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Vibrational Analysis of a Shell and Tube Type of Heat Exchanger In Accordance With Tubular Exchanger Manufacturer's Association (Tema) Norms

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--ABSTRACT--
Heat exchangers are devices used to transfer heat between two or more fluid streams at different temperatures. A very serious problem in the mechanical design of heat exchangers is flow induced vibration of the tubes. There are several possible consequences of tube vibration, all of them bad. The tubes may vibrate against the baffles, which can eventually cut holes in the tubes. In extreme cases, the tubes can strike adjacent tubes, literally knocking holes in each other. The repeated stressing of the tube near a rigid support such as a tube sheet can result in fatigue cracking of a tube, loosening of the tube joint, and accelerated corrosion. The flow induced vibrational analysis is considered as integral part of mechanical and thermal design of shell and tube heat exchangers. TEMA has developed standards in areas of flow induced vibrational analysis which have achieved worldwide acceptance. The paper explains depth vibrational analysis of a real world project in accordance to TEMA regulations.

KEYWORDS: *TEMA, Vortex shedding, turbulent buffeting, shell and tube heat exchanger, critical velocity*

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I. INTRODUCTION

The shell and tube type heat exchanger is a non-fired pressure system consisting of two different pressure chambers (shell chamber and tube chamber), separated by the internal tube wall ,two media flow past each other with such alignment that, if there is a heat difference, they will mutually exchange heat without mixing in the process. Vibration is caused by repeated unbalanced forces being applied to the tube. There are a number of such forces, but the most common one in heat exchangers is the eddying motion of the fluid in the wake of a tube as the fluid flows across the tube. The unbalanced forces are relatively small, but they occur tens, hundreds, or thousands of times a second, and their magnitudes increase rapidly with increased fluid velocity. Even so, these forces are ordinarily damped out with no damage to the tube. However anybody can vibrate much more easily as certain frequencies (called "natural frequencies") than at others. If the unbalanced forces are applied at "driving frequencies" that are near these natural frequencies, resonance occurs; and even small forces can result in very strong vibrations of the tube. Although progress has been made, the prediction of whether or not a given heat exchanger configuration will adequately resist vibration is not yet a well-developed science. The best way to avoid vibration problems are to support the tubes as rigidly as possible and to keep the velocities low. Both of these often conflict with the desire to keep the cost of the heat exchanger down. F. L. Eisinger [1] has presented various methods for predicting and solving tube and acoustic vibration problems in heat exchangers in cross flow. They include use of stability diagrams comprising in-service experience of heat exchangers, for a general multispan tube model; a method of selecting efficient baffle configurations for prevention of acoustic vibration. Shahab Khushnood et al. [2] have researched on two-phase cross-flow induced vibration in tube bundles. Despite the considerable differences in the models, there is some agreement in the general conclusions. The effect of tube bundle geometry, random turbulence excitations, and hydrodynamic mass and damping ratio on tube response has also been reviewed. Fluid–structure interaction, void fraction modeling/measurements and finally Tubular Exchanger Manufacturers Association (TEMA) considerations have also been highlighted. H.G.D. Goyder et al. [3] explain that heat exchanger tube bundles may fail due to excessive vibration or noise. The main failure mechanisms are generated by the shell side fluid that passes around and between the tubes. This fluid may be a liquid, gas or multi-phase mixture. The most severe vibration mechanism is a fluid elastic instability, which may cause tube damage after only a few hours of operation. They review the various mechanisms that cause vibration and noise. Particular attention is given to methods for achieving good tube support arrangements that minimize vibration damage. They have given references to the most recent sources of data and discussed good working practice for the design and operation of standard and high-integrity heat exchangers.

II. SHELL AND TUBE TYPE OF HEAT EXCHANGER

Heat exchangers are devices used to transfer heat between two or more fluid streams at different temperatures. Heat exchangers find widespread use in power generation, chemical processing, electronics cooling, air-conditioning, refrigeration, and automotive applications. A shell and tube heat exchanger is a cylindrical vessel housing a set of tubes (called the tube bundle) containing fluid at some temperature and immersed in another fluid at a different temperature. The transfer of heat occurs between the fluid flowing over the tubes and the fluid flowing inside the tubes. The fluid flow inside the tubes is said to be "tube side" and the fluid flow external to the tube bundle is said to be "shell side".

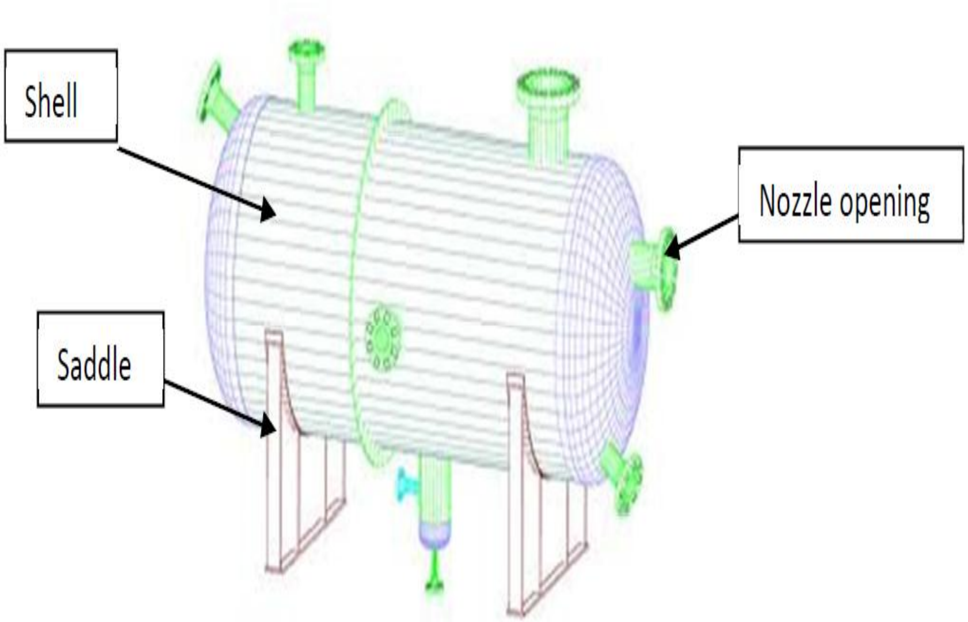


Figure 1. Representation of a shell and tube type of heat exchanger.

III. TUBULAR EXCHANGER MANUFACTURER'S ASSOCIATION, INC. (TEMA)

TEMA is a trade association of leading manufacturers of shell and tube heat exchangers who have pioneered the research and development for over 60 years. The TEMA standards have achieved worldwide acceptance as an authority on shell and tube heat exchangers mechanical design. TEMA standards provide a recognized approach to end users and allow comparison between competitive designs for a given application. TEMA is set of standards developed by leading heat exchanger manufacturers that define the heat exchanger style and the machining and assembly tolerances to be employed in the manufacturing of a given unit. The TEMA mechanical standards are applicable to shell and tube exchanger with inner diameter not exceeding 60 inches and maximum product of nominal diameter and design pressure should be less than 6000 psi. However a section on recommended good practice is provided to extend the standards to units with larger diameter.

IV. DESIGN PARAMETERS OF SHELL AND TUBE TYPE OF HEAT EXCHANGER

While designing a shell and tube type of heat exchanger the following considerations are made.

- Selection of heat exchanger TEMA layout and number of passes.
- Specification of tube parameters- size, layout, pitch and material.
- Setting upper and lower design limits on tube length.
- Specification of shell side parameters such as materials, baffle cut, baffle spacing and clearances.

Table 1. Design parameters of shell and tube type of heat exchanger

Parameters	*Nomenclature*	*Range*
Outside Diameter of tubes	D_0	11.43 cm
Thickness of the tube	T	0.66 cm
Inside diameter of tube	Di	10.11 cm
Tube length	L	304.8 cm
Longitudinal Pitch of the tubes	P_l	7.45 cm
Transverse pitch of tube	P_t	25.81 cm
Layout Pitch for tubes	P	14.9 cm
Added mass coefficient	C_m	1.53
Span geometry	2	One end fixed & other simply supported
Shell side pressure	P_s	53.9 kg/cm^2
Density of tube material	ρ_{tube}	7.86E-03 kg/cm^3
Density of tube inside fluid	ρ_{in}	7.62E-07 kg/cm^3

Density of tube outside fluid	ρ_{in}	7.80E-04 kg/cm^3
Weight tube per unit length	We	0.1754 kg/cm
Weight of inside fluid per unit length	Wt	0.001 kg/cm
Hydro dynamic mass	H_m	0.1225 kg/cm
Effective weight of tube per unit length	W	0.298 kg/cm
Moment of inertia of tube	I	325 cm^4
Young modulus of tubes at design temperature	E	1.8E+06 kgf/cm^2
Gravitational constant	g	981 cm/sec^2
Strouhal number	St	0.8
X_l	P_l / D_0	0.65
X_t	P_t / D_0	2.26
Dynamic viscosity	µ	0.01 centipose
Reynolds number	R_e	8.92E+06
Tube outside fluid velocity (at full load)	V	100 cm/s
Specific Heat ratio of shell side gas	ϒ	1.603
Distance between reflecting wall	B	304.8 cm
Log decrement of tubes	δ_r	0.02
Fluid elastic parameter of operating condition	X	0.0608
Tube natural frequency in empty condition	f_{n1}	36.993 Hz
Tube natural frequency in operating condition	f_{n2}	36.927 Hz
Acoustic frequency	f_a	25567.18 Hz
Critical Flow velocity in operating condition	V_{cr}	734.412 cm/sec

4.1 Natural Frequency of Each Tube (F_n):

Most of the heat exchangers have multiple baffle supports and varied individual unsupported spans. Calculation of the natural frequency of the heat exchanger is an essential step in estimating its potential for its flow induced vibration failure. The current state of the art flow induced vibration correlations are not sophisticated enough to warrant treating the multispeed tube vibration problem potential for vibration is evaluated for each individual unsupported span with the velocity and natural frequency considered being that of the unsupported span under examination.

Following are the equation are used to work out natural frequency of tubes for given end condition [8]

$$f_n = 0.159 \times \frac{A \times C}{L^2} \times \sqrt{\frac{Elg}{W}} \tag{i}$$

Where, C = 15.42, A =1

2.2 Acoustic frequency (f_a):

Acoustic resonance is due to a gas column oscillation. Gas column oscillation can be excited by a phased vortex shedding or turbulent buffeting .oscillation normally occurs perpendicular to both the tube axis and flow direction. When the natural acoustic frequency of the shell approaches the exciting frequency of the tubes, a coupling may occur and kinetic energy in the flow stream is converted into acoustic pressure waves acoustic resonance may occur independently. Following are the equation are used to work out acoustic frequency of tubes for given end condition [8]

$$f_a = \frac{865.37}{B} \times \sqrt{\left(\frac{P_s \Upsilon g}{\rho_{out} \times C1}\right)}$$

(ii)

$$C1 = 1 + 0.5 \times \frac{{D_0}^2}{P_l \times P_t} = 1.34.$$

4.3 Vortex Shedding Frequency (f_k):

Gas flow across a tube produces a series of vortices in the downstream wake formed as the flow separates alternately from the opposite sides of the tube. This alternate shedding of vortices produces alternate shedding of vortices produces alternating forces which occur more frequently as the gas velocity increases. Vortex shedding is fluid-mechanical in nature and does not depend upon any movement of tubes. For a given arrangement and tube size the frequency of vortex shedding increases as the velocity increases. Following are the equation are used to work out vortex shedding frequency of tubes for given end condition. [8]

$$f_k = \frac{S_t \times V}{D_0}$$
(iii)

4.4 Turbulent Buffeting Frequency (f_{tb}):

Turbulent buffeting is defined as the fluctuating forces acting on tubes due to extremely turbulent flow on shell side of the gas. This turbulence buffets the tubes which selectively extracts energy from the turbulence at their natural frequency from the turbulence at their natural frequency from spectrum of frequencies present. When the dominant turbulent buffeting frequency nearly matches the natural frequency of a tube a considerable transfer of energy is possible, leading to significant tube vibration amplitudes. [8]

$$f_{tb} = \frac{V}{D_0 \times X_l \times X_t}\left[3.05\left(1 - \frac{1}{X_t}\right)^2 + 0.28\right] \qquad \text{(iv)}$$

4.5 Estimate of Critical Flow Velocity (v_c):

The critical flow velocity Vc for a tube span is the minimum cross flow velocity at which that span may vibrate with unacceptably large amplitudes. The critical flow velocity for tube spans in the window overlap, inlet and outlet regions-bends and all atypical locations should be calculated. The cross flow velocity V should always be less than critical flow velocity V_c.
The critical velocity is defined by [8]

$$V_c = \frac{D f_n D_0}{12}$$
(v)

Where, D = 1.74 (for 60° tube pattern)

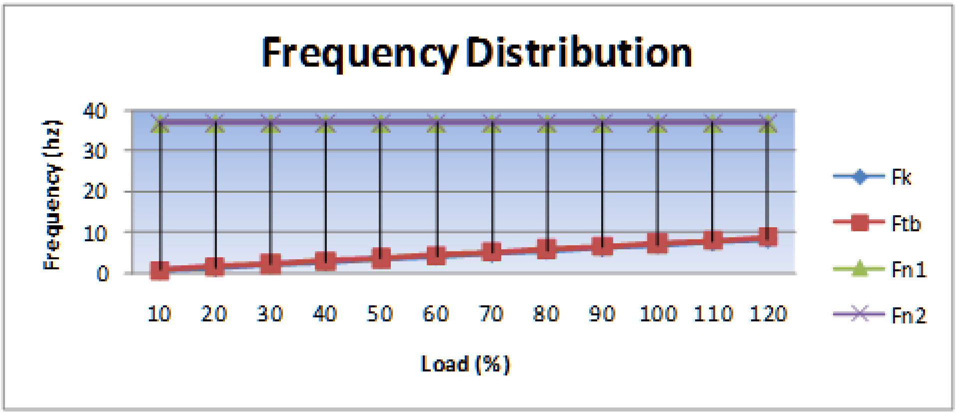
V. RESULTS AND DISCUSSIONS

The following table shows various effects on frequencies by using multiple load conditions

Table 2. Results for Multiple Load Conditions

Load	*Velocity*	*Critical flow Velocity*	*Vortex Shading Frequency*	*Turbulent Buffeting Frequency*	*Natural frequency Empty condition*	*Natural frequency in operating condition*	*Acoustic frequency*
	V	V_{cr}	F_k	F_{tb}	F_{n1}	F_{n2}	F_a
%	*(cm/s)*	*(cm/s)*	*(Hz)*	*(Hz)*	*(Hz)*	*(Hz)*	*(Hz)*
10	10.00	734.412	0.700	0.713	36.933	36.927	25567.180
20	20.00	734.412	1.400	1.463	36.933	36.927	25567.180
30	30.00	734.412	2.100	2.194	36.933	36.927	25567.180
40	40.00	734.412	2.800	2.926	36.933	36.927	25567.180
50	50.00	734.412	3.500	3.657	36.933	36.927	25567.180
60	60.00	734.412	4.200	4.388	36.933	36.927	25567.180
70	70.00	734.412	4.899	5.120	36.933	36.927	25567.180
80	80.00	734.412	5.599	5.851	36.933	36.927	25567.180
90	90.00	734.412	6.299	6.582	36.933	36.927	25567.180
100	100.00	734.412	6.999	7.314	36.933	36.927	25567.180
110	110.00	734.412	7.699	8.045	36.933	36.927	25567.180
120	120.00	734.412	8.399	8.777	36.933	36.927	25567.180

Graph 1. Frequency Vs Load Distribution

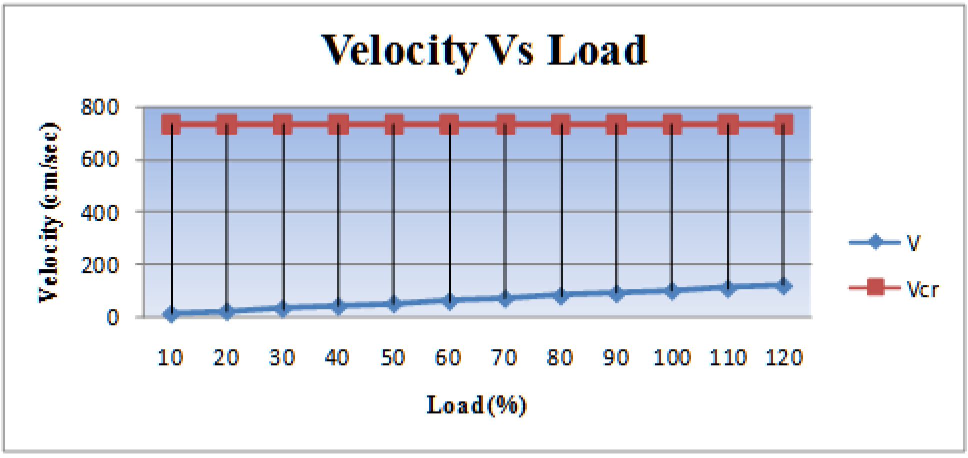


Where, F_k -Vortex Shedding Frequency, F_{tb} -Turbulent Buffeting Frequency

F_{n1} - Natural frequency Empty condition, F_{n2} - Natural frequency in operating condition

The above frequency Vs load graph shows us a vibration performance curve in which we increase load gradually with the step size of 10%. The objective of this graph is to illustrate that the non-coinciding nature of the Vortex Shading Frequency, Turbulent Buffeting Frequency with the Natural frequency.

Graph 2. Velocity Vs Load distribution



Where,

V - Velocity, Vcr - Critical flow Velocity

The above frequency Vs load graph shows us a vibration performance curve in which we increase load gradually with the step size of 10%.The objective of this graph is to illustrate that the non-coinciding nature of the velocity with the critical velocity.

VI. CONCLUSIONS

In a shell and tube type heat exchanger involving a fire tube boiler the vibration in the tubes carrying the hot flue gasses poses a major risk to the functioning and longevity of the entire setup. If the frequencies of the various vibrations coincide with the natural frequency the resultant resonance may causes damages which lead to a complete failure of the heat exchanger and more importantly compromise the safety of anyone in its vicinity. The paper comprises of an in depth vibrational analysis of a real world project in accordance to TEMA regulations in which the following conclusions were reached

- Natural Frequency of heat exchanger is apart from vortex shedding frequency, thus no vibration.
- Natural Frequency of heat exchanger is apart from turbulent Buffeting frequency, thus no vibration.

- Acoustic Frequency of heat exchanger is apart from vortex shedding frequency, thus no vibration
- Critical velocity is well apart from actual velocity, so there won't be any fluid elastic instability.

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