SCALING FLUIDELASTIC INSTABILITY IN HEAT EXCHANGER TUBE ARRAYS SUBJECTED TO TWO-PHASE CROSS-FLOW

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ABSTRACT

In heat exchanger tube arrays, fluidelastic instability is a flow-induced vibration mechanism that can produce large oscillations and early tube failure. Thus, it is important to be able to predict the fluidelastic stability threshold of a tube array at the design stage. Unfortunately, the traditional approach to FEI analysis of tube arrays in two phase flows produces results which do not follow either the general trend observed in single-phase experiments or the predictions of Connors equation. An experimental program was undertaken, introducing a number of changes from the traditional approach in terms of working fluids, void fraction and damping measurement and data analysis. The collapse observed in the resultant stability map suggests that the mechanism of fluidelastic instability is the same in single and two-phase flows. In addition, the proposed scaling parameters seem to capture the characteristic features of fluidelastic instability in two phase flows.

1. INTRODUCTION

During the last two decades, research devoted to two-phase flow induced-vibrations has increased, mainly driven by the nuclear industry. This is primarily due to the susceptibility of the U-bend region in nuclear steam generators to vibration, caused by the cross-flow of the steam-water mixture over the long-span and low-stiffness tubes. The phenomenon is very complex, and it depends on factors which are nonexistent in single-phase flows. It has been postulated that the occurrence of fluidelastic instability can be predicted using the two non-dimensional parameters used for single-phase flows: the reduced velocity and the mass-damping parameter. However, in two-phase flows, additional parameters as void fraction, liquid-to-gas density ratio, surface tension and flow regime must be considered. Figure 1 shows a stability map where two-phase data has been plotted, based on the same analysis used in single-phase flows. The data points seem to follow neither the general trend observed by Weaver and Fitzpatrick (1988) nor the predictions of Connors equation. This behaviour suggests that more research is required to deal with the unique difficulties of scaling parameters and data analysis in two-phase flows.

Axisa et al. (1988) presented results for fluidelastic instability in parallel triangular, normal triangular, normal square and rotated square arrays (P/D = 1.44), using air-water and steam-water mixtures. They found that using air-water data was reasonable to simulate steam-water mixtures in terms of fluidelastic instability predictions. Pettigrew et al. (1989a, b) presented a series of papers concerning two-phase turbulence buffeting, fluidelastic instability, hydrodynamic mass and damping. The four standard tube array configurations were investigated using cantilevered tubes with pitch over diameter ratios of 1.32 and 1.47. They found that the fluidelastic instability behaviour is different for continuous flow regimes than for intermittent flow regimes. Interestingly, they commented that the fluidelastic stability threshold does not appear to be greatly affected by changing the fluids. Also, a relationship between damping and void fraction was presented, showing a maximum damping ratio for void fractions from 40 to 80%. According to their research, the damping of the system is strongly influenced by the two-phase fluid used, and the air-water combination tended to provide larger damping than the steam-water experiments. This is primarily due to the differences in density ratio between the liquid and gas phases for different fluids. Pettigrew and Taylor (1994) presented a review paper discussing turbulence buffeting and fluidelastic instability in two-phase flows. Both the axial-flow and cross-flow configurations were considered, and design guidelines were proposed for hydrodynamic mass and damping. The experiments of Pettigrew (1989) and Pettigrew and Taylor (1994) were carried out using air-water flows, with void fractions ranging

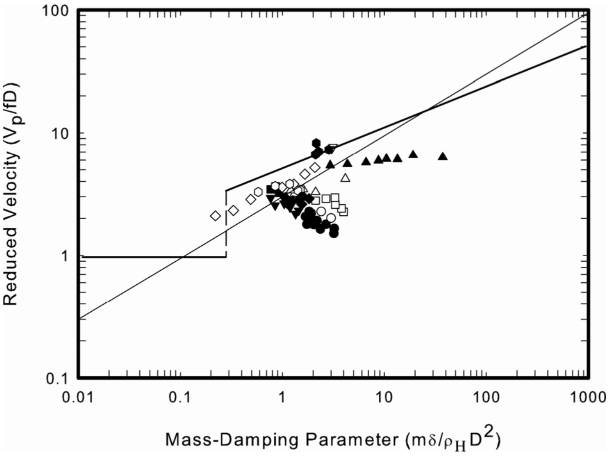

Figure 1: *Stability Map for fluidelastic instability in two-phase flows*

from 5 to 99%. These values are based on the Homogeneous Equilibrium Model (HEM) in order to compute the “average” velocity and density of the mixture and allow for comparison using stability maps. The HEM is a model for determining the void fraction of the two-phase flow that assumes no “slip” between the gas and the liquid, that is, both phases are moving at the same velocity. This assumption may be suitable for uniform flows, were the bubbles are small and evenly distributed. However, the use of the HEM for intermittent flows is not valid, since the distribution of void is not uniform and because of the ``slip'' or relative velocity between the phases.

Feenstra et al (1995) presented one of the first experiments using a single component two-phase mixture of refrigerant 11. The fluidelastic instability threshold values obtained were less conservative than for previous experiments with air-water and, by using a gamma densitometer, it was shown that the real void fraction was considerably lower than the values predicted by the HEM. Pettigrew et al. (1995) reported experiments using R-22. They found that the damping ratio is highly dependant on void fraction, with a maximum around 60-65%. They also reported that for voids of 65% and larger (based on HEM) the onset of instability decreases, that is, the larger the void fraction, the more prone is the array to becoming unstable. A direct explanation for this phenomenon was not provided and it was attributed to flow regime effects. Feenstra et al. (2002) carried out a series of experiments using Refrigerant 11 as the working fluid, but in this case, a new void fraction model was implemented to account for the slip between the phases. Also, an alternate definition of two-phase velocity was presented (equivalent velocity), which accounted for the kinetic energy of each phase. They found that the fluidelastic instability threshold was slightly lower than for air-water mixtures. Comparing data from different researchers using their void fraction model, they found that the critical reduced velocity decreases with increasing mass damping parameter for an increasing void, as seen in Figure 1, suggesting that the reduced velocity and the mass damping parameter may be insufficient to describe two-phase flow-induced vibration for intermittent regimes.

Nakamura et al. (2000) studied unsteady forces, damping and fluidelastic instability in two-phase flow using steam-steam water cross-flow in an in-line array. It was found that the fluidelastic stability threshold was almost constant for void fractions from 70 to 96%, because of the invariance of the flow regime. However, it is also pointed out that even though fluidelastic instability can be predicted with reasonable accuracy for homogeneous flows, a new approach is needed for non-homogeneous flows.

Feenstra et al. (2003) investigated the onset for fluidelastic instability of a parallel triangular and a normal square array subjected to two-phase R-11 cross-flow. The parallel triangular configuration is particularly important because it is less stable than the other array patterns for the same P/D ratio. For these studies, an “interfacial” velocity correlation, introduced by Nakamura et al. (2000), was used to compare the fluidelastic data from several researchers. There is a remarkable collapse in the data “in terms of the reduced velocity”, and seems to be in agreement with the Connors theory for K=3.0. However, the flow regime does not affect this collapse. More recent reviews of flow-induced vibration mechanisms in two-phase flows across tube bundles, (Goyder (2002), Pettigrew and Taylor (2003, 2004)) have stressed the need for more research regarding the physical mechanisms that play a role in two-phase flows, especially flow regime effects, void fraction distribution, damping and surface tension.

Regarding the estimation of the damping ratio, Moran and Weaver (2006) proposed a new measurement technique that can be used in experiments with two-phase flow across a confined tube array. The device can produce a steady and controlled oscillation of the tube in a non-intrusive fashion. It was found that the half-power bandwidth method over-predicts the damping when compared to the logarithmic decrement method, particularly in bubbly and intermittent flows where the effects of fluid added mass are significant. Moran and Weaver (2007) found a strong dependence of damping on flow regime by plotting the interfacial damping (surface tension in the form of the Capillary number combined with the two-phase component of the damping ratio) versus the void fraction.

2. EXPERIMENTAL FACILITY

2.1 Two-Phase Flow Loop

The experiments were carried out in a two-phase flow loop located at McMaster University. The working fluid is Refrigerant 11 (Freon), and is evaporated using a set of heaters located below the test section (see Figure 2). The heaters are capable of transmitting up to 48 kW of power to the fluid. A gear pump is used to circulate the Freon throughout the loop. The maximum pitch mass flux attained by the pump is 1000 kg/m^{2}s (based on single-phase flow). A condenser located downstream the test section removes the heat from the mixture and allows for a better control of the thermodynamic parameters in the test section. A detailed description of the flow loop can be found in Feenstra et al. (2002, 2003).

2.2 Test Section and Model Tube Bundle

The test section has a rectangular cross-section of 49.2 mm by 197 mm. It has two glass windows on the sides for observation, as well as a frontal window. Half-tubes were attached to the sides in order to minimize the effect of the flat walls on the flow configuration. The array consists of ten cantilever-mounted brass tubes, with an external diameter of 9.525 mm (0.375 in). The geometric pattern of the bundle is a parallel triangle, with a pitch-over-diameter ratio of 1.49, similar to that in CANDU steam generators. The tubes were tuned to within 1% of the average natural frequency measured in air. For the monitored tube, the natural frequencies in liquid and vapor Freon were 41.75 Hz and 48.25 Hz respectively. The vibratory response of the tube was measured by using two strain gauges, located on the cylindrical support between the tubes and the base plate of the array (see Figure 3). These strain gauges were positioned at 90 degrees from each other, allowing for the measurement of displacement in both the transverse and stream-wise directions. For the damping measurements, the monitored tube is excited to vibrate only in the lift direction. Hence, the damping reported in this study corresponds only to the transverse plane. The output signal was collected using a data acquisition card and a dynamic analyzer (HP 35670A). The data acquisition card provided the time history information of the monitored tube, while the dynamic analyzer provided the averaged frequency response. For each trial, the dynamic analyzer collected a total of 100 averages from 0 to 100 Hz, with a resolution of 0.25 Hz.

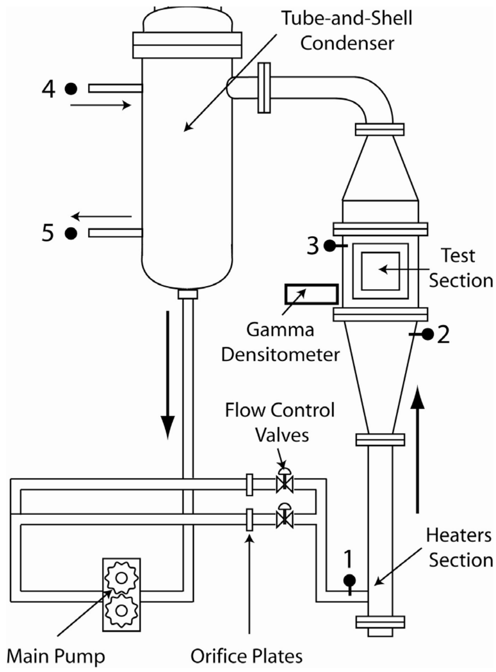

Figure 2*: Two-Phase Flow Loop*

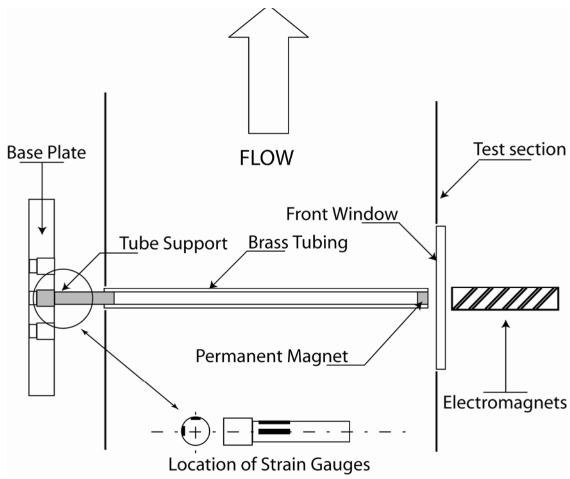

Figure 3*: Schematic diagram of the model tube showing the strain gauges and the electromagnets.*

2.3 Damping Measurements

The damping was determined by using an electromagnetic excitation device, as described by Moran and Weaver (2006). Figure 3 shows a diagram of the electromagnetic coils in position. The polarity of these temporal magnets is changed, producing the excitation required to obtain the decay trace. An exponential function is then fitted to the decay trace response to compute the damping ratio. This methodology has proven to be less sensitive to the continuous change in added mass and subsequent frequency fluctuations than the traditionally used half-power bandwidth method.

2.4 Experimental Procedure

For each experiment, the pitch mass flux was held constant while the void fraction was changed by increasing the heat transferred to the fluid. The pitch mass fluxes studied ranged from 100 to 500 kg/m^2s in steps of 50 kg/m^2s. The temperature of the Freon was measured at several points along the loop, including locations upstream and downstream of the test section, at the heaters and downstream of the condenser. When the temperatures had remained constant for a certain period of time, then the void fraction and tube response were recorded. Waiting for "steady state" ensures that the flow regime and void fraction will not change while the measurements are performed. The averaged frequency spectra of the tube were captured while the void fraction was measured directly using the gamma densitometer. The latter was located upstream of the model tube bundle, as shown in Figure 2. Two series of experiments were carried out. For the first (Series A), only the monitored tube was flexible, while all the other tubes were fixed. This feature allowed measurement of the damping caused by the two-phase flow on the monitored tube. See Moran and Weaver (2006) for details. The second series (Series B) was performed with a fully-flexible array, which permitted to determine the critical velocity for the tube bundle for each mass flux.

2.5 Two-Phase Flow Modelling

A reliable measurement of void fraction is a key element in the analysis of two-phase damping and fluidelastic instability. Traditionally, the Homogeneous Equilibrium Model (HEM) has been used for the estimation of void, because of its ease of application. However, the HEM assumes that there is no slip between the liquid and gas phases, that is, they flow together at the same velocity. For the case of vertical-upwards gas-liquid flows, the buoyancy contributes to accelerate the gas phase, causing a velocity difference that should not be neglected. Feenstra et al. (2002) used gamma densitometry in order to improve the two-phase density and velocity calculations. This is especially important when the flow regime changes from bubbly to intermittent, because the unsteadiness and turbulence present in the flow departs from the physical behaviour assumed in the HEM. In this study, the void fraction (RAD Void - Radiation Attenuation Determination) was measured using a gamma densitometer, but also the HEM void was calculated for comparison purposes. The flow regimes were determined based on the flow regime map proposed by Ulbrich and Mewes (1994) and corroborated by visual observation.

Regarding the models used to determine the average velocity of the two-phase flow, the traditional approach suggests the use of the pitch velocity, based on the density calculated from the HEM. More recently, Nakamura et al. (2000) proposed the interfacial velocity for analyzing fluidelastic data. The interfacial velocity was the result of experimental measurements of bubble velocities using bi-optical probes. It comes from an expression originally developed by Nicklin in 1962 for the measurement of slug velocity that required some adjustments to make it suitable for tube arrays. The expression for the interfacial velocity is

$$V_i = C_i(U_{ls} + U_{gs}) + \sqrt{\frac{gD_e(\rho_l - \rho_g)}{\rho_l}},$$

where U_{gs} and U_{ls} are the superficial velocities of the gas and liquid phases respectively. The interfacial coefficient C_i depends on the array pattern, and is equal to 0.77 for parallel triangular arrays, 0.95 for rotated square arrays and 0.73 for normal square arrays. The use of this velocity in a stability diagram produces the collapse the two-phase fluidelastic data, regardless of the fluids used, array pattern or flow regime, as can be seen in Feenstra et al. (2003).

3. RESULTS

The present results were first plotted in a stability map by following the traditional approach. This includes using the half-power bandwidth method for the damping ratio, the Homogeneous Equilibrium Model for the void fraction and flow velocity, and taking the damping at half the critical mass flux to calculate the mass-damping parameter. The results agreed with previously published data, as shown in Figure 4. However, the trends observed in the stability maps were similar to those obtained in the past by Pettigrew et al. (1989a) and Feenstra et al. (2002) in the sense that the reduced velocity decreased when the void fraction was increased. This effect has been attributed to intermittent flow regime effects, although it could be caused by the use of incorrect scaling parameters to represent two-phase flow fluidelastic results. One of the features observed in Figure 4 is that as the void increases, the critical reduced velocity seems to decrease, deviating from the behavior suggested by Connors' model. As the void fraction increases, its density reduces, increasing the value of the mass-damping parameter. If fluid density were the only parameter being changed, one would expect a monotonic increase of critical reduced velocity with increasing mass-damping parameter. Surprisingly, the opposite trend is observed, shown by the arrows

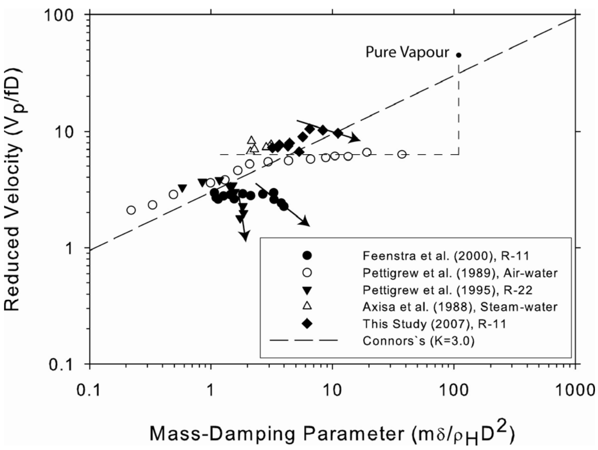

Figure 4*: Current results plotted on a stability map based on the traditional criteria*

in Figure 4. This behavior is still unexplained and has been attributed to flow regime effects, more particularly, the consequence of intermittent flows. It is this unexplained behavior which motivated high void fraction experiments carried out during this research. The observed trend downward with increasing void fraction must ultimately reverse its direction to approach the data for gas flows at very high void fractions. However, the fluidelastic data obtained in this research shows the same trend as the previous results, even when the fluidelastic instability was observed in dispersed flows for four of the ten experiments. It can be concluded that there must be a problem with the trend exhibited by the results, and this may be a consequence of the choice of parameters used to characterize the phenomenon.

If the interfacial velocity is used to compute the reduced velocity and the RAD density is taken for calculating the mass-damping parameter, the data collapses as previously observed by Feenstra et al. (2003). The HEM density data reported by Pettigrew et al. (1989, 1995) and Axisa (1988) was converted into a more realistic density value by using the void fraction model introduced by Feenstra et al. (2002). The collapse observed is mainly due to the implementation of the measured void fraction as the HEM significantly over-predicts the actual void fraction.

3.1 Proposed Approach for Fluidelastic Analysis

The trends observed in the stability maps still do not reflect the expected smooth transition from liquid to vapor. However, the RAD void fraction and interfacial velocity seem to introduce a considerable improvement over the HEM density Langre (2003) and Weaver and El-Kashlan (1981)

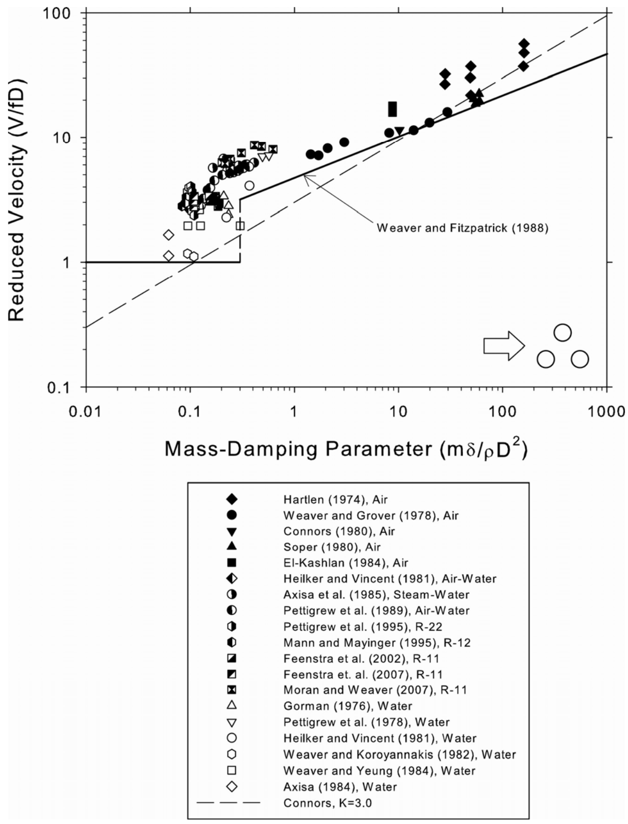

Figure 5: *Stability map based on damping in quiescent fluid. The reduced velocity is based on the pitch velocity for single-phase data and the interfacial velocity for two-phase data.*

that the net damping must be zero at the critical velocity. Thus, it appears logical that all damping due to the flowing fluid should be neglected in the parameters characterizing fluidelastic instability. Therefore, only the total damping with no-flow represents a logical measure of the energy dissipation which must be overcome by the flow effects in order to produce fluidelastic instability. In two-phase flows, measurement of no-flow damping would appear impossible because of buoyancy of the gas phase. Baj and de Langre (2003) extrapolated damping data, plotted as a function of flow velocity, back to the zero flow datum, and such an approach seems reasonable.

When the tubes are surrounded by liquid, the viscous damping observed when the flow velocity is zero is generally much larger than the structural component. The total damping in the system at this point is close to the viscous component alone. For the case of tubes surrounded by air, the viscous damping is very small, and the total damping can be considered as close to the structural damping. Based on these ideas, it was decided to use the damping in quiescent fluid as the reference value for fluidelastic stability analysis. This means that for results in air (or vapor), the damping in-air was used to calculate the mass-damping parameter. For two-phase and liquid data, the damping in stagnant pure liquid was utilized as a conservative estimate in the absence of better data. The in-flow damping was not used to determine the quiescent damping because of the lack of data, as stated above. Figure 5 shows how this approach collapses the two-phase data and shows a progressive transition from the liquid to the gas data. Moreover, the two-phase data follows the design guidelines proposed by Weaver and Fitzpatrick (1988) for single-phase flows very well. If it is accepted that the basic mechanism of fluidelastic instability is the same in single and two-phase flows (de Langre, 2006), then it appears that the choice of proper scaling parameters is a crucial factor to developing a reliable stability map.

4. CONCLUSION

Flow-induced vibration experiments were conducted with the objective of studying two-phase damping and fluidelastic instability. Two sets of experiments were carried out, in order to both measure the damping and determine the critical velocity for a parallel triangular tube array. A comparison was made with previously published data, showing that when the traditional HEM density and the half-power bandwidth damping here used, a good agreement between those studies and the present investigation was observed. The combination of RAD void fraction, interfacial velocity and quiescent fluid damping seems to be the best for producing the expected behavior in transition from liquid to gas flows in terms of fluidelastic instability analysis. Arguably, these parameters must also best capture the physics involved. The use of the RAD density, interfacial velocity and quiescent-fluid damping collapses the available data well and provides the expected trend of two-phase flow stability data over the void fraction range from liquid to gas flows. The resulting stability map represents a significant improvement for predicting fluidelastic instability of tube bundles in two-phase flows. This result also tends to confirm the hypothesis that the basic mechanism of fluidelastic instability is the same for single and two-phase flows.

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