

EXPERIMENTAL STUDY ON FLUID-ELASTIC INSTABILITY IN A HEAT EXCHANGER TUBE BUNDLE HAVING A NORMAL TRIANGULAR TUBE ARRANGEMENT, SUBJECTED TO CROSS FLOW OF WATER

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Abstract

Flow-induced vibration is a crucial consideration in the design of thermal-hydraulic apparatus. The nuclear, industrial, and power industries have expressed considerable worry regarding heat exchangers that may encounter elevated liquid or gas flow rates. Heat exchangers are tube bundles with multiple geometric arrangements, subjected to cross-flow. The tubes within a bundle represent the most flexible elements of the structure. Heat exchangers and steam generators have incurred damage from severe flow-induced vibrations. Flow-induced vibration mechanisms fail through mechanical wear, fretting, and fatigue cracking, ultimately causing tube leakage. Expensive plant shutdowns have led to studies into fluid cross-flow caused vibrations in steam generators and process heat exchangers. The current research investigated the effect of fluid elastic instability in heat exchangers using a regular triangular tube arrangement. Connor's equation was used to derive the relation between critical reduced velocity and mass damping parameters and to plot stability maps for a reduced velocity range of 1.19 to 5.97 m/s using a regular triangular tube arrangement. After doing amplitude, spectrum, and stability analysis, it is concluded that for the given case study ($P/D=1.45$, tube dia.=16mm), instability of the tube against the reduced velocity is more in both parallel and perpendicular flow directions when the tube was placed in the second row of the tube bundle.

1. INTRODUCTION

Shell and tube heat exchangers are prevalent mechanical devices in nuclear power, petrochemical, pulp and paper industries, food processing, chemical manufacturing, and power generation facilities. Excessive vibrations of the

heat exchanger tube, induced by fluid forces, may lead to tube-to-tube collisions and result in early tube failure owing to fatigue or fretting wear. Consequently, flow-induced vibration is a critical design consideration, particularly in the nuclear

power sector, owing to stringent safety standards and the exorbitant expenses associated with unanticipated plant shutdowns and repairs. The recognized processes of tube bundle excitation are: (a) turbulent buffeting, (b) vorticity excitation, (c) fluid-elastic excitation, and (d) acoustic resonance. The focus will be on fluid excitation, leading to an analysis of the FEI phenomenon and a description of the effects of various parameters on FEI. [1].

Tube bundles exposed to cross-flow exhibit vibrations even at minimal fluid velocities. The vibrations result from turbulence and may be superimposed vortex excitation. During the examination of stability theories (i.e., Analytical, Quasi-Static, and Semi-Analytical Models), it was noted that the escalation of upstream turbulence significantly influenced the stability threshold. Moreover, stability maps were created based on these theories. [2]. Fluid elastic instability

originates from self-excited forces that emerge from the interplay between tube motion and fluid dynamics. Fluid elastic instability often commences with fluid forces proportional to tube displacement, influencing the system's stiffness. The flow field surrounding an array of tubes displaces them from their initial positions, while the damping force endeavours to return them to their equilibrium state. Consequently, a struggle arises between fluid forces and damping. When the energy dissipated by damping exceeds the energy supplied by the fluid, vibrations diminish. This happens when fluid forces exceed damping forces, leading to an unstable state where the tube vibrates with considerable amplitude, potentially damaging heat exchanger tubes. This phenomenon is termed fluid elastic instability (shown in Figure 1).

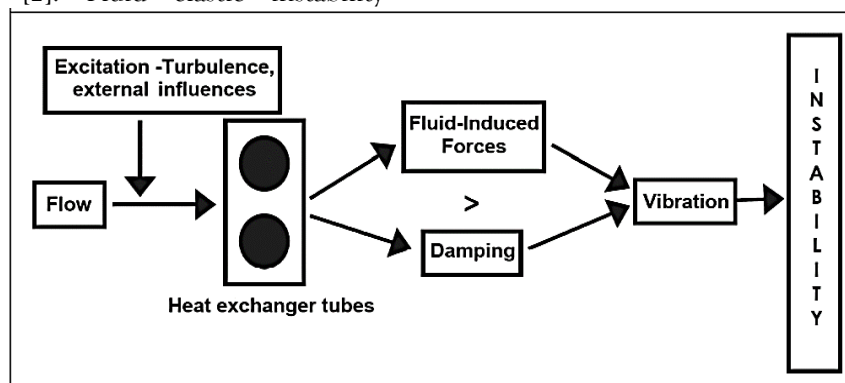


Figure 1: Fluid elastic instability schematic diagram

2. Literature Review

Amro Elhelaly comprehensively studied the phenomenon of fluid elastic instability in heat exchanger tube and its impact on the dynamic behavior of tube arrays in cross flow by using four different tube configurations, pitch ratios and array size. The effect on the onset of FEI in both transverse and streamwise directions was investigated [3].

Yibo Yin extensively analyzed the flow-induced vibrations characteristics of three tube arrangements: normal triangular, parallel triangular, and rotated non-regular triangular, under cross-flow conditions. The influence of tube bundle arrangement, pitch ratio, and the

rigidity of adjacent rods on FIV was examined. The theoretical model was adjusted by the experimental findings [3]. In heat exchangers, the tubes inside a bundle are generally the most flexible components of the unit. The theoretical stability boundary is profoundly affected by upstream turbulence. The current analysis suggests that the third row demonstrates the least stability at a pitch ratio 1.60 [1]. The instability threshold for rotating square tube arrays is deferred compared to parallel triangular tube arrays. The instability limits for large and finely finned tubes are postponed compared to plain tubes and are elevated for finned tubes with increased fin density [5]. When system damping is

minimal, a rise in flow velocity alters the stability characteristics of the tube array. At a specific flow velocity, the stability of the tube array attains the initial critical state, resulting in a dynamic bifurcation [6]. This led to the understanding that the critical velocities at instability are significantly high, requiring a greater flow capacity for the pump. To accurately imitate fluid elastic vibrations during tests, fin tubes are secured with solid rods of 260mm in length to reduce the natural frequency of the fin tube, thereby decreasing the critical reduced velocity at which instability occurs [7]. It was subsequently observed that internal tube flow resulted in increased vibration amplitudes within the tube relative to the absence of such flow. Damping had no significant effect on the vibrational properties of the tube within the present velocity range [2]. Additionally, to examine the vibrations of cylinders at different flow velocities and to obtain essential design data, it was noted that once the flow velocity reached a specific threshold, the amplitude of the cylinder's oscillation escalated swiftly with the flow [8]. The reduced velocity significantly influences the forces. Critical velocity is significantly influenced by the features of fluid dynamics forces, which fluctuate with lower velocity [9]. The analysis of the results suggested that fluid elastic instability may, in certain instances, be triggered by interactions with vortex shedding processes [10]. The impacts of turbulence and fluid-elastic excitation were examined individually and in conjunction. The U-tube with unsecured supports subjected to fluid-elastic and turbulent stresses did not exhibit fluid-elastic instability. Fluid-elastic instability emerged when additional supports were activated, aligning with the test results [11]. Furthermore, the mode-weighted averaging method is suitable for assessing the equivalent flow velocity under nonuniform flow conditions. Regardless of the mathematical model employed in the assessment, analogous findings are achieved [12]. The stability of the cylinder is significantly influenced by the geometric arrangement and spacing of the neighboring cylinders, despite their rigidity and lack of involvement in the dynamic analysis [13]. The instability of tube arrays exposed to cross flow

may be ascribed to fluid damping forces, fluid stiffness forces, or a combination. Therefore, the fluid force components must be forecasted to enhance the stability chart. Potential flow theory will most likely be deemed satisfactory [14]. Fluid elastic instability was detected in a straight tube bundle with a normal square pitch of 1.44 under air-water and steam-water flow conditions. Moreover, the damping of two-phase flow in air-water and steam-water systems is comparable, with a peak value of roughly 2% at a void fraction of about 0.5 [15]. The correlation length escalates significantly with tube vibration. The initiation of instability in a tube array escalates with variations in tube-to-tube frequencies and when certain tubes are fixed in place [16]. The lack of discrete flow areas in axial-flow-induced vibration has facilitated the advancement of analytical forecasting tools. Nonetheless, the designer's capacity to forecast vibration amplitude, without any specialized supporting data, is only marginally superior to one order of magnitude. In numerous instances, these vibrations are self-excited. The fluid-elastic process seems predominant in numerous applications; experiments have demonstrated that vortex shedding also transpires in arrays [17]. In certain instances, it is feasible to discern the predominant mechanism, whereas in others, multiple mechanisms interact with a lesser one. Impact of Nonuniform Flow. If the flow is non-uniform across the tubes, its impact is immediately considered [18]. The fluid elastic instability induces oscillation in the tube, with the oscillation frequency rising proportionally to cross-flow velocity. The effect of the supporting tube generates substantial impact forces on the tube, resulting in its unpredictable motion [19]. The aerodynamic noise in STHX-CHB is significantly lower than in STHX-SB at the same Reynolds numbers. STHX-CHB exhibits a remarkable enhancement in decreased resistance performance and a considerable decrease in aerodynamic noise, resulting in pressure drop and sound pressure decreases of 98% and 23%, respectively, relative to STHX-SB [20]. The lift force on a flexible vibrating tube mostly depends on the intensity of the tube's vibrations in its upward direction, with minimal influence from

the Degree of freedom, rotational direction, and principal vibration direction of the tube [21]. The external heat transfer rate of elastic tube bundles with varying tube arrangement configurations typically decreases with an increase in fluid pulsation frequency and rises with the fluid Reynolds number. Upon assessing various tube arrangement configurations, the overall transfer efficiency of tube bundles is ranked as follows: bilateral distribution- uneven configuration > one-sided allocation - uneven configuration > one-sided allocation - linear configuration [22]. The vibration amplitude and heat transfer coefficient of the HETB markedly increase with an elevation in entrance velocity or helix diameter. The impact of vibration-enhanced heat transfer escalates with an increase in entrance velocity. The average heat transfer factor on the upper side of the HETBs is 2.205 times superior to that on the lower side [23]. It may be deduced that tube vibration initially occurs in the stream-wise direction when flow velocity increases, followed by the cross-stream direction. The amplitudes of the front tubes exceed those of the rear tubes [24]. The revised code can precisely design shell and tube heat exchangers, including baffles, and furnish design specifications before damage caused by FEI [25]. The resonant frequencies depend on the fluid flow velocity, and buckling instability in these tubes can be seen at a flow velocity exceeding the critical threshold. Enhancing top tensions may reduce the influence of inside flow on pipe vibrations caused by vortex shedding [26]. The influence of tube positioning on unsteady behavior was examined, contrasting the outcomes of a singular elastic tube with those of a comprehensive elastic tube array, and analyzed in depth [27]. The flow velocity exceeded the starting point Hopf bifurcation (negative-damping fluid elastic instability), causing limit-cycle motion; additional increases in flow velocity resulted in erratic behavior due to the cylinder's interaction with the supports [28]. Alterations in the boundaries due to deformations in baffles

from extended usage and corrosion or scaling may increase or reduce the effective length of the tube, resulting in the underestimation or overestimation of natural frequencies [29]. The stochastic excitation forces and responses are computed for multi-span tubes for distinct velocity ranges. The quantity of velocity zones along a tube span is contingent upon the intricacy of the velocity and density distributions within the tube and the constraints of the computational code [30]. The model was altered to address several of the study's shortcomings. The primary distinction was incorporating a perturbation decay function to address the dissipation of disturbances from a vibrating tube. Consequently, the current model signifies a substantial enhancement compared to the previous lever and weaver approach [31]. The literature review reveals that the influence of fluid elastic instability on heat exchanger tube bundles with a diameter of 16 mm is little understood, and there is a lack of extensive experimental data. This study investigates the experimental analysis of heat exchanger tube bundle failures related to fluid-elastic instability in flow-induced vibrations using a normal triangular tube arrangement. Furthermore, the effects of instability will be analyzed across various flow velocities.

3 Experimental Setup

3.1 Low Speed Water Tunnel

Experiments were conducted in the low-speed water tunnel, with speeds in the test section ranging between 0.1 m/s and 0.6 m/s. The converging-diverging component of the device is fabricated from metal, whilst the test part is made of acrylic plastic. Figure 2 depicts the experimental configuration. The test component is 228.6 mm × 228.6 mm and comprises acrylic plates secured with screws. A 10-horsepower centrifugal pump and an 800-litre water tank maintain the closed-loop water circulation. The main valve at the water pump output controls water velocity in the test area, permitting increments of up to 0.10 m/s to attain its maximum value.

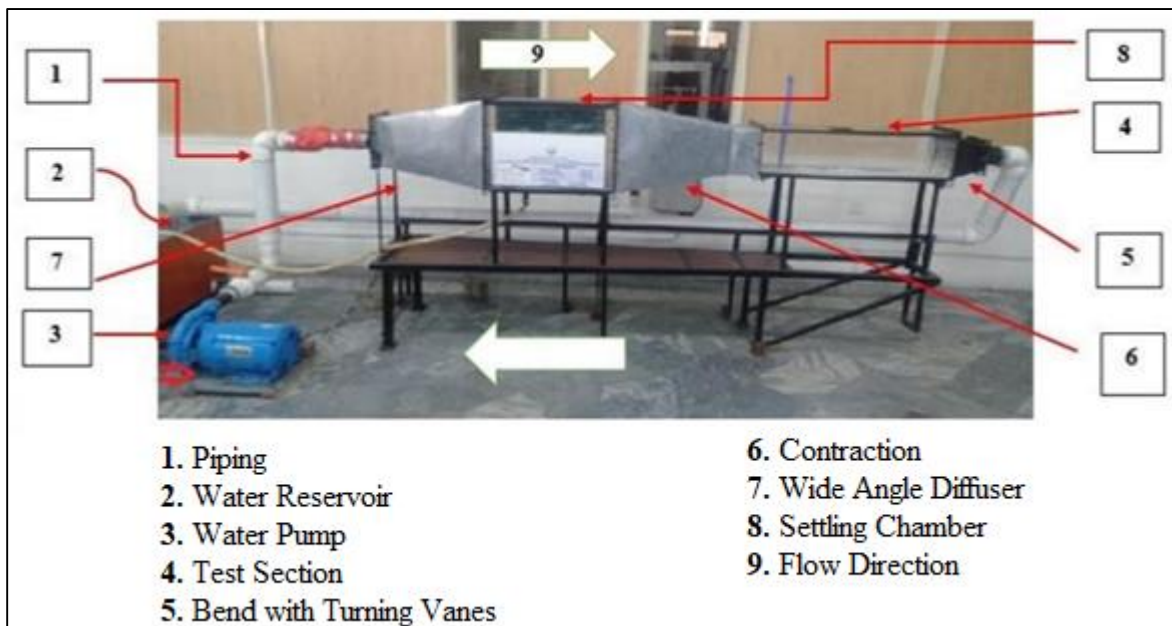


Figure 2: Low-speed water tunnel

3.2 Tube Bundle Preparation

The tube bundle was constructed in compliance with TEMA requirements. The concept, presented by Weaver and Lever, has been utilized by numerous researchers due to its considerable simplification of vibration analysis in tube arrays. However, it only implies, as it overlooks the stiffness phenomenon that transpires between the tubes inside a flexible tube array. This research

employed aluminum tubes to fabricate a standard triangular tube bundle. A standard triangle tube array had 25 tubes, one flexible and the remaining fixed within the assembly. A flexible tube was positioned near the center of the bundle, precisely in the fifth row from the upstream and the first row from the downstream side of the tube bundle. Figure 3 depicts the tube bundle configuration utilized in this experiment, with a P/d_o ratio 1.45.

3.2.1 Supporting End Plate Geometry

Supporting end plate geometry was designed on the Creo Software by TEMA standards, as shown in Figure

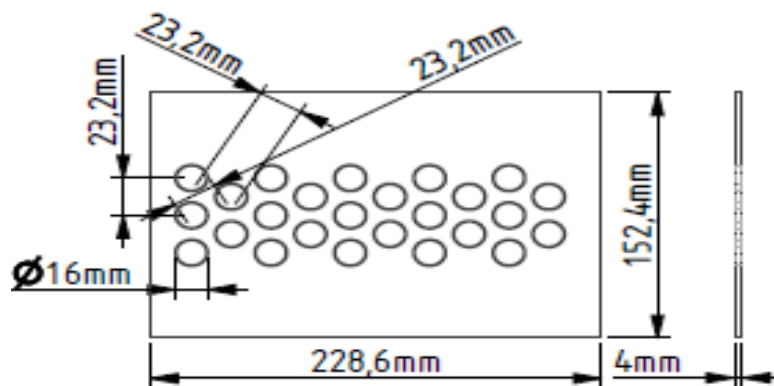


Figure 3: Supporting end plate drawing of NTA with P/d_o ratio of 1.45

3.2.2 Specifications of Tube Bundle

Specifications of the tube bundle being used are given below:

Table 1: Tube bundle specifications

Material of Tube	Aluminium
Number of tubes	25 for NTA
Type of tube array	Normal Triangular
Tube Mass	86 g
Pitch to Dia (P/d_o) ratio	1.45
Outer/Inner tube diameter	16 mm
Length of Tube	228.6 mm
Modulus of Elasticity of the material	69000 MPa
Density of water	999.9 kg/m ³
Thickness of Baffle	4.5 mm

3.2.3 Tube Bundle Configuration

Figure 4 illustrates the tube bundle arrangement used in this experiment with a P/d_o ratio 1.45.



Figure 4: Tube bundle configuration

The flexible tube, under observation, was attached with a tri-axial accelerometer to record vibrations in both the parallel and perpendicular flow directions, with the tube's natural frequency set to approximately 8.5 Hz. The monitoring tube was attached with 0.2 mm-thick piano wire, which was tightened to modify its natural frequency. The accelerometer was fixed to the upper section of the monitored tube to record the movement of the tube in cross-flow. The entire setup was upheld by two acrylic plates: one for securing the rigid tubes and the other for accommodating the tensioning mechanism. The tube bundle plates were designed and fabricated to conform to the water tunnel's

test section standards. The plates typically measured 228.6 mm by 152.4 mm. Before the tests, the plates were secured in the testing section to prevent variations.

3.3 Experimental Procedure

Experiments on each tube have been carried out in the following steps.

3.3.1 Natural Frequency

After the attachment of the accelerometer to the flexible tube, it is subsequently placed into the tube array to determine its natural frequency. Damping is a critical characteristic in vibrations,

and for the analyzed tube array, the aim is to ensure that only mechanical damping is present inside the system. All tubes in the array were secured, except the instrumental tube, which was detached. The amplitude reduction was subsequently documented and evaluated using FFT to determine the natural frequency of the

tube, which remained consistent across all tubes at 8.5 Hz with an error margin of ± 0.05 . Furthermore, the signal conversion process from Node Commander to FFT is illustrated in Figure 5.

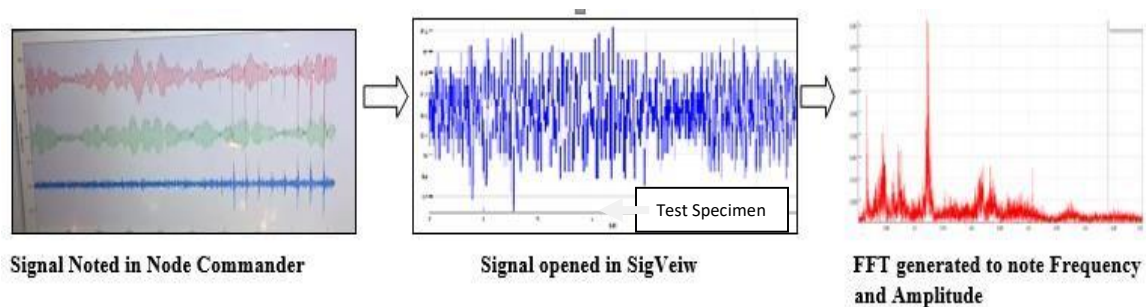


Figure 5: Procedure for converting a signal recorded in Note Commander to FFT

3.3.2 Signal Analysis

The accelerometer’s signal was recorded and observed using the application Node Commander. The software archives the data in an Excel file. The signal was evaluated by transferring

data from Excel files to text files, which were subsequently examined using signal analysis software, Sigview. The data acquisition loop is illustrated in Figure 6.

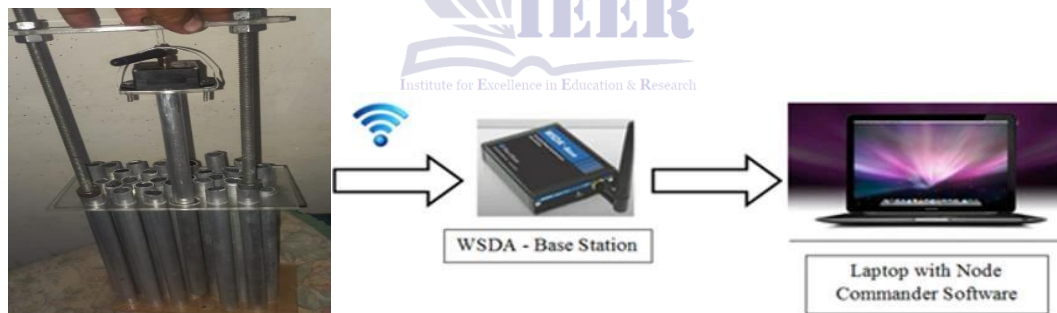


Figure 6: Data acquisition loop

3.3.3 Parameters for Current Research

The following parameters were used during the research. Selected parameters are explained in Table 2, given below:

Table 2: Parameters for current research

Parameter	Considered Value
Tube material	Aluminium
Number of tubes	25
Type of tube array	Normal Triangular
Mass of the tube	86 g
P/D ratio	1.45
Tube outer/inner diameter	16 mm

Tube length	228.6 mm
Modulus of Elasticity	69000 MPa
Density of water	998 kg/m ³
Thickness of Supporting End Plate	4.5 mm
Frequency	8-10 Hz
Flow Velocity	0.1-0.5 m/s

4. Results and Discussions

This research investigates the impact of fluid-elastic instability in heat exchanger tube bundles with a standard triangular tube arrangement. The results, presented as amplitude response and frequency spectrum, illustrate the behavior of the tube within the normal triangular array of tubes. The experimental results were validated using the

stability map by plotting the test results against published mathematical models.

4.1 Natural Frequency

The natural frequency of a single flexible tube was obtained using the pluck method. The tube is initially excited and then set for free vibrations. The free vibration frequency corresponds to the natural frequency of the tube.

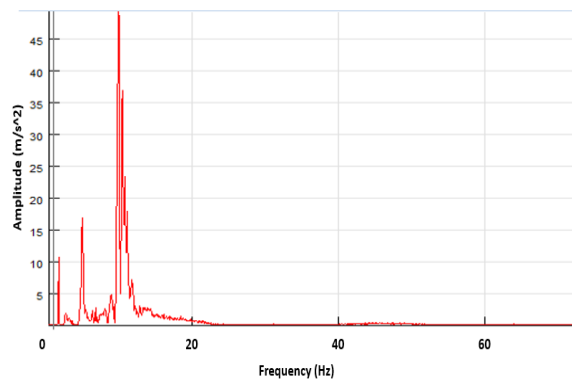


Figure 7: FFT response of the received vibration signal

As presented in Figure 7, the natural frequency was nearly 8.5-9.5 Hz. The tube’s translational and rocking modes were also observed here.

4.2 Amplitude Responses of Tube

4.2.1 Streamwise and Transverse Reactions of a Tube

Figure 8 depicts the streamwise and perpendicular response of the observed tube in a regular

triangular tube bundle arrangement, having a pitch to diameter ratio of 1.45, subjected to water crossflow. The monitored tube was arranged across five rows, and its location within the tube bundle markedly affects its reaction behaviour.

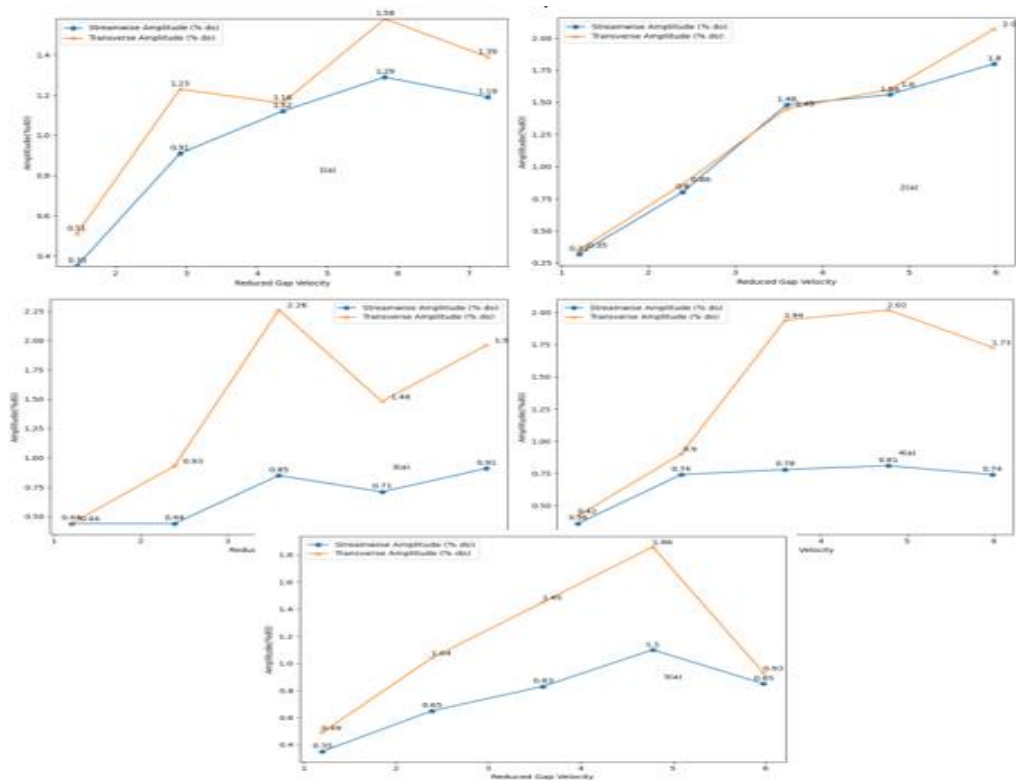


Figure 8: Amplitude response of flexible tube in normal triangular tube bundle arrangement with pitch ratio of 1.45 when tube was placed in 1(a) First row 2(a) Second row 3(a) Third row 4(a) Fourth row 5(a) Fifth row

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Figure 8(a) depicts instability in both the parallel and perpendicular flow directions for the monitored tube located in the first row of the tube bundle, with the highest amplitudes of less than 1.29% and 1.58% of the tube diameter, respectively. The flexible tube in the first-row exhibits instability at a reduced velocity of approximately 5.9 m/s in parallel and perpendicular flow directions. Figure 8(b) depicts instability in both the parallel and perpendicular flow directions for the flexible tube located in the second row of the tube bundle, with peak amplitudes of less than 1.8% and 2.07% of the tube diameter, respectively. The monitored tube in the second-row exhibits instability at a reduced velocity of approximately 5.9 m/s in parallel and perpendicular flow directions. Figure 8(c) depicts instability in both the parallel and perpendicular flow directions for the flexible tube in the third row of the tube bundle, with maximum

amplitudes of less than 0.85% and 2.26% of tube diameter, respectively. In the third row, the observed tube exhibits instability at a reduced velocity of approximately 3.5 m/s in both the parallel and perpendicular flow directions. Figure 8(d) depicts instability in both the parallel and perpendicular flow directions for the flexible tube in the fourth row of the tube bundle, with maximum amplitudes of less than 0.81% and 2.02% of the tube diameter, respectively. The monitored tube in the fourth-row exhibits instability at a reduced velocity of around 4.8 m/s in both the parallel and perpendicular flow directions. Figure 8(e) shows instability in both the parallel and perpendicular flow directions for the flexible tube in the fifth row of the tube bundle, with maximum amplitudes of less than 1.1% and 1.86% of the tube diameter, respectively. In the fifth row, the observed tube shows instability at a reduced velocity of around

4.8 m/s in both the transverse and streamwise orientations.

4.2.2 Resultant Amplitude and Reduced Velocity for Tube Bundle

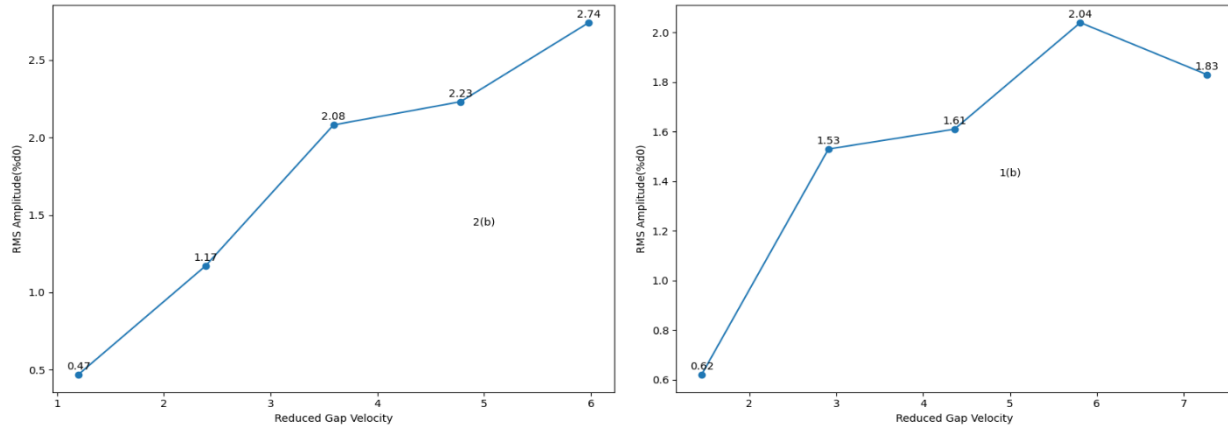


Figure 9 depicts the amplitude comparison of the monitored tube inside five rows of a standard triangular tube bundle featuring a pitch-to-diameter ratio of 1.45, exposed to water crossflow. The resultant amplitude of the observed tube has been plotted as a function of reduced velocity.

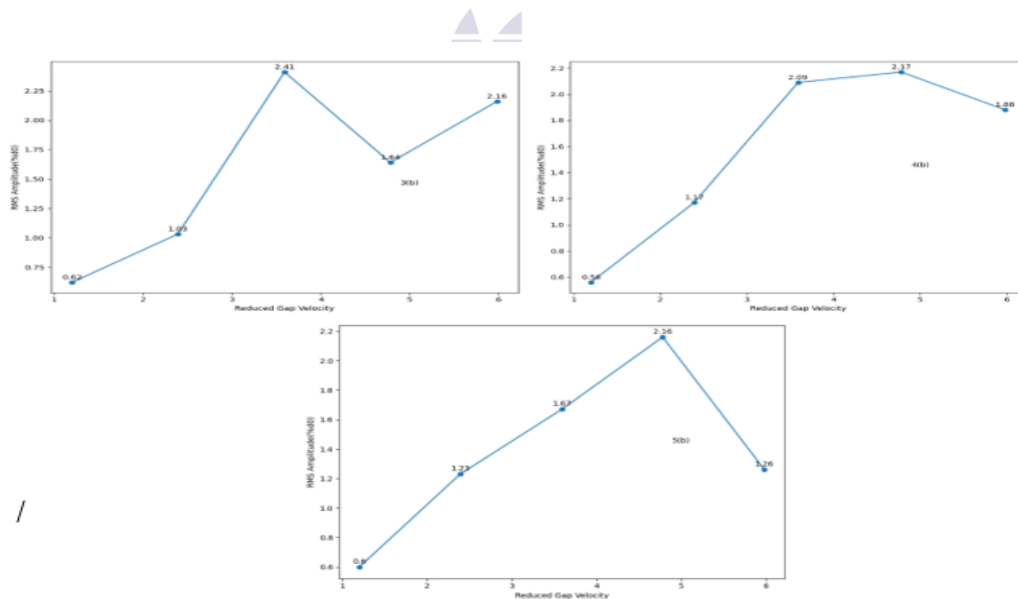


Figure 9: Resultant amplitude response of flexible tube in normal triangular tube bundle arrangement with pitch ratio of 1.45 when tube was placed in 1(b) First row 2(b) Second row 3(b) Third row 4(b) Fourth row 5(b) Fifth row

4.2.3 Stability Analysis

The stability diagram in Figure 10 below shows the current study plot over already available models, i.e., Price (1995), Weaver and Fitzpatrick (1988), and Pettigrew and Taylor (1991).

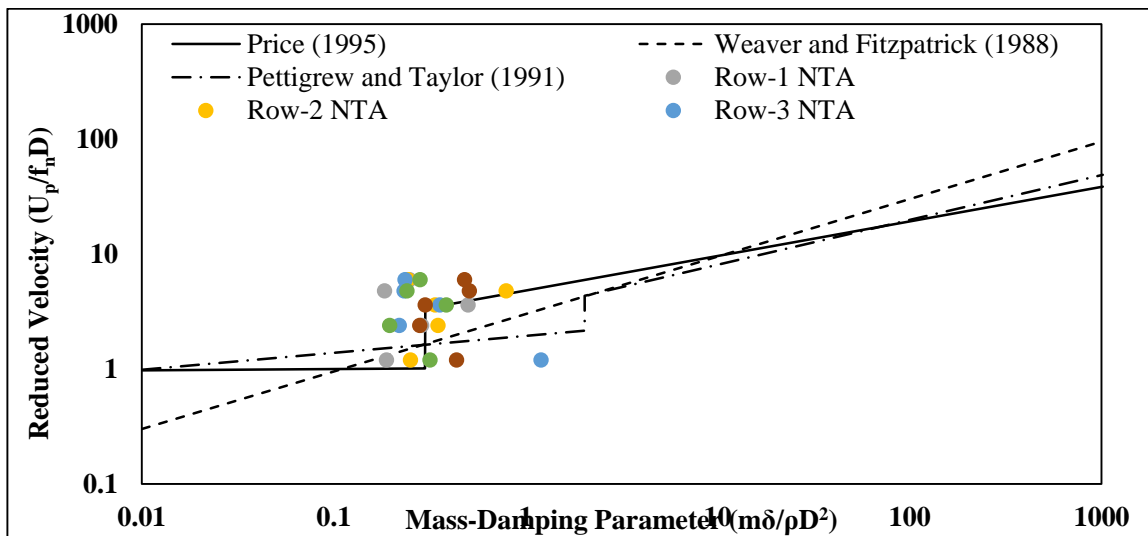


Figure 10: Stability diagram of a single flexible tube bundle for a regular triangular tube arrangement with (P/d_o) ratio of 1.45

Figure 10 of the stability diagram illustrates that the data points fall within the theoretical stability bounds for a single flexible tube bundle across all standard triangular tube configuration arrangements. Furthermore, the third row was determined to be more critical than the others. It may be noted that both the layout of the tubes and the flow velocity significantly contribute to the instability observed in the monitored tube.

5. Conclusions

This study is concerned with the effect of fluid-elastic instability in a heat exchanger tube bundle subjected to cross flow with a standard triangular tube arrangement at different reduced velocities (V_r) values and its validation with the already published mathematical models. The observed tube response in both the parallel and perpendicular flow orientations appear to be significantly influenced by its position within a particular row. The second row is critical as it generates rapid instability in the monitored tube, especially in the perpendicular flow direction. The following results are drawn from the analysis;

1. From amplitude analysis, it is concluded that rows 2, 3, 4, and 5 experience instability in

the transverse flow direction because their RMS amplitude value exceeds 2.0% of the tube diameter. However, row 2 is the most vulnerable among the others.

2. From the resultant amplitude analysis, it is concluded that the second row is the least stable among the others at the reduced velocity value of 5.9 m/s.

3. The stability map depicts that some of the current data points lie under the theoretical stability boundaries, whereas more data lie above them, which shows more instability for rows 1-5 in the case of a normal triangular tube arrangement.

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