Int. J. Mech. Eng. & Rob. Res. 2013

International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 2, No. 2, April 2013

Review Article

REVIEW ON FLUID-ELASTIC INSTABILITY IN FINNED TUBE ARRAYS

Vikram B Yadav[1]*, S R Desai[2] and M M Mirza[1]

**Corresponding Author: Vikram B Yadav,* ✉ *vikramautomobile1@gmail.com*

Among several flow induced vibration mechanisms, fluid elastic instability can cause a fretting wear of tubes of heat exchanger in a short time. For plain tube array of heat exchanger much research is carried out but for finned tube arrays very less work is carried out by considering different parameters. Effect of different parameters of finned tube array on fluid elastic instability, also concept of effective diameter and Connor's equation are described in this work. This paper reviews theoretical analysis of fluid elastic instability in finned tube array and review on work carried out by different researchers in fluid elastic instability. Lastly the scope to find out effect of various parameter of finned tube array on a fluid elastic instability are clearly described.

Keywords: Connors equation, Effective diameter, Finned tube, Fluid elastic instability

INTRODUCTION

Shell and tube heat exchangers are common mechanical equipments utilized in nuclear power, petrochemical, pulp and paper industries, food industry, chemical, and power plants. When the fluid forces cause excessive vibrations of the heat exchanger tubes, tube-to-tube clashing may occur and premature tube failure may arise due to fatigue or fretting wear. As such, flow-induced vibration is an important design concern, especially in the nuclear power industry due to the strict safety regulations and the extremely high cost of unplanned plant shutdown and repair (Shravan *et al.*, 2011).

Flow induced vibrations in structures is caused due to the different five mechanisms namely, i) Turbulent Buffering, ii) Vortex Shedding, iii) Jet switching, iv) Acoustic Resonance, v) Fluid elastic instability. Out of different mechanisms of flow induced vibrations, fluid elastic instability mechanism is very crucial mechanism. Fluid elastic instability has been recognized as a major cause of failure in shell and tube type heat exchangers due to tube repairs and plant down

1 Department of Mechanical Engineering, R. I. T. Sakharale, Maharashtra, India.
2 Department of Automobile Engineering, R. I. T. Sakharale, Maharashtra, India

time. Damage caused by first four mechanisms is in over the service of years, but damage caused by fluid elastic instability is in matter of hours. Fluid elastic instability causes sudden and huge failure of heat exchanger. Therefore, fluid elastic vibrations in heat exchanger tube arrays are required to be predicted so that same can be taken into account during mechanical design of the heat exchangers without compromising their thermal performance (Deepanjan *et al.*, 2009; and Shravan *et al.*, 2011). Marwan Hassan et al. have described estimation of Fluid elastic instability in tube arrays by using numerical approach. The fluid elastic forces are approximated by the coupling of unsteady flow model with CFD. The effect of pitch to diameter ratio, Reynolds number on FEI threshold was also investigated (Hassan and Hayder, 2008; and Marwan *et al.*, 2010).

For plain tube bundles of heat exchanger, much research is conducted over the past 40 years and given design guide-lines to prevent fluid elastic instability in heat exchanger tube arrays. A rare study is carried out for fluid elastic instability in finned tubes.

This paper gives comprehensive review on fluid elastic instability in finned tube arrays. Effect of finned tube parameters, on fluid elastic instability is presented in this paper. A review on concept of an “effective diameter” also given in this paper.

FLUID-ELASTIC INSTABILITY AND ITS MECHANISM

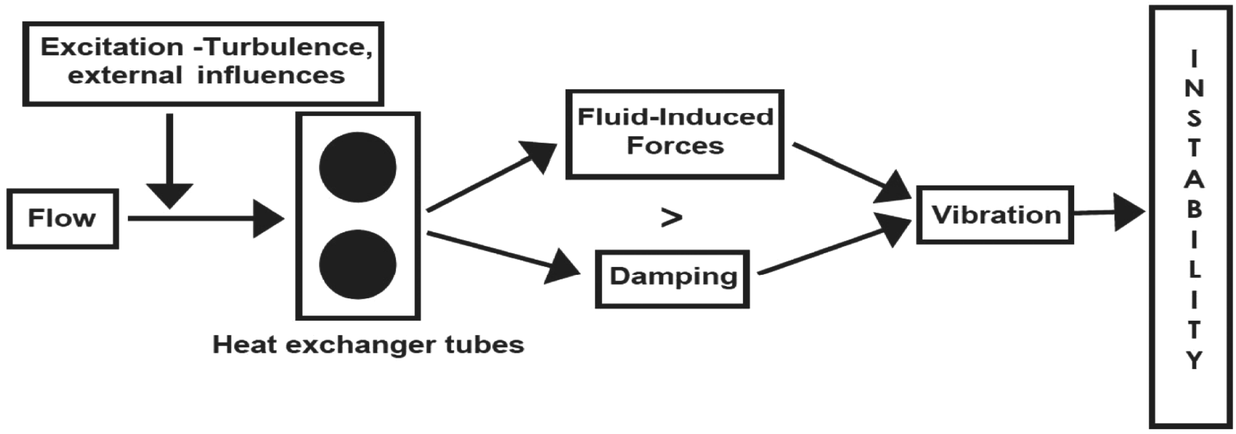
The phenomenon of fluid elastic instability can be described as a mechanism between tube motion and fluid forces. When a tube bundle is subjected to cross flow, the tubes vibrate with an amplitude proportional to the upstream flow velocity until the flow velocity reaches a threshold limit called the critical velocity where the tube’s response amplitude increases dramatically, potentially causing catastrophic failure.

From a mechanistic view, the flow field around an array of flexible tubes causes the tube to be displaced from its initial position. This displacement causes a further shift in flow field changing the fluid forces acting on the tubes. The damping force of the tube that tries to restore it back to its equilibrium position opposes this change in fluid force. Thus, a competition results between the energy input by the fluid force and the energy expended in damping. When the energy expended in damping is more than the energy input by the fluid, the vibrations die down. However, if the fluid forces dominate, sufficient energy is imparted to the tube to sustain the vibrations and an unstable situation is reached where the tube vibrates with large amplitude. In tube heat exchangers, this limit is known as fluid-elastic instability and leads to tube damage. A schematic of this mechanism is shown in Figure 1.

TWO PHASE FLOW INDUCED VIBRATION OF TUBE BUNDLES

Deepanjan *et al.* (2009) carried out work for two phase flow induced vibration of tube bundles. They had conducted experiments in air water cross flow with a fully flexible 5 $\times$ 3 normal square array having pitch to diameter ratio of 1.4. The tubes have a diameter of 0.016 m and a length of 0.21 m. The vibrations are

Figure 1: Mechanism of Fluid-Elastic Instability in a Tube Array



measured by using strain gages installed on piano wires used to suspend the tubes. They had compared instability results with the air water experiments of Joo and Dhir with a single flexible tube in rigid array and comparison of results when plotted using the Connor's criteria indicates that the instability threshold is lower for a fully flexible array as compared to a flexible tube in a rigid array. Flow induced vibration characteristics of a U-tube bundle were experimentally investigated in air-water two-phase flow by In-Cheol *et al.* (2011). For experimentation they used rotated square array with a pitch of 31.11 mm and pitch to diameter ratio of 1.633. Vibration responses of six U-tubes were measured with ten 3-axis accelerometer. The instability constant of the Connor's equation for the U-tube bundle was evaluated to be in the range of 6.5-10.5. Much study is required to find out effect of different two phase fluid flow on a fluid elastic instability.

CONCEPT OF AN EFFECTIVE DIAMETER

Finned tubes have been used for their increased heat transfer performance. So researchers have required to develop the concept of an effective diameter, which allows the users of finned tubes to convert their finned tube into an equivalent bare tube. This allows the designers of heat exchangers to use the existing bare tube data available to predict the response of finned tubes. An effective diameter concept was developed to allow the performance of finned tubes to be compared to that of bare tubes. If this idea should prove to be valid, this might permit the vast data available for bare tubes to be used for predicting the performance of finned tubes. Several different models have been suggested for the effective diameter D_{eff} of finned tubes. Mair et al. suggested a model based on the projected area of the finned tube.

$$D_{eff} = D_b + \frac{t\left(D_f - D_b\right)}{p} \qquad ...(1)$$

where p is the fin pitch, t is the fin thickness, D_f is the fin diameter, and D_b is the bare tube diameter.

Another model was suggested by Halle *et al.* which is a volumetrically based effective diameter but no equation was provided. Hirota *et al.* also proposed an effective diameter based on fin volume in the form of

$$D_{vol} = \sqrt{\left(D_f^2 - D_b^2\right)\frac{t}{f} + D_b^2} \qquad ...(2)$$

Although the definition for the volumetric effective diameter is different from the effective diameter of Mair *et al.*, the difference between the two values is between 4% and 6%. An area based model presented by Harrison, was used in heat transfer for comparing different types of finned tubes, including plate and tube heat exchangers. This model is a weighted average of the surface areas of the tube and fins. The heat transfer results of different finned heat exchangers collapse quite well using this method. The calculation of this effective diameter is quite lengthy for a serrated, helically wound finned tube. Mair *et al*. showed that their effective diameter predicts vortex shedding over plain no helical winding, no serration finned tubes quite well and it has been shown that this model is reasonable for predicting vortex shedding from serrated, helically wound finned tubes (Robert and David, 2010; and Wang and David, 2012).

FINNED TUBE ARRAY

A rare study is carried out for fluid elastic instability in finned tube arrays. Research in fluid elastic instability in finned tube array has been driven by Robert and David (2010) and Wang and David (2012). They considered different tube array geometry like: i) Normal parallel triangular array, ii) Parallel triangular array, iii) In-line square tube array, iv) Rotated square tube array for these different tube array geometry, effect of fins on fluid elastic instability are determined.

Parameters of Finned Tube Array

- Fin density,
- Fin height,
- Fin thickness,
- Fin material,
- Finning length
- Fin pitch.

Fin Density: Fin density means, the number of Fins Per Inch (FPI) on a finned tube. Fin density affects on the damping of tube, the damping increases monotonically with the addition of fins and increasing fin density. Depending on number of fins per inch, finned tubes are classified in two types: i) Coarse finned tube, ii) Fine finned tube. As the number of fins per inch are rare say up to 1-4 FPI then it is called as coarse finned tube and if fins per inch are more say up to 5-9 FPI then it is called as fine finned tube.

Fin Height: Fin height of fin gives the fin diameter of finned tubes. As the fin height of finned tube increases, then an effective diameter increases.

Fin Thickness: An effective diameter is directly proportional to the fin thickness of finned tubes. According to fin height of finned tube, thickness of fin varies. If fin height increases its fin thickness also increases and vice versa.

Fin Material: Fin material of finned tube affects on the natural frequency of finned tube. Density of different material are different. So, as the density of fin material increases its natural frequency decreases.

Finning Length: Finning length of finned tube gives, length of tube on which fins are fabricated. Finning length is considered according to dimensions of test section.

Fin Pitch: Fin pitch is the distance between the two consecutive fins of finned tube. Fin pitch affects on a natural frequency of finned tube. As fin pitch decreases, then the natural frequency of tube decreases.

Fluid Elastic Instability in Finned Tube Array

Connor's Equation: Connor's critical flow velocity equation has been used as a key parameter to measure the incipient of ûuid elastic instability. One particular aspect of modeling ûuid elastic instability is the use of Connors equations, which express the critical velocity for ûuid elastic instability to occur. Following Equation (3) gives Connor's equation.

$$\frac{V_{cr}}{F_n D} = K\left(\frac{m\delta}{\rho D^2}\right)^a \qquad ...(3)$$

where, V_{cr} = critical pitch flow velocity, D = diameter of tube, F_n = structural Natural frequency, m = tube mass per unit length, δ= logarithmic decrement, K, a = connors constants (V_{cr}/F_nD) = reduced velocity (Stuart, 2001).

Experimental Results of Finned Tube Arrays

Experimental results for finned tube array of different tube array geometry are derived by Robert and David (2010) and Wang and David (2012). They considered an array of industrial serrated finned tubes with much larger fin height. The specification of fins for: i) In-line square tube array, ii) Rotated square tube array, iii)) Normal parallel triangular tube array, iv) Parallel triangular tube array geometries are as shown in Table 1.

For in line tube array and rotated square tube array 88.2 mm tube pitch is taken. For normal parallel triangular tube array and parallel triangular tube array geometries 89.2 mm tube pitch is taken. In this experimental study h/D_b ratio 50% is taken, where h is fin height and D_b is a base tube diameter. Base tube diameter D_b is 38.3 mm (Robert and David, 2010; and Wang and David, 2012).

Experimental Results of Critical Reduced Velocity for in-Line Square Tube Array and Rotated Square Tube Arrays of Finned Tubes

For both tube array geometry, 3.3 *fpi* and 5.7 *fpi* finned tubes and a bare tube were considered. Tube pitch and mass ratio were kept constant. While addition of fins to in-line tube arrays, the critical velocity is delayed becomes less well defined. In in-line square tube array tubes become unstable at a reduced velocity about 53. For in-line square array, the fins appear to stabilize the tubes to higher critical reduced velocity.

Table 1: Specification of Fins

Type of Fin	No. of Fins per inch (*fpi*)	Fin Width in mm	Fin Thickness in mm	Fin Pitch in mm	Fin Height in mm
Serrated Fin	3.3	4.4	1.3	8.4	18.5
	5.7	4.5	1.3	4.2	19.1

In rotated square tube array, all tubes become unstable at a reduced velocity of about 42. The addition of fins to the rotated square tube array, appears to reduce the fluid elastic threshold value and make it more clearly defined. Experimental results of critical reduced velocity for both in-line square tube and rotated square tube arrays are shown in Table 2 (Robert and David, 2010).

Table 2: Experimental Results of Critical Reduced Velocity for In-Line Square Tube and Rotated Square Tube Arrays

Tube Type	Reduced Velocity (V_{cr}/F_nD_{eff})	
	In-Line Square Tube array	Rotated Square Tube Array
Bare	19	50-75
Serrated Finned Tube with 3.3 *fpi*	44	42
Serrated Finned Tube with 5.7 *fpi*	48 ± 5	35

Experimental Results of Critical Reduced Velocity for Parallel Triangular Tube Array and Normal Parallel Triangular Tube Array of Finned Tubes

For both tube array geometry, 3.3 *fpi* and 5.7 *fpi* finned tubes and a bare tube were considered. Tube pitch and mass ratio were kept constant. Parallel triangular array of coarse finned tube become unstable at a reduced velocity of about 53 and that of fine finned tube array critical reduced velocity is about 46. For fine finned tube array critical reduced velocity is well defined and it is less than that of the coarse finned tube array. In normal triangular array, coarse finned tubes become unstable at a critical reduced velocity about 72 and that of fine finned tube becomes unstable at a critical reduced velocity about 43. The critical velocities in normal and parallel triangular arrays are substantially delayed by the addition of coarse serrated fins (Wang and David, 2012).

CONCLUSION

Major failure of shell and tube type heat exchangers in short time are caused due to fluid elastic instability. Fluid elastic instability is the most important vibration excitation mechanism for heat exchanger and steam generator tube bundles. It leads to very high vibration amplitude of tubes of heat exchanger tube bundles. Due to fluid elastic instability vibrations, short term failure of heat exchanger tube bundles occur by fatigue and wear. This failure of tube bundles directly affects on efficiency of heat exchanger and also on over all plant performance.

From literature survey, it is observed that the rare work has been carried out for fluid elastic vibrations of finned tube arrays considering effect of different variable parameters. So there is wide scope to determine fluid elastic vibration response of finned tube array of heat exchanger. An effective diameter concept was used to allow the performance of finned tubes to be compared to that of bare tubes. For serrated finned tube array effect of fluid elastic instability are determined by considering different tube array geometry. So there is scope to find out effect of fins, tube array geometry, pitch to diameter ratio etc. on fluid elastic instability in finned tube array and much more study is required for that.

REFERENCES

1. Deepanjan Mitra, Vijay K Dhir and Ivan Catton (2009), “New Experimental Data

and Analysis for Two-Phase Flow-Induced Vibration of Tube Bundles: Preliminary Results", Department of Mechanical and Aerospace Engineering, University of Los Angeles, Los Angeles, USA.

2. Hassan M and Hayder M (2008), "Modelling of Fluidelastic Vibrations of Heat Exchanger Tubes with Loose Supports", *Journal of Nuclear Engineering and Design*, Vol. 238, pp. 2507-2520.

3. In-Cheol Chu, Heung June Chung and Seungtae Lee (2011), "Flow Induced Vibration of Nuclear Steam Generator U-Tubes in Two-Phase Flow", *Journal of Nuclear Engineering and Design*, Vol. 241, pp. 1508-1515.

4. Marwan Hassan, Andrew Gerber and Hossin Omar (2010), "Numerical Estimation of Fluidelastic Instability in Tube Arrays", *Journal of Pressure Vessel Technology*, Vol. 132.

5. Robert H Lumsden and David S Weaver (2010), "The Effect of Fins on Fluid Elastic Instability in In-Line and Rotated Square Tube Arrays", *Journal of Pressure Vessel Technology*, Vol. 132.

6. Shravan H Gawande, Appasaheb A Keste, Laxaman G Navale, Milindkumar R Nandaonkar, Vaishali J Sonawane and Umesh B Ubarhande (2011), "Design Optimization of Shell and Tube Heat Exchanger by Vibration Analysis", *Modern Mechanical Engineering*, Vol. 1, Augutst 15, pp. 6-11.

7. Stuart J Price (2001), "An Investigation on the Connors Equation to Predict Fluid Elastic Instability in Cylinder Arrays", *Journal of Pressure Vessel Technology*, Vol. 123, April, pp. 448-453.

8. Wang J and David S Weaver (2012), "Fluid Elastic Instability in Normal and Parallel Triangular Arrays of Finned Tubes", *Journal of Pressure Vessel Technology*, Vol. 134.