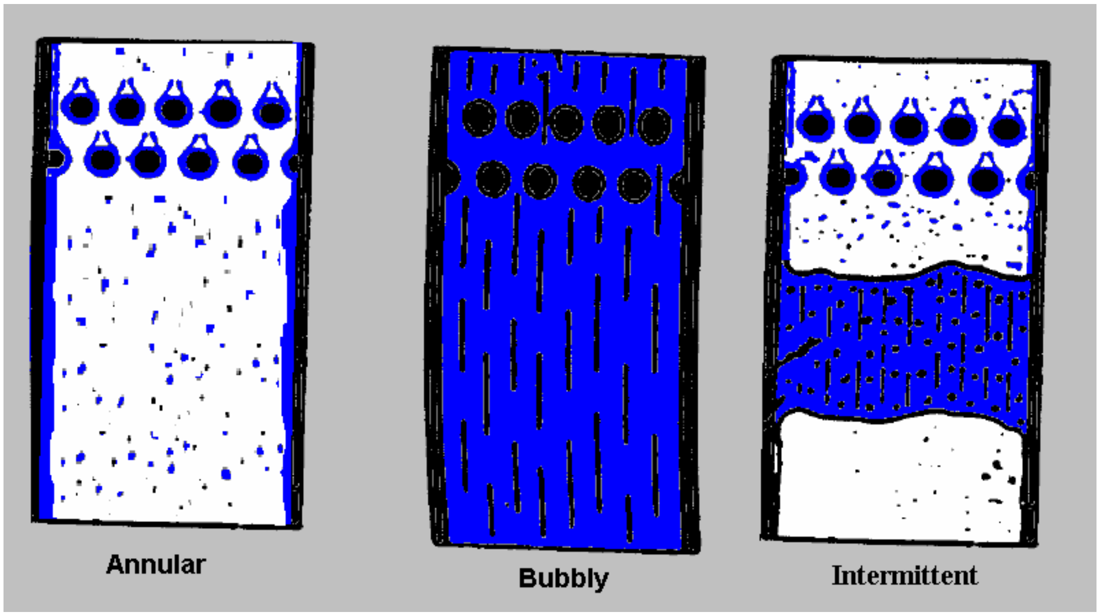

Figure 2: Flow pattern in two-phase cross flow proposed by Grant et al. [6]

These flow patterns have been chosen by analogy to internal flow patterns. Some authors have used visual observation [6, 10, 12], others local measurement of void fraction [7, 9, 11]. Ulbrich and Mewes [10] used pressure drop and visual observation while Pettigrew et al. [12] used flow-induced vibration to deduce the flow patterns. Ulbrich and Mewes, Noghrekar et al. and Pettigrew et al. [10, 11, 12] have also proposed flow patterns maps.

Pettigrew et al. developed their map using Grant's data. The Martinelli parameter and dimensionless gas velocity were chosen as coordinates. This map (Figure 3) is used to correlate flow-induced vibration response and two-phase flow patterns in tube bundles.

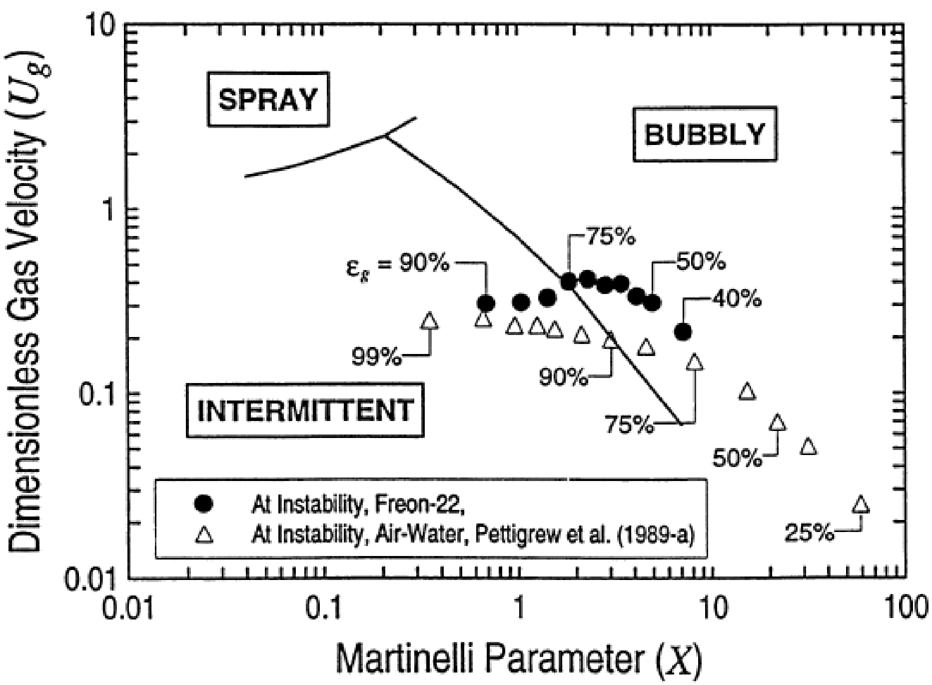

Figure: 3 Flow pattern in air-water vs. Freon-vapor [11]

Noghrekhar et al. [12] measured the local void fraction using resistivity probe. The criterion chosen to classify the flow patterns was the void fraction probability density function. Like Ulbrich et al. and Pettigrew et al. they selected the three flow patterns mentioned above.

VOID FRACTION MEASUREMENT

As we have seen above, the measurement of void fraction is a useful tool to classify flow patterns. Already used by Noghrekar et al. the void fraction probability density function is often used as an objective selection criterion for flow patterns. We can refer to the excellent work of Costigan and Whalley [14] for internal flow. Figure 4 shows their flow pattern classification compared to typical void fraction

measurements.

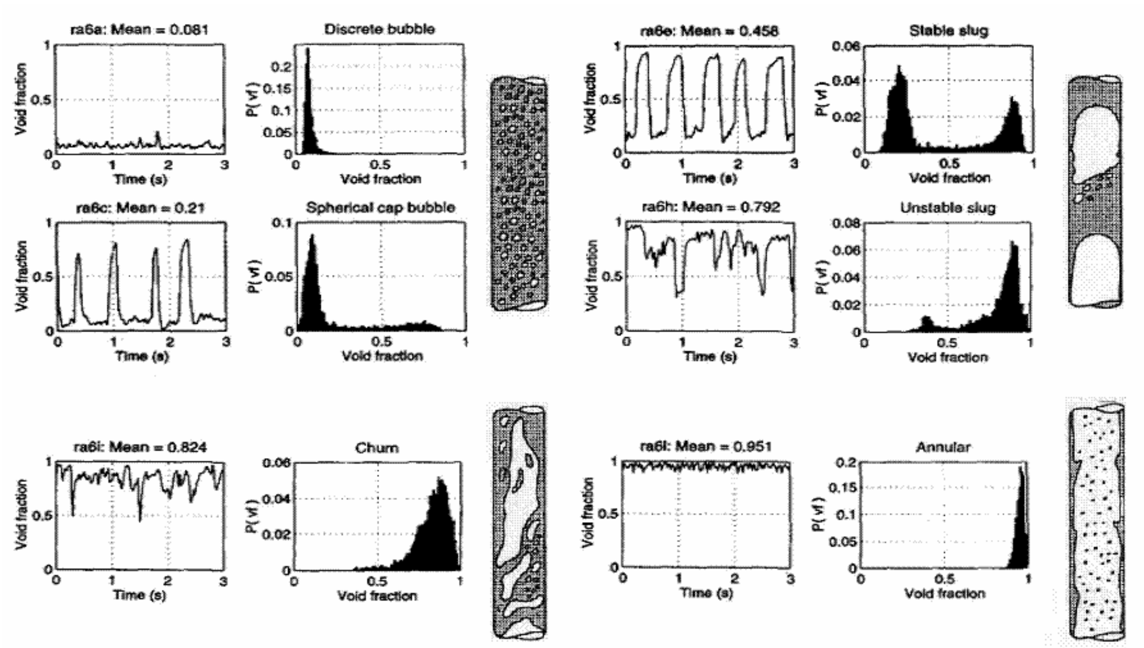

Figure 4 Flow pattern and void fraction measurement Costigan et al. [14]

Many techniques are used to measure void fraction. The most popular are optical probes, gamma densitometer and capacitance probes.

We have already developed fiber-optic probes to measure void fraction in tube bundle [15]. However, this technique is only appropriate for local measurements of void fraction. Capacitance probes on the other hand measure the mean void fraction of the two-phase mixture between the electrodes. In other words, we can say that capacitance probes measure the void fraction in a volume whereas fiber-optic probes measure at a point.

CAPACITANCE PROBES

The principle of capacitance probes is based on the difference in electrical properties between water and air. The capacitance of two electrodes depends on the medium between them. If an air-water mixture is between the electrodes, their electric resistance and capacitance depend mainly on the void fraction. With the appropriate electronic circuit to measure the capacitance in real time, we can measure the void fraction as well as its temporal fluctuation.

The method was first tested for internal flow (Figure 5). In this case, the electrodes were placed in series with an inductance. A shunt resistance and capacitance are commonly used to model the electrodes.

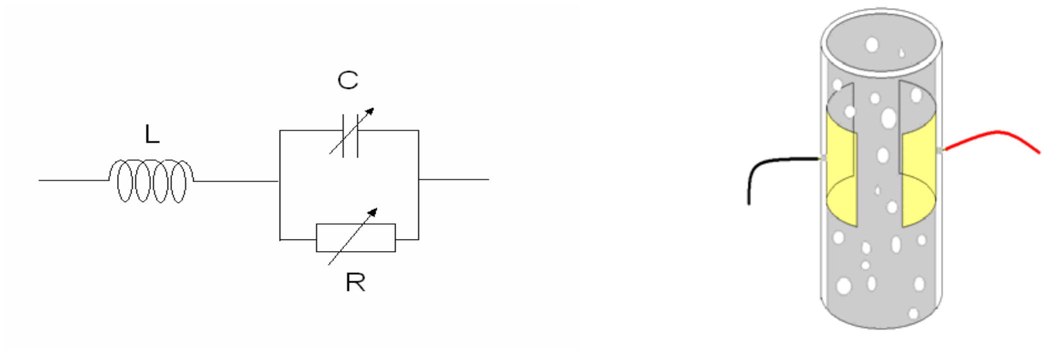

Figure 5: Electrical model and schematic diagram of electrodes for internal air-water flow

Due to the different electric properties in air and in water, the electrical circuit acts like a filter with a resonant frequency depending on the mixture (air or water) between electrodes. Figure 6 presents the transfer function of the circuit shown in Figure 5. Two approaches are possible to measure the electrical properties of the electrodes and then deduce the void fraction. One is to measure the characteristic frequency of the filter; the second is to measure the output voltage of the filter when the circuit is excited with a fixed frequency chosen between the characteristic frequencies of pure water and pure air. Depending on the series inductance and the size of the electrodes, the characteristic frequency can vary from a few kHz to hundreds of MHz.

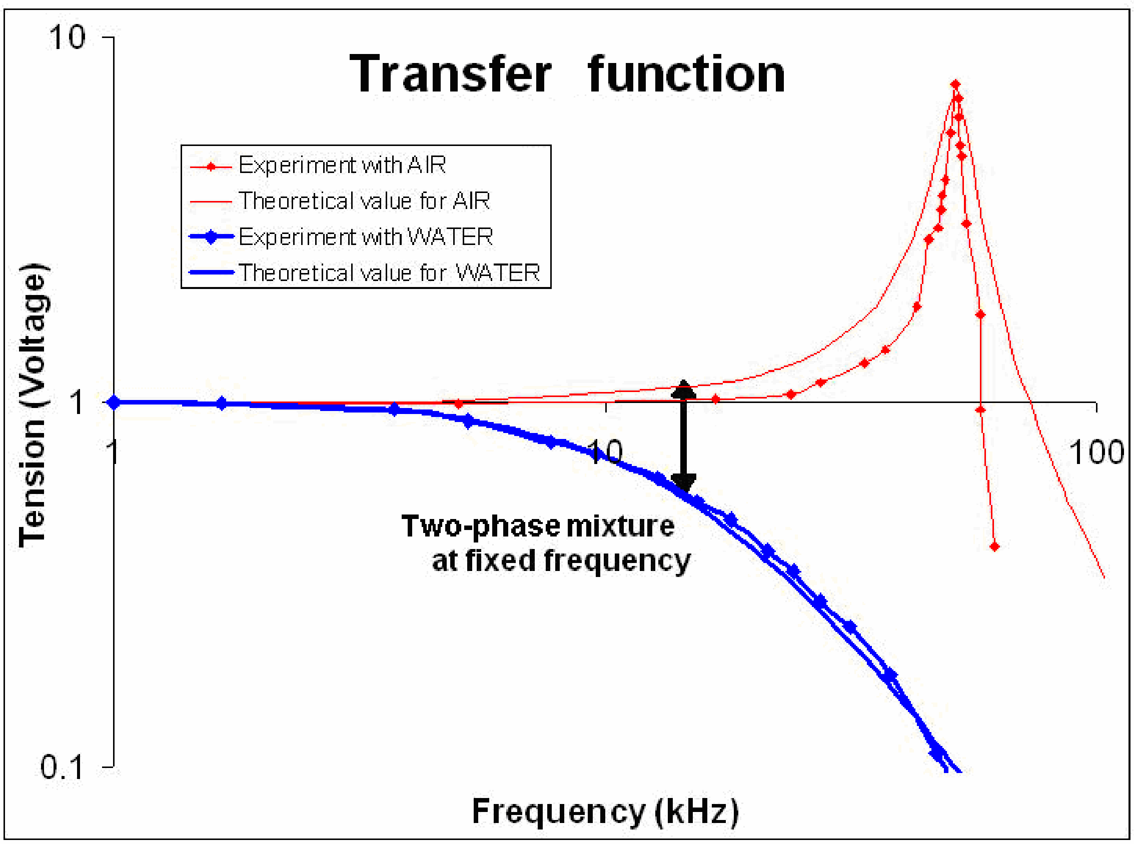

Figure 6: Transfer function of an electrode mounted for internal flow measurements

CALIBRATION AND OBSERVATION IN INTERNAL FLOW

For measurements with internal flow, we chose to measure the voltage with a fixed excitation frequency. In Figure 7, we present the resulting calibration. The two-phase flow patterns are deduced with the Taitel et al. map. [5]. The void fraction values are obtained from the measurement of volumetric quality and the evaluation of the slip ratio.

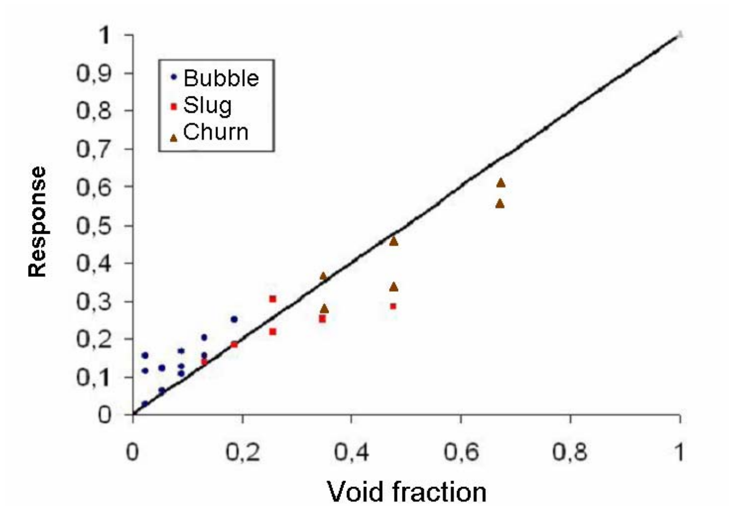

Figure 7: Calibration curve for internal two- phase flow

This first calibration exercise was complemented by visual observation and photographic work and by measurement of the dynamic characteristics of the test section (in particular the two-phase damping ratio [1]). Taking good quality pictures of two-phase flows demands great care. Considering that the typical size of bubbles is in the order of millimeters, the exposure time must be short if we want the bubbles to travel less than one millimeter. For a flow velocity of 5 m/s, the exposure time must be less than 0.2 ms. Thus to impress the CCD sensor of a digital camera in such a short time requires intense lighting.

The photographs are compared to void fraction measurements and flow patterns in Figure 8.

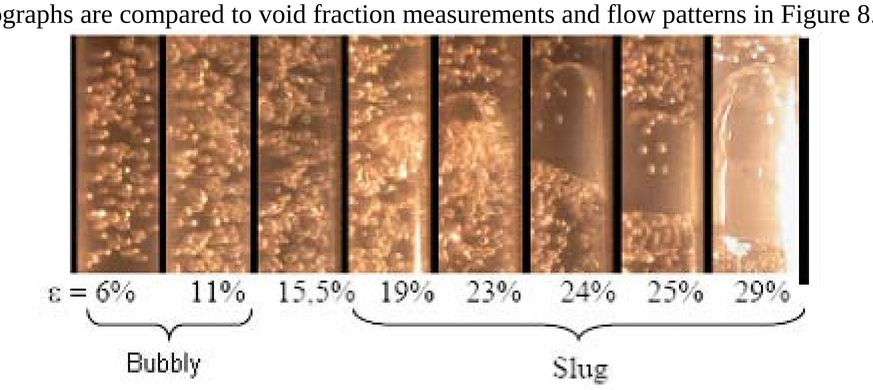

Figure 8 : Picture of two-phase flow for different void fraction measurements

EXPERIMENTAL SET-UP FOR TWO-PHASE CROSS FLOW

Figure 9 shows the air-water loop used for the tests. Water circulates in a closed loop and compressed air is introduced upstream of the test section through an injector. A mixer homogenizes the two-phase mixture.

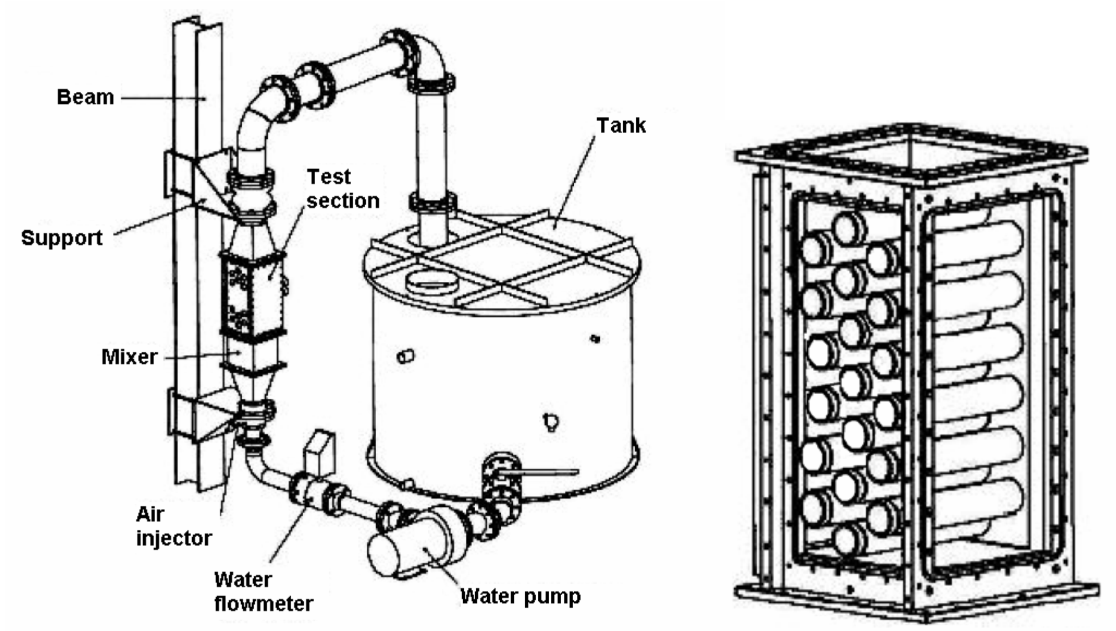

Figure 9: a) Two-phase flow loop b) Test section

The test section (Figure 9.b) contains a triangular tube bundle of pitch over diameter ratio, P/D=1.5. The tube bundle is subjected to two-phase cross flow to simulate the U-tube region of a steam generator. To measure the void fraction in different zones of the tube bundle, we chose a probe design that is easy to install and remove. The electrodes are installed on curved plastic bars as shown in Figure 10. The bars are designed to fit in any tube location within the bundle. The shape of the electrodes is concave to focus on the central zone between the electrodes (Figure 10). The instrumented tubes can easily be changed.

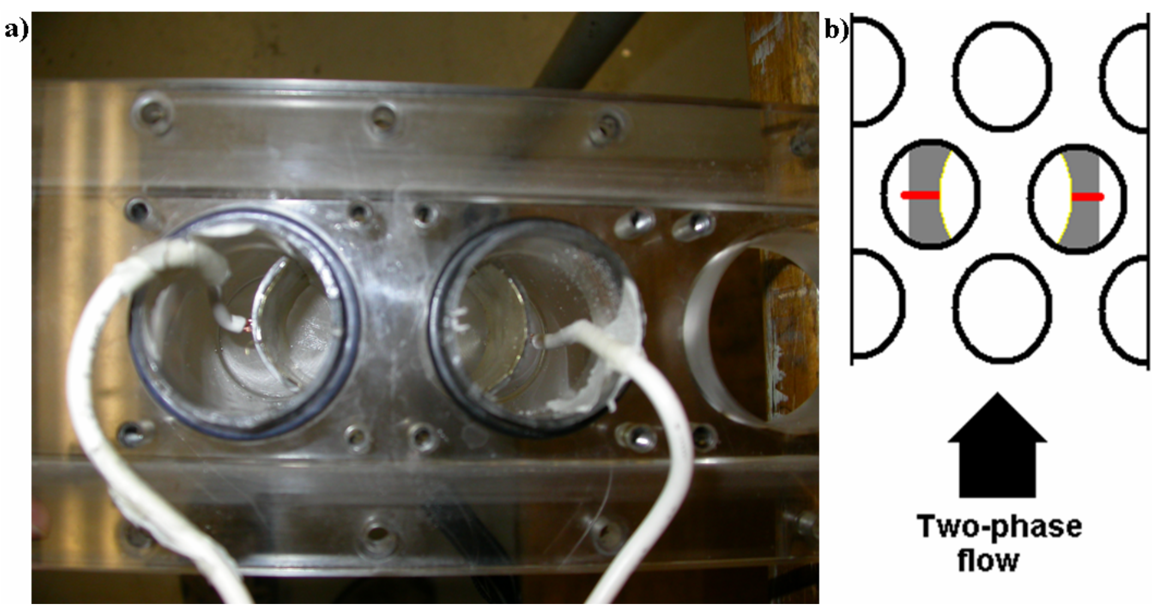

Figure 10: (a) Photograph and (b) schematic cross section of the test section with two instrumented tubes

Only capacitance change can be measured across the Plexiglas tube wall. Thus the measurements must be done at high frequency. The electrical impedance of the electrodes corresponding to shunt resistance and capacitance may be calculated from:

$$Z = \left(\frac{1}{R} + jC\omega\right)^{-1} = \frac{R}{1 + jRC\omega} \approx \frac{1}{jC\omega}$$

$$if \qquad \omega >> \frac{1}{RC}$$

We chose in this case to measure the resonant frequency of the LC circuit (Figure 11). To obtain a resonant circuit we use an operational amplifier acting as a negative resistor. The inductance is chosen to operate at high frequency.

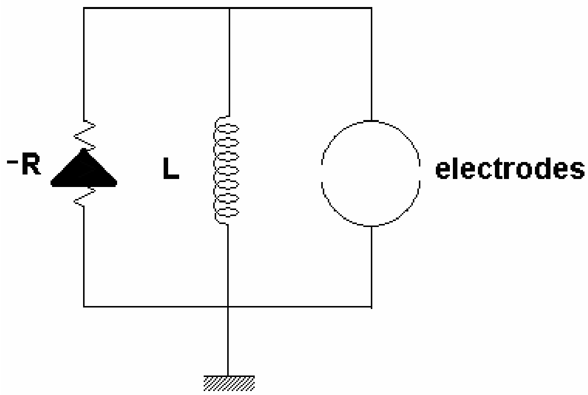

Figure 11: Measurement electrical circuit for capacitive probes

For an operational frequency of 82.9 MHz, we measure a frequency reduction of 3.3 MHz when the tubes are immersed in water. However, the heterogeneity of the flow complicates the calibration work. Visualization work has been done to understand the flow heterogeneity

TWO-PHASE CROSS FLOW VISUALIZATION

For internal flow, flow patterns may be studied with both void fraction measurement and visual observation. In two-phase cross flow, the visualization is much more difficult because of the size and the complexity of test section area. We have conducted two photographic studies to understand two-phase cross flow and, in particular, the heterogeneity of this kind of flow. The first study was to take photographs using a mirror inclined at 45º inside a transparent tube as illustrated in Figure 12. By rotating the mirror around the axis of the tube, we obtain pictures as if we were inside the tube (Figure 13).

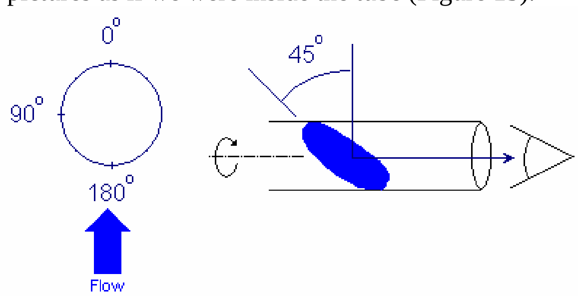

Figure 12: Principle of the method

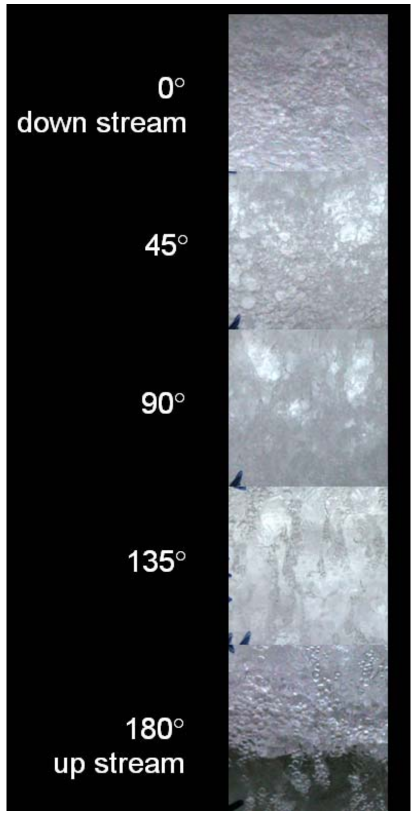

Figure 13: Pictures taken around the periphery "from inside the tube" with flow velocity 5 m/s and void fraction of 80%.

Figure 13 shows clearly the quasi-stagnant zones up and down stream. Between 135º and 180 º and between 0 º and 45 º the flow is apparently like a bubble flow. Around 90 º it appears more like churn flow.

The stagnant zone is composed of low void fraction bubbly flow and an oscillating jet of high void fraction flow. The picture in Figure 14 presents two distinct zones one black and one white. It was taken with intense light going through the mixture. The black zone corresponds to bubbly flow. Thus, the mixture of liquid and gas phase prevents the light to go through. On the other hand the white zone corresponds to high void fraction. Indeed the light goes through without much attenuation because the mixture is essentially composed of air.

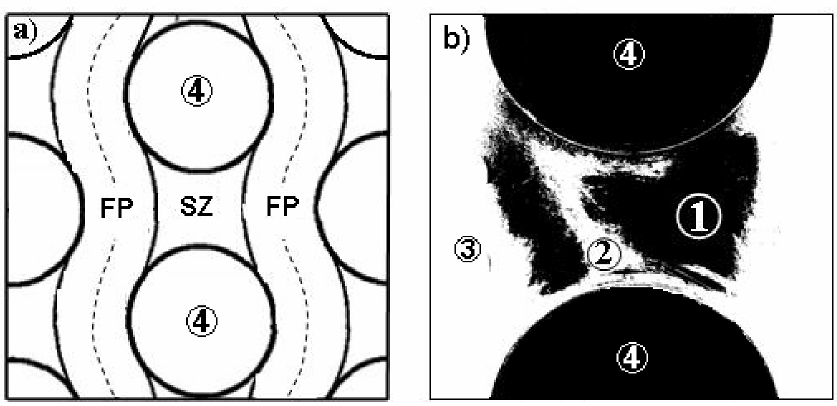

Figure 14: a) Schematic view of tube bundle; SZ: Stagnant Zone, FP: Flow Path.
b) Black and white picture ; (1) Stagnant zone (bubbly) (2) Oscillating jet of high void fraction (3) Flow path (high void fraction) (4) Tubes.

CONCLUSION

The goal of this project is the development of flow pattern maps for two-phase cross flow. To be able to classify the flow patterns we need to design void fraction measurement probes. Void fraction measurements are shown to be useful to develop flow pattern maps

The probes have been designed to measure at different locations within the tube bundle and to obtain the dynamic characteristics of the flow from the heterogeneity of void fraction. Surprisingly, although, it is well known that two-phase cross flows are inhomogeneous, no one has attempted to study flow patterns in this way.

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