Techniques for Thermal Damping in Tube Bundles

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ABSTRACT

Flow-induced vibration in heat exchangers has been a source of concern in the process, power generation and nuclear industry for several decades. Damping has a major influence on the flow induced vibrations and is dependant on a variety of factors such as mechanical properties of the tube material, geometry of intermediate supports, the physical properties of shell-side fluid, type of tube motion, number of supports, tube frequency, shell-side temperature etc. Various damping mechanisms have been identified and quantified. Generally, the effects of the higher operating temperatures on the various damping mechanisms are neglected in the general design procedure. This paper focuses on the thermal aspects of damping mechanisms subjected to single phase cross-flow in shell and tube heat exchanger and a comparison is carried out safer design based on experimental and empirical formulations.

Key Words: **Thermal Damping, Tube Bundles, Damping Mechanisms, Flow Induced Vibration, Heat Exchangers, Steam Generators, Multi Span.**

1. INTRODUCTION

Many incidents of failure of heat exchangers due to apparent flow-induced vibration have been reported [1]. Specifically, shell and tube type heat exchangers experience flow induced vibration due to high velocity flow over the tube banks. Flow-induced vibration in these heat exchangers leads to equipment breakdown and hence expensive repair and process shutdown.

For flow over a tube bank or array, the type of instability mechanism known as fluid elastic instability is the major cause of flow-induced vibration. 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 alteration in flow field changing the fluid forces acting on the tubes [2]. The damping force of the tube that tries to restore it back to its equilibrium position opposes this change in fluid force. Thus, a balance 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 diminish. However, if the fluid forces dominate, sufficient energy is imparted to the tube to sustain the vibrations and an

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unstable situation is reached where the tube vibrates with large amplitude. The damping of heat exchanger tubes is of primary importance especially when gas is the shell side fluid. System damping has a strong influence on the amplitude of vibration. Damping depends upon the mechanical properties of the tube material, geometry of intermediate supports and the physical properties of shell-side fluid. The importance of damping is further highlighted due to current trend of larger exchangers with increased shell-side velocities in modern units. The damping of a tube is a measure of its ability to absorb energy [3]. It is characterized by its damping ratio, , associated with the fundamental mode of lateral vibration of the tube. The damping ratio is a function of the ratio of the energy dissipated by the structure due to damping to the total stored energy. Most commonly used methods for the measurement of damping is presented by Mitra [4]. Yang, et. al. [5] implemented this technique and showed its applicability to random excitation utilizing only the response data. Damping can be calculated by several different methods including log decrement from autocorrelation to response to white noise input or from a "plunk" test, magnification factor at resonance, bandwidth of frequency response function and measurement of input power at resonance as concluded by Wambsganss, et. al. [6]. Damping ratio can also be calculated by the curve fit method suggested by Pettigrew, et. al. [7]. There are several possible energy dissipation mechanisms that contribute to tube damping [8]. Pettigrew concluded that the effect of material damping was negligible and found that its effect is only found in ends welded tubes having no intermediate support. Erskine, et. al. [9] also highlighted the influence of tube material and Young's modulus variation with temperature as one of the cause of damage. The variation of modulus of elasticity of tube material with the increase in temperature can be significantly high; up to 10% for 3.5% nickel steel over a 20-300°C temperature range and up to 16.7% for 0.15% carbon steel over a temperature range of 20-500°C [10-11] and the fundamental natural frequency of the tube is also dependant on the modulus of elasticity [12]. Throughout the paper, the term "natural frequency" will denote the fundamental natural frequency of lateral vibration of the tube. Upon significant increase of temperature, the resultant theoretical natural frequency can decrease by up to 3-4% of the original natural frequency at room temperature conditions based on the formulation developed by Lowery, et. al. [12]. Collard, et.al. [13] however, noted no significant change in damping due to the decrease in stiffness of tube. Hartlen and Simpson [14] have observed the tube frequency and damping characteristics are sensitive to temperature. First the natural frequency is modified because the tube vibration is less constrained. Secondly the interaction between tube and baffle provide friction sites that dominate the tube damping. Natural frequency is the measure of the rigidity of tube. It is inversely proportional to the span length squared, Lowery, et. al. [12]; the natural frequencies of support-inactive modes can be significantly lower than those of support-active modes as examined by Chen, S.S., [15]. These terms will be proportional to the fluid density so that for the same motions of the structures the magnitude of these terms will depend directly on the density ratio between the fluid and the structure [16]. Thus, in water the structural damping will often be relatively small compared to the hydrodynamic damping, and may therefore be of secondary influence; while in air the reverse may be true. Since the added mass may vary considerably, this means that the eigen frequencies are not well defined in water [16]. Goyder [17] developed an assessment equation for the evaluation of damping based on the statistical average and mode shape factor. This method needs more research to mature as a method. A number of researchers have found an increase of damping with large amplitudes. The reason is the contact with the baffle tube. Taylor, et al. [18] carried out tests with different temperatures 25, 60 and 90°C. Their results indicated a slight increase change in damping over the range of temperatures tested and a decrease of viscous damping and no significant effect on wear rate. Carlucci, et. al. [19] was found that two-phase damping varied in inverse proportion to the combined cylinder and two-phase hydrodynamic masses. Dynamic interaction between tube and supports may be categorized in three main types, namely: sliding, impacting, and scuffing, which is impacting at an angle followed by sliding. Nakamura, et. al. [20] have emphasized the importance of carrying out two-phase tests at high temperature and pressure. Very recently Khushnood, S., et. al. [21-22] carried out experimental analysis of thermal aspects of damping in tube bundles under no flow and heated water flow. The material properties required for the experiment has been taken from the ASME Boiler and Pressure Vessel Code [23]. Iqbal, Q., et. al. [24-27] has carried out critical investigation of damping mechanism in flow induced vibrations and utilized theoretical and experimental techniques to elaborate thermal damping in shell and tube heat exchangers. Liu [28] develop a mathematical process to determine unknown mechanical parameters from measured vibration data for inverse vibration problem. In this study the data of displacement are chosen in order to identify a time-dependent function of damping or stiffness.

The objective of this paper is to study the effects of temperature on the overall damping of shell and tube heat exchanger. Experimental testing was carried out on tube bundles at varying shell side fluid temperatures ranging from 30-100^{o}C. Significant results for damping and tube natural frequencies were found and compared with theoretical findings.

2. EXPERIMENTAL WORK

A test section that simulates a typical shell and tube heat exchanger was developed and subsequently instrumented, to establish the modal parameters (fundamental natural frequencies and associated damping), PSD Plot and µ-strains of heat exchanger tubes at 30, 50, 70 and 90°C. The schematic diagram of the test section with data acquisition instruments and equipment is shown in Fig. 1.

The key component of the test section is the tube bundle which consists of an array of 10 stainless tubes with nominal diameter 12mm, triangular pitch of 15.875mm and a tube length of 2000mm, with different span length between baffle plates. The tube bundle specification is listed in Table 1.

The tube bundle has been appropriately instrumented to measure the displacement of the tubes and relevant key

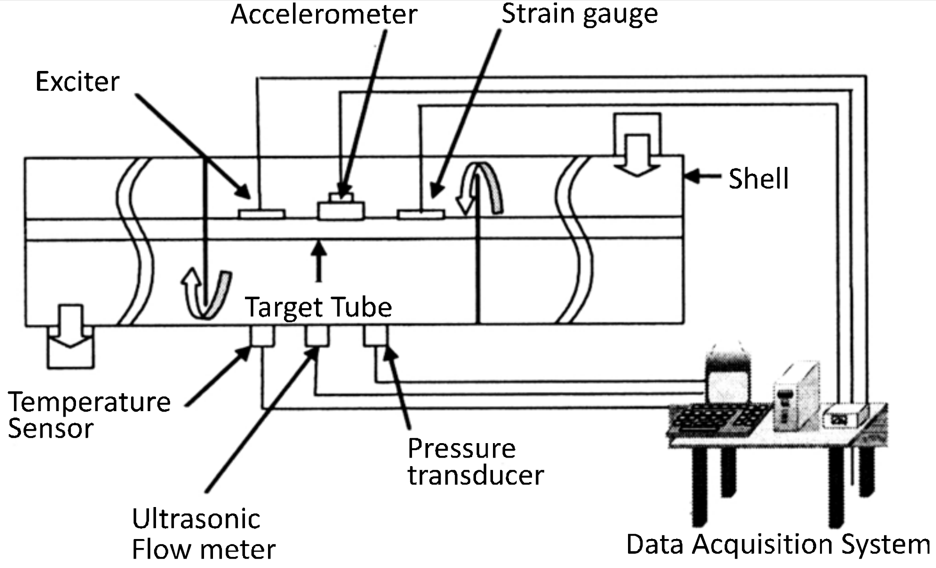


FIG. 1. SCHEMATIC DIAGRAM OF THE DATA ACQUISITION

variables. Accelerometers and strain gages were placed on the target tube in the middle span of 486mm. The detail is as shown in Figs. 2-3.

The test section consists of a number of instrument and equipment. The test rig was equipped with the following equipments to facilitate and enable conducting the planned experimental program.

(i) Accelerometer to measure the tube acceleration.

(ii) Strain gauge to measure the strain in tube and ultimately the tube displacement.

(iii) Signal conditioner Amplifier to set the gain of strain gages.

(iv) Charge amplifier to get acceleration signal.

(v) Data acquisition card to get data of acceleration and strain gage in Excel sheet.

(vi) Flow meter to measure water flow rate.

(vii) Temperature sensor to measure the temperature of water.

(viii) Pressure transmitter to measure and display the pressure of water at the inlet and outlet of test rig.

(ix) Centrifugal pump to circulate the water through the heat exchanger tube bundle.

(x) Make-up pumps to maintain the test rig pressure and vary as per requirement.

TABLE 1. PARAMETERS OF HEAT EXCHANGER TEST RIG

Items	Specification
Material of Construction	Stainless Steel
Shell Diameter	102 mm
Number of Tubes	12
Tube Diameter Outer/Inner	12 mm/8.6 mm
Number of Baffles	07
Baffle Clearance	0.5 mm
Tube Pitch	15.875 mm, 60° Triangular
Tube-Side Fluid	Air
Shell-Side Fluid	Water

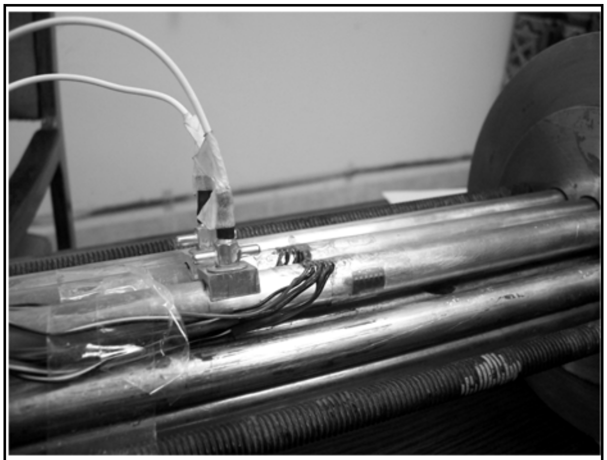


FIG. 3. PHOTOGRAPH OF INSTRUMENTS PLACED ON THE TUBE

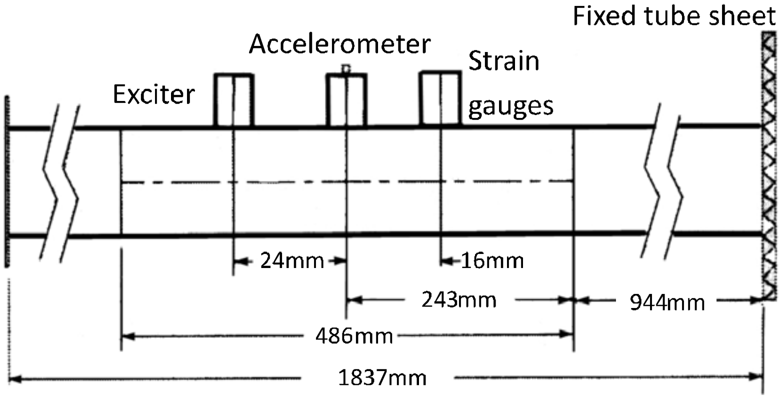


FIG. 2. DETAILS OF INSTRUMENTS PLACED ON THE TUBE

The data acquisition flow diagram is shown in details in Fig. 4.

Under flow condition the water temperature was varied and tube displacement and tube acceleration was measurement with accelerometers and strain gauges. Tube displacement and acceleration were measured for water temperatures of 30, 50, 70 and 90ºC. The results obtained are given in Fig. 5 which show lateral vibration amplitude of the tube in the frequency domain. Fig. 5 shows that the natural frequency is higher at lower temperatures.

3. ANALYTICAL MODELING

The natural frequency of circular tube (ω) can be obtained from the Equation (1) given by Lowery, et.al. [12] (converted to SI units).

$$\omega = \frac{9.87}{l^2}\sqrt{\frac{EI}{m_e}} \tag{1}$$

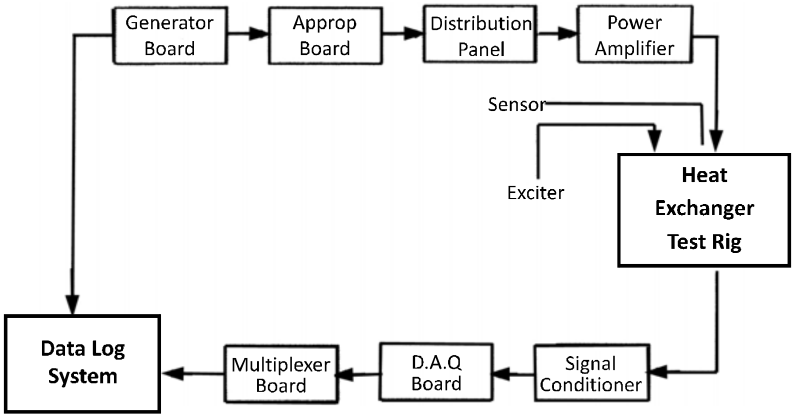


FIG. 4. DATA ACQUISITION FLOW DIAGRAM

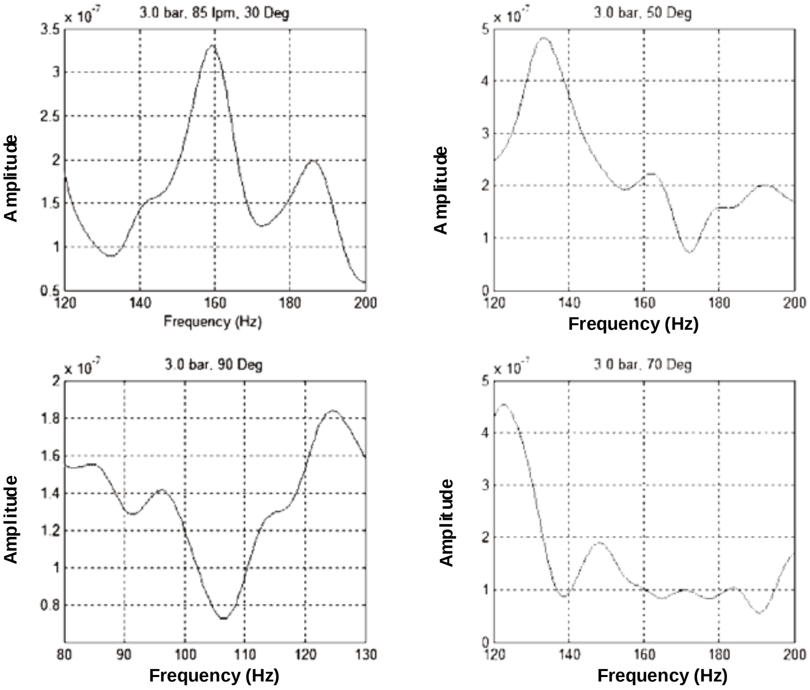


FIG. 5. PSD GRAPH OF ACCELEROMETER RESPONSE TO CROSS FLOW AT 3 BAR AND 85 LPM

The Equation (1) can be reformed by taking in to consideration the temperature effects in the overall natural frequency of the tube. The variation of modulus of elasticity with temperature shown has been in Fig. 6.

It is clear from this Equation (1) that the only parameter which can be influenced with the temperature is the modulus of elasticity. The dependence of modulus of elasticity on temperature can be described by Equation (2). The variation of modulus of elasticity with temperature for steel 304 [23] commonly used in heat exchangers is presented in Equation (2).

$$E = -7.16 \times 10^{7}T + 1.97 \times 10^{11} \tag{2}$$

Where, T is the temperature in degree C to obtain modulus of elasticity, E in Pascal. From Equations (1 and 2) the estimation of natural frequency as a function of temperature for SS304 is given in Equation (3).

$$\omega = \frac{9.87}{l^2}\left(\frac{(-7.16\times10^{7}T+1.97\times10^{11})I}{m_e}\right)^{\frac{1}{2}} \tag{3}$$

Pettigrew [16] had shown that damping can be related to natural frequency using the Equation (4):

$$\zeta = \frac{V_c}{\sqrt{\omega}.d} \tag{4}$$

Here the dimensional constant (V_c) will reflect the other factors as here the prime focus is the effect of temperature on damping.

Based on the facts reported above the natural frequency of the tube is related to temperature as presented in Equation (3) for Steel 304. It could be concluded that increase in temperature will result in decrease in frequency and subsequently increase in damping. The result could be concluded from Fig. 7 which displays the effect of temperature on damping as obtained from Equation (5). Based on the above discussion, it is shown in Fig. 7 that the effect of temperature results in, the increase in damping.

4. RESULTS AND DISCUSSION

The variations in natural frequency with temperature are shown in Fig. 8 at 3 bar and 3.5 bar with flow rate 85 lpm. The temperatures were varied from 30, 50, 70 and 90ºC and corresponding change in frequency were plotted.

Moreover the variations in natural frequency with temperature are also shown in Fig. 9 at 3.5 bar with flow rate of 75 lpm and 85 lpm. The graph shows that as the temperature raises the natural frequency of the tube decrease for different flow rates and pressures. The flow rates are selected such that the velocity through the test rig would remain in the recommended range, for the shell and tube heat exchangers.

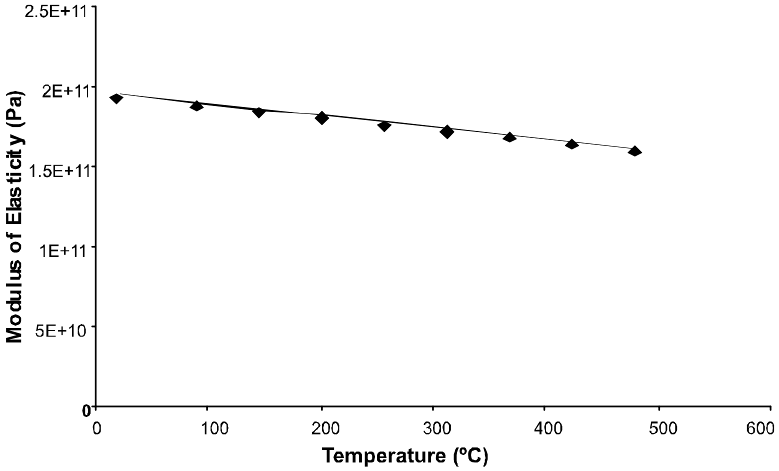


FIG. 6. MODULES OF ELASTICITY VARIATION WITH TEMPERATURE [23]

The variation in damping with temperature is shown in Fig. 10 for temperatures of 30, 70 and 90ºC.

Fig. 10 shows that the damping values obtained vary with the temperature range of experiments. Table 2 shows that the damping values obtained vary with the temperature range of experiments. The results are comparable with those of Taylor, et. al. [18] and Khushnood, S., et. al. [22].

The difference between the two measured values of damping ratios for the temperature of 90ºC or others may be due to parameters such as support alignment, tube straightness, relative position of tube with in the support and side loads. The work conducted by the researchers as listed in Table 2 was carried out at different temperature ranges. The same has been presented graphically in Fig. 11 to show the trends for comparison purposes.

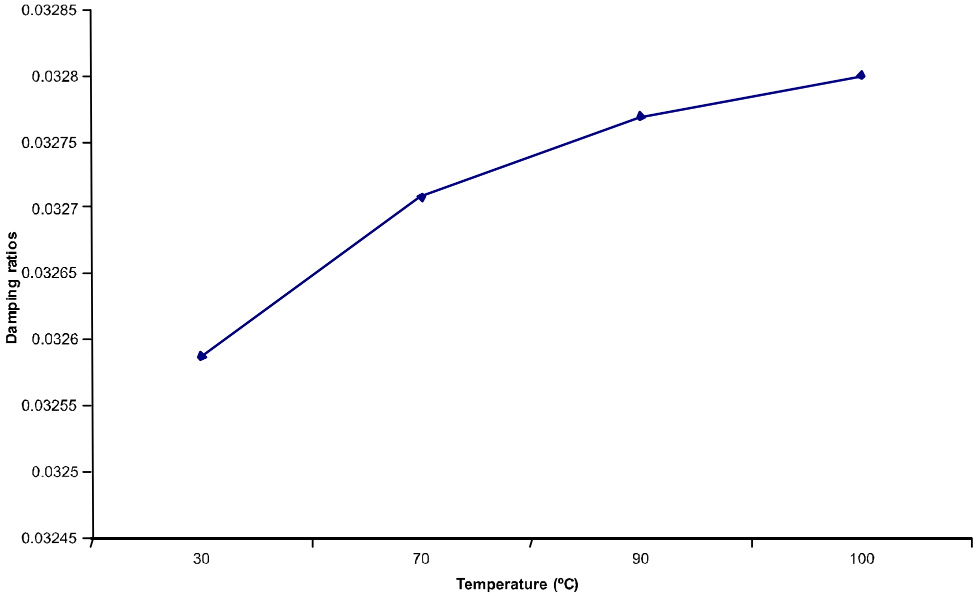


FIG. 7. THEORETICAL DAMPING VARIATION WITH TEMPERATURE CHANGES

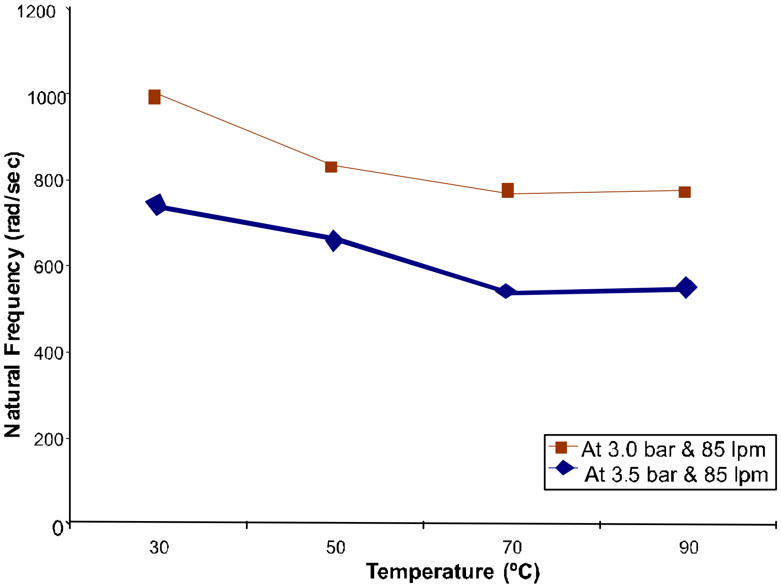


FIG. 8. VARIATION IN NATURAL FREQUENCY WITH TEMPERATURE CHANGES AT DIFFERENT PRESSURE

The variation in damping with temperature at different pressures and flow rates has also been shown in Fig. 12. It indicates an increasing trend in damping ratios with change in temperature.

The experimental frequencies compare favourably to the obtained theoretically. It is further remarked that the difference in the experimental and code results of natural frequencies may be due to added mass, tube-to-baffle support gap interaction and the change in effective length of tube due to bent tubes, which have been in use for quite sometime. Contaminated tubes may possibly be another cause of deviation in experimental and code values. Lower natural frequencies may not necessarily be better for the design because it is the resonance state, which has to

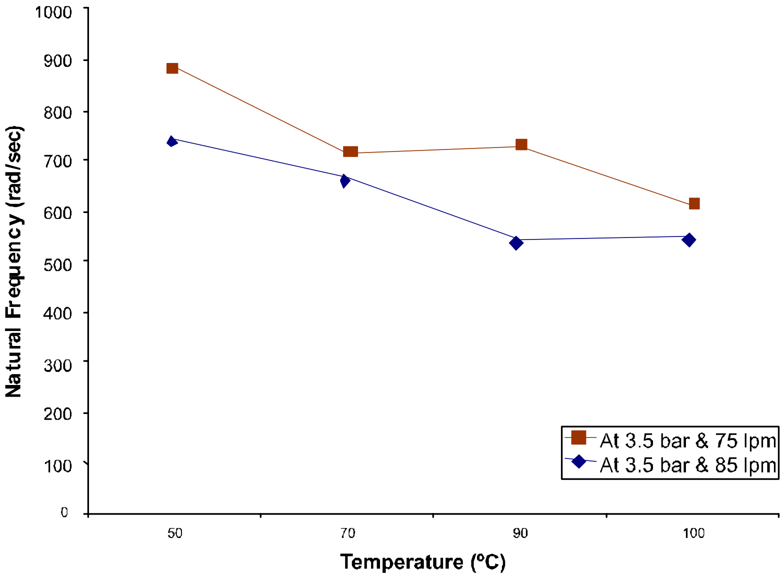


FIG. 9. NATURAL FREQUENCY VARIATION WITH TEMPERATURE CHANGES FOR DIFFERENT FLOW RATES

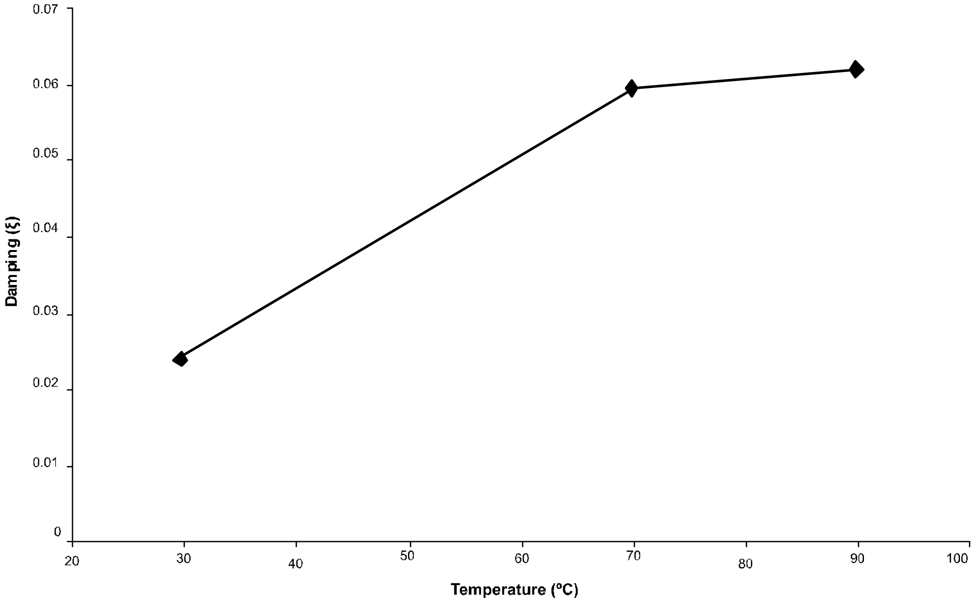


FIG. 10. EXPERIMENTAL DAMPING VARIATION WITH CHANGE IN TEMPERATURES

be prevented in the ultimate design. The experimental data has some variation which is mostly due to the very nature of the problem. .Heat exchanger tube damping depends on parameters that are difficult to control, such as support alignment, tube straightness, relative position of tube with in the support and side loads. These parameters are statistical in nature and probably contribute much of the scatter in the damping data.

TABLE 2. MEASURED DAMPING RATIOS IN COMPARISON WITH OTHER RESEARCHERS.

Taylor, et. al. [18]		Khushnood, S., et. al. [22]		Iqbal, Q., et. al. [26]			
Temperature (ºC)	Measured Damping (Ratios)	Temperature (ºC)	Measured Damping (Ratios)	Pressure (bar)	Flow Rate (lpm)	Temperature (ºC)	Measured Damping (Ratios)
25	0.042	32	0.0167	3	85	30	0.0336
						50	0.0568
						70	0.0583
60	0.052	100	0.047	3.5	85	50	0.041
						70	0.0428
						90	0.0652
90	0.059	Not Considered/ Tested	Not Considered/ Tested	3.5	75	50	0.0469
						70	0.046
						90	0.067
Not Considered/Tested		Not Considered/Tested		3	90	30	0.027
						50	0.0221
						70	0.0238
						90	0.0646

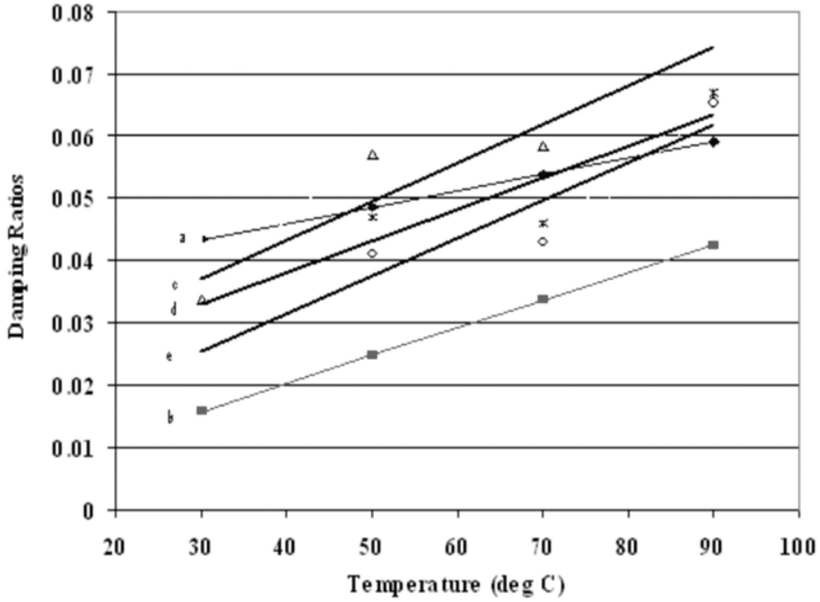
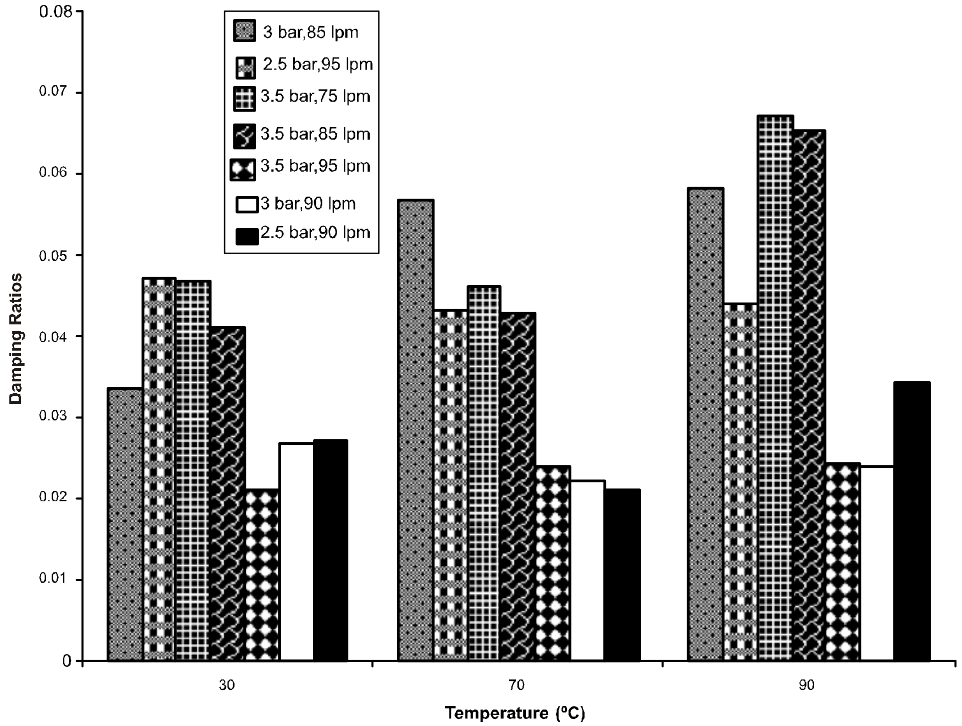


FIG. 11. TREND LINES AT DIFFERENT TEMPERATURES, PRESSURES AND FLOW RATE CONDITIONS (A) STILL WATER AT ATMOSPHERIC PRESSURE BY TAYLOR [18], (B) IN AIR AT ATMOSPHERIC PRESSURE AND NATURAL DRAUGHT CONDITIONS BY SHAHAB [22], (C) AT 3 BAR AND 85 LPM WATER FLOW RATE (∆), (D) AT 3.5 BAR AND 75 LPM WATER FLOW RATE (×) AND (E)



AT 3.5 BAR AND 85 LPM WATER FLOW RATE (O)

FIG. 12. EXPERIMENTAL RESULT OF DAMPING VARIATION WITH CHANGE IN TEMPERATURE

5. CONCLUSION

The experimental data analysis shows decrease in natural frequency of the heat exchanger tubes. The finding is also supported by the theoretical calculation as presented. Secondly, the experimental data has been analyzed to find out the damping by half power band method. The increase in damping with rise in temperature has been found out. The phenomenon obtained from the experimental results shows similar trend as calculated by theoretical model. The system damping has a strong influence on the amplitude of vibration. So effect of temperature on damping must be incorporated in flow induced vibration guidelines with a focus in structural integrity as well.

6. NOMENCLATURE

FIV	Flow-Induced Vibration
TEMA	Tubular Exchanger Manufacturers Association
lpm	Liters per minute
ω	Fundamental natural frequency (radian/s)
E	Modules of elasticity (N/m^2)
I	Area moment of inertia of tube x section (m^4)
l	Tube span length (m)
m_e	Effective tube mass (kg/m)
ζ	Damping ratio
d	Diameter of the tube
V_c	Dimensional constant
SS304	Stainless Steel 304

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REFERENCES

[1] Wootton, L.R., "Industrial Implications of Flow Induced Vibrations", Proceeding of Institution of Mechanical Engineers, C 416/111, International Conference, Bedford Hotel, pp. 1-6, Brighton, England, 20-22 May, 1991.

[2] Blevins, R.D., "Flow Induced Vibration", 3rd Edition, Van Nostrand Reinhold Ltd, New York, 1993.

[3] Goyder, H.G.D., "Flow Induced Vibration in Heat Exchanger", Transactions of Institute of Chemical Engineers, Volume 80, Part-A, pp. 226-232, UK, April, 2002.

[4] Mitra, D.R., "Fluid-Elastic Instability in Tube Arrays Subjected to Air-Water and Steam-Water Cross-Flow", Ph.D. Thesis, University of California, USA, 2005.

[5] Yang, J.C.S., Mark, C.H., Jiang, J., Chen, D., Elahi, A., and Tsal, W.H., "Determination of Fluid Damping using Random Excitation", Journal of Energy Resource Technology, Transactions of the ASME, Volume 107, No. 2, pp. 220-225, 1985.

[6] Wambsganss, M.W., Chen, S.S., and Jendrzejcyk, J.A., "Added Mass and Damping of a Vibrating Rod in Confined Viscous Field", Report No.ANL-CT-75-08, pp.1-25, Argonne National Laboratory, Illinois, USA, 1974.

[7] Pettigrew, M.J., Tromp, J.H., Taylor, C.E., and Kim, B.S., "Vibration of Tube Bundles in Two-Phase Cross-Flow: Part-2 Fluid-Elastic Instability", Journal of Pressure Vessel Technology, Transactions of the ASME, Volume 111, pp. 478-487, 1989.

[8] Pettigrew, M.J., Goyder, H.G.D., Qiao, Z.L., and Axisa, F., "Damping of Multi-Span Heat Exchanger Tubes, Part I: In Gases", Proceedings of Pressure Vessel and Piping Conference, ASME, Volume 104, pp. 81-87, 1986.

[9] Erskine, J.B., and Waddington, W., "A Review of Tube Vibration Failure in Shell & Tube Heat Exchanger and Failure Prediction Methods", International Symposium of Vibration Problem in Industry, pp. 1-20, UK, 1973.

[10] Kimball, A.L., and Lovell, D.E., "Variation of Young's Modulus with Temperature from Vibration Measurements", Physical Review, Volume 26, No. 1, pp. 121-124, 1925.

[11] Goodfellow, “Metals, Alloys, Compounds, Ceramics, Polymers & Composites”, Catalogue 1993/94.

[12] Lowery, R.L., and Moretti, P.M., "Natural Frequencies and Damping of Tubes on Multi-Span Supports", 15th National Heat Transfer Conference, American Institute of Chemical Engineers, Paper No. 1,pp 1-20, San Francisco, USA, 1975.

[13] Collard, B., Pisapia, S., Bellizzi, S., and Broc, D., "Flow Induced Damping of PWR Fuel Assembly", Flow Induced Vibration Conference, , pp. 1-6, Paris, France, 2004.

[14] Hartlen, R.T., and Simpson, F.J., "Wind Tunnel Determination of Fluid-Elastic Vibration Threshold for Typical Heat Exchanger Tube Patterns", Ontario Hydro Research Division Report-26479 (New 4-74), pp. 1-31, Canada, 1974.

[15] Chen, S.S., "Dynamic Tube/Support Interaction in Heat Exchanger Tubes", 5th International Conference on Flow Induced Vibration, Conf-910561-1, England, 1991.

[16] Pettigrew, M.J., "Damping of Heat Exchanger Tubes", Proceeding of 9th Canadian Congress of Applied Mechanics, Saskatoon, pp. 125-126, Canada, 1983.

[17] Goyder, H.G.D., "An Assessment Method for Unstable Vibration in Multi-Span Tube Bundles", Journal of Fluids and Structures, Volume 18, pp. 555-572, 2003.

[18] Taylor, C.E., Pettigrew, M.J., Dickinson, T.J., Currie, I.G., and Vidalou, P., "Vibration Damping in Multi-Span Heat Exchanger Tubes", Journal of Pressure Vessel Technology, Transactions of the ASME, Volume 120, pp. 283-289, August, 1998.

[19] Carlucci, L.N., and Brown, J.D., "Experimental Studies of Damping and Hydrodynamic Mass of a Cylinder in Confined Two-Phase Flow", ASME Journal of Vibration, Acoustics, and Stress Reliability in Design, Volume 105, pp. 83-89, 1983.

[20] Nakamura, T., Fujita, K., and Tsuge, A., "Two Phase Cross-Flow Induced Vibration of Tube Arrays", JSME International Journal, Volume 36, No. 3, pp. 429-438, 1993.

[21] Khushnood, S., Malik, M.A., Khan, Z.M., Khan, A., Iqbal, Q., Khalil, M.S., Rashid, B., and Hussain, S.Z., "Modeling and Analysis of Thermal Damping in Heat Exchanger Tube Bundles", Proceedings of International Conference on Nuclear Engineering (ICONE14),pp. 1-14, Miami, Florida, USA, July 17-20, 2006.

[22] Khushnood, S., "Vibration Analysis of a Multi-Span Tube in a Bundle", Ph.D. Thesis, Department of Mechanical Engineering, National University of Sciences and Technology, Pakistan, 2005.

[23] ASME Boiler and Pressure Vessel Code, Section-II, Part-D, Subsection-2, 2001.

[24] Iqbal, Q., Khushnood, S., El-Ghalban, A.R., Khan, M.A., Qureshi, M.A., and Khalil, M.S., "Modeling of Thermal Damping in a Multi-Span Tube Bundle", International Conference on Nuclear Engineering (ICONE-15), pp. 1-7, Japan, April, 2007.

[25] Iqbal, Q., Khushnood, S., El-Ghalban, A.R., Sheikh, N.A., Malik, M.A., and Arastu, A., "Damping in Heat Exchanger Tube Bundles: A Review", International Conference on Nuclear Engineering (ICONE-15), pp.1-10, Nagoya, Japan, April, 2007.

[26] El-Ghalban, A.R., Iqbal, Q., Khushnood, S., Qureshi, M.A., and Khalil, M.S., "Effect of Temperature on Damping in Shell and Tube Heat Exchanger", International Conference on Nuclear Engineering (ICONE-16), pp. 1-6, Florida, USA, 2008.

[27] Sheikh, N.A., Iqbal, Q., Khushnood, S., and El-Ghalban, A.R., "Fluid Structure Interaction of Flow Induced Vibration: A Study of Laminar and Turbulent Flow Fields", Journal of Power and Energy Systems, Volume 2, No. 2, pp. 1-9, Japan, 2008.

[28] Liu, C.S., "Identifying Time-Dependent Damping and Stiffness Functions by a Simple and Yet Accurate Method", Journal of Sound and Vibration, Volume 318, pp. 148-165, 2008.