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NUMERICAL PREDICTION OF THE STREAMWISE FLUIDELASTIC INSTABILITY IN TWO-PHASE FLOWS

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ABSTRACT
This paper reports the development of a numerical model to predict the onset of the streamwise FEI. Simulations were conducted for a parallel triangular tube bundle. The model was validated and tested against the available experimental data in the literature for single phase and two-phase air-water mixture flows. Two pitch-to-diameter ratios of 1.5 and 1.7 were investigated and presented in this study for water and 60% air void fraction flows. The study confirms the strong dependency of the onset of streamwise FEI on the pitch-to-diameter ratio and void fraction.

NOMENCLATURE
a: Air void fraction [-]
c: Normalized force coefficient [-]
D: Tube diameter [m]
$\boldsymbol{g}$: Gravity field vector [m/s^2]
m: Mass per unit length [kg/m]
p: Pressure field [Pa]
P/D: Pitch-to-diameter ratio [-]
$\boldsymbol{u}$: Velocity field vector [m/s]
U_∞: Inlet velocity [m/s]
U_r: $= \frac{2\pi U_\infty}{\omega D\left[1-\left(\frac{P}{D}\right)^{-1}\right]}$ reduced velocity [-]
y: Coordinate system in streamwise direction [m]

Greek letters:
δ: Damping logarithmic decrement [-]
μ: Flow viscosity [N.s/m^2]
ρ: Flow density [kg/m^3]
ω: Angular frequency of tube oscillation [rad/s]

Subscripts:
air: Air
m: Mixture
k: Phase

INTRODUCTION
Fluidelastic Instability (FEI) is considered to be the most dangerous mechanism as it can cause severe damage to steam generators in a very short span of time. Therefore, it gained much of the attention in both research and industrial communities. It was generally accepted that if FEI does not occur in transverse direction, streamwise FEI will not occur. Therefore, for decades most of the research work in this area targeted the transverse FEI for both single and two-phase flows, as such Mohany *et al.* [1]. However, the recent incident of failure of steam generator units in San Onofre Nuclear Generation Station (SONGS) was attributed to streamwise FEI. Consequently, this has brought much interest for studying this mechanism. Several experimental works were initiated to examine the vulnerability of tube bundles to streamwise FEI. Mureithi *et al.* [2] and Nakamura *et al.* [3] studied the phenomenon for air flow in different arrangements of flexible tubes and different pitch-to-diameter ratios (P/D). They concluded that unlike the transverse FEI, streamwise FEI is difficult to excite for a single flexible tube in an otherwise rigid array and thus, the onset of instability is dependent on the proximity of tubes in the bundle. Violette *et al.* [4] investigated

the threshold of streamwise instability for air-water mixture and found that it is 20% higher than that of the single phase air flow for the same dimensionless mass-damping parameter. Olala and Mureithi [5] performed detailed measurements for the unsteady fluidelastic forces acting on a moving tube which showed larger force magnitude for water compared to a 60% air void fraction.

Theoretical models and numerical methods were developed to provide a predictive tool for the study of both transverse and streamwise FEI [6]. Hassan and Weaver [7] modified the semi-analytical model of Lever and Weaver [8] to allow for an bidirectional motion for the tubes. The new model permits the study of both transverse and streamwise FEI simultaneously. Their analysis showed that streamwise FEI can become dominant if the tubes natural frequency in the in-flow direction is 20% less than the one in transverse direction. In a subsequent work [9] they also showed that if both transverse and streamwise frequencies are equal, streamwise FEI can take place for small P/D and low mass-damping parameter. In the last decade Computational Fluid Dynamics (CFD) technique has been utilized to study FEI, such as the work of Hassan *et al.* [10], Khalifa *et al.* [11], Burns *et al.* [12] and El-Bouzidi *et al.* [13]. Yet, these CFD models were limited to single phase-flows not to the two-phase flows found in steam generators.

Therefore, this work focuses on developing a CFD model which is capable of providing the necessary terms for the streamwise FEI theoretical models for a two-phase air-water flow. Then, the provided terms will be implemented into an unsteady FEI model to determine the instability threshold. Two pitch-to-diameter ratios of 1.5 and 1.7 at air void fractions of 60% are tested with the CFD model to judge its validity.

GOVERNING EQUATIONS AND DOMAIN SETUP

The used CFD model is based on the Reynolds Average Navier-Stokes (RANS) casting of the flow dynamics governing equations and the simple mixture two-phase model. The semi-analytical model of Lever and Weaver [8] revealed the strong dependency fluidelastic instability phenomenon on the coupling between the cylinder motion and the flow channels. Moreover, the relatively high flow velocity in the flow channel aids the dispersion of the air bubbles and reaching a more homogeneous mixture. Such high velocities are typical at the onset of the streamwise FEI. Therefore, the simple mixture two-phase flow is considered a valid representation for the FEI in two-phase flows. In this context, the conservation of mass and momentum equations are as follow:

$$\frac{\partial}{\partial t}(\rho_m) + \boldsymbol{\nabla}.(\rho_m\, \boldsymbol{u_m}) = 0 \qquad \text{(1-a)}$$

$$\frac{\partial}{\partial t}(\rho_m \boldsymbol{u_m}) + (\boldsymbol{u_m}.\boldsymbol{\nabla})(\rho_m \boldsymbol{u_m}) = \rho_m \boldsymbol{g} - \boldsymbol{\nabla} p + \boldsymbol{\nabla}.\left(\mu_m(\boldsymbol{\nabla u_m} + (\boldsymbol{\nabla u_m})^T)\right) + \boldsymbol{\nabla}.\left(\sum a_k\, \rho_k \boldsymbol{u_{dr,k}}\, \boldsymbol{u_{dr,k}}\right) \qquad \text{(1-b)}$$

The last term is added to the RHS of Eq. (1-b) to account for the momentum transfer between the phases of the flow which occurs due to the difference (slip) between the local velocity of the gas and liquid phases. A formulation of the slip is based on a local equilibrium of the forces acting on the air bubbles. Such formulation shall account for the dissipation of momentum due to the turbulent Reynold's stresses. The drift velocity $\boldsymbol{u_{dr,k}}$ is used as representation of this slip by referencing the velocity of each phase k to the mixture local velocity $\boldsymbol{u_m}$. The mixture local density and local velocity are calculated as follow:

$$\rho_m = \sum a_k \rho_k \qquad (2)$$

$$\boldsymbol{u_m} = \frac{\sum a_k \rho_k \boldsymbol{u_k}}{\rho_m} \qquad (3)$$

The complete solution of the momentum equation requires a simultaneous coupling with a transport equation for the air void fraction a_{air} as:

$$\frac{\partial}{\partial t}(a\, \rho_{air}) + \nabla.(a\, \rho_{air} \boldsymbol{u}_m) = \nabla.\left(a\, \rho_{air} \boldsymbol{u}_{dr,air}\right) \qquad (4)$$

The above expression neglects the mass diffusion between air and water and assumes an isothermal system where water will not boil into vapor. Comprehensive details about the model and the interaction between the air bubbles and water can be found in the work of Sadek *et al.* [12].

The Spalart-Almaras turbulence model is implemented for the closure of turbulence stress terms. Such a model have been developed for flow against adverse pressure gradient, and later corrected to account for rotation and curvature effects. Therefore it is considered valid to be used in the tube bundle as the flow passes in curved channels between the tubes and the flow faces an adverse pressure gradient as it separates around each individual tube in the bundle.

A 2-D CFD domain is considered in this work which represents a parallel triangular tube bundle with 19 tubes each of which is 38 mm in diameter (D) arranged in 3 columns as shown in Fig. 1. Air-water mixture is introduced at the bottom and flows upward. The lengths of upstream and downstream sections are $5.5D$ which were found to be appropriate representations of the bundle's boundary conditions at the inlet and outlet sections.

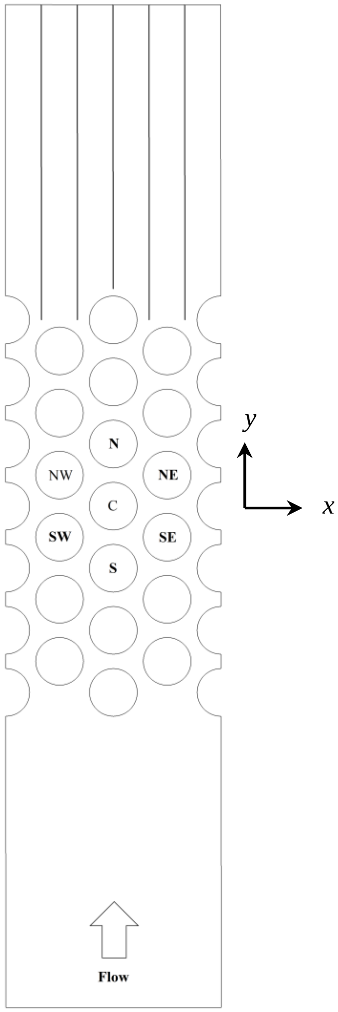

FIGURE 1: 2-D FLOW DOMAIN.

Also, five equally spaced baffle plates are introduced downstream of the tubes for the same purpose. Unstructured quadrilateral mesh elements are used for discretizing of the space field. A total mesh count of 150k elements with 14 prism layers around the tubes were found to be sufficient to avoid any numerical effects result from the mesh element size.

Each unsteady simulation is carried out by first obtaining a steady-state solution for the domain which is then used as an initial point for the time-dependent simulation. The flow enters the domain at a pre-specified velocity with air bubbles uniformly distributed across it. During the unsteady stage, a harmonic motion is introduced to tube C in the streamwise direction at a frequency (ω) of 50 rad/s and amplitude of 15% the gap size between tubes. Meanwhile, the drag forces are monitored for the moving tube and the 6 neighbouring tubes. These forces are then refined into their corresponding magnitudes $c_{f,y}$ and phase angles ϕ_f between the forces and the imposed motion. This procedure is repeated for matrix of different flow velocities and pitch-to-diameter ratio.

RESULTS

Olala and Mureithi [5] provided important experimental set of data for the dynamic drag forces acting on a tube due to its motion or the motion of an adjacent tube in a 60% air void fraction air-water flow. Their results were presented for P/D of 1.5; therefore their data are used here to validate the model for the same geometry, and to extend to other pitch-to-diameter ratios.

Figure 2 shows the variation of the dynamic drag force acting on the moving tube C with the flow velocity as a function of the dimensionless reduced velocity U_r, two pitch-to-diameter ratios, and for 60% air content. As can be noted, the simulated forces of P/D=1.5 agrees very well with the experimental data in both magnitude and phase. The simulated force is lagging the motion of the tube which confirms that the streamwise FEI is a stiffness-controlled mechanism. This is true for the range of the simulated flow velocities up to $U_r = 20$. It can be noted that the phase angle reaches its lowest value at $U_r = 17.5$, and then it levels off. Similar quantitative and qualitative trends of the phase angle vs. U_r for P/D 1.7 is also observed. However, the forces' amplitudes are different; as the gap between the tubes is larger; the flow coupling force becomes weaker. This is evident from the clear difference between the 1.5 and 1.7 pitch-to-diameter ratio cases. For another tube SW which is adjacent to the oscillating tube, similar observations can be concluded from Fig. 3. It worth noting that although the model is underestimating the phase angle compared to the experimental values, the maximum difference falls within 15% of the total variation of the phase angle in the covered flow velocity range. This is believed to be an acceptable accuracy.

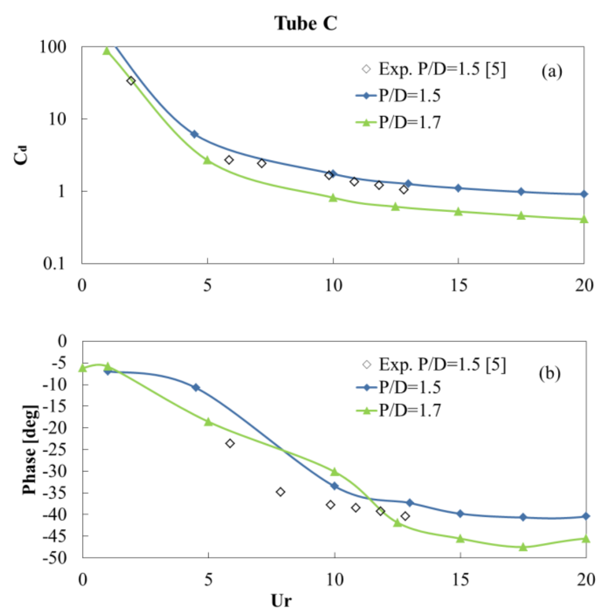

FIGURE 2: EXPERIMENTAL AND NUMERICAL PREDICTION OF 60% VOID FRACTION FOR TUBE C: (A) FORCE COEFFICIENT, (B) FORCE PHASE.

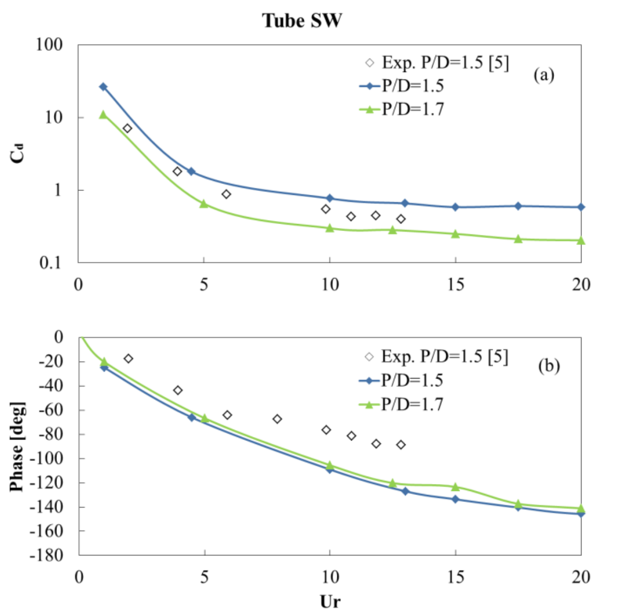

FIGURE 3: EXPERIMENTAL AND NUMERICAL PREDICTION OF 60% VOID FRACTION FOR TUBE SW: (A) FORCE COEFFICIENT, (B) FORCE PHASE.

To predict the streamwise FEI stability threshold, a classical kernel of seven tubes is assumed to be flexible only in the streamwise direction. For each void fraction, the mass-damping parameter is calculated from the knowledge of mixture's density and structural parameters. Here, the tube mass per unit length (m) is taken as 3.3 kg/m while the in-vacuu logarithmic decrement δ is 0.176. To find the onset of instability, the reduced flow velocity is increased incrementally at each void fraction and the stability of the system is evaluated by checking the real part of the corresponding eigen-values. The simulation and experimental results are shown for P/D = 1.5 and 1.7 in Fig. 4. The figure shows an excellent comparison between the generated stability points and the experimentally located by Violette *et al.* [4] for the 1.5 pitch-to-diameter ratio. Moreover, the stability threshold for P/D =1.7 is higher than that for 1.5. This indicates that there is weaker flow coupling forces between the tubes as evident by Fig. 2 and 3. This trend was reported in the literature for single phase flows, and from Fig. 4, it remains valid for two-phase flows.

CONCLUSIONS

A 2-D CFD model was developed using the unsteady RANS model with Spalart-Allmaras turbulence model for flow interaction and coupled with the simple mixture model for simulating two-phase flows in tube bundles. The model was implemented to extract the necessary data of dynamic unsteady forces which are required to generate the stability map of the streamwise FEI using an unsteady model. The geometry under consideration was a parallel triangular tube array with pitch-to-diameter (P/D) of 1.5. Two air void contents were tested; a single phase flow of pure water and 60% air content in an air-water mixture flow. The simulated unsteady flow forces were validated and agree well with the experimental counterpart provided in the literature for both the magnitude the phase angle. The investigation is then extended to cover another extra pitch-to-diameter ratio of 1.7. The tube bundle with P/D =1.5 was shown to be the more prone to streamwise FEI for both void fractions.

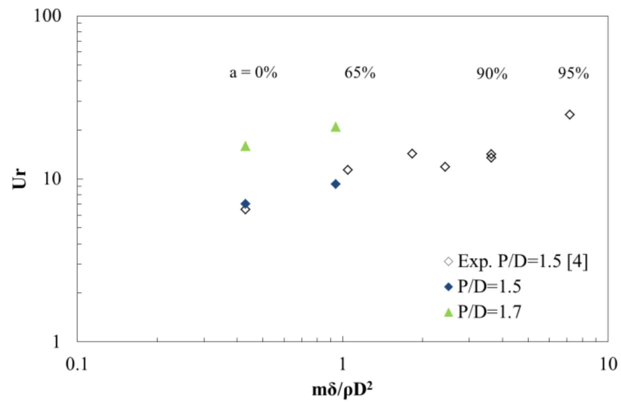

FIGURE 4: STREAMWISE FEI STABILITY THRESHOLD MAP.

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