Thermal and Vibrational Analysis of Shell and Tube Heat Exchanger

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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. In this paper a simplified approach to optimize the design of Shell Tube Heat Exchanger [STHE] by flow induced vibration analysis [FVA] is presented. The vibration analysis of STHE helps in achieving optimization in design by prevention of tube failure caused due to flow induced vibration. The main reason for tube failure due to flow induced vibration is increased size of STHE. It is found that in case of increased size of STHE, the surface area and number of tubes increases, thus the understanding and analysis of vibration becomes a very difficult task. Again it is found that flow induced vibration analysis is considered as an integral part of mechanical & thermal design of STHE. The detailed design and analysis work was carried out at Precision equipments (Chennai) Pvt.Ltd.

Key words: Vibrational Analysis, Tube Heat Exchanger

I. Introduction

Tube failures due to excessive vibration must be avoided in heat exchangers and nuclear steam generators, preferably at the design stage. Thus, a comprehensive flow-induced vibration analysis is required before fabrication of shell-and-tube heat exchangers. It must be shown that tube vibration levels are below allowable levels and that unacceptable resonances and fluid elastic instabilities are avoided. The purpose of this overview paper is to summarize our design guidelines for flow-induced vibration of heat exchangers. The overview can be used by the designer as a guideline for vibration analysis, by the project engineer to get an overall appreciation of flow-induced vibration concerns, or by the plant operator to understand tube failures. This paper pertains to shell-and-tube heat exchangers such as nuclear steam generators, heat exchangers, coolers, condensers and moisture-separator-reheaters.

The principal culprit in flow induced vibration of tubes of STHE is the unsupported tube lengths subjected to large flow rates on shell side. The increased size of STHE due to large flow rates is responsible for vibration of tubes, which further leads to tube failure. Also the design of STHE is made safer by modifying shell type and/or baffles style and baffle design. Thus, the vibration analysis is of utmost importance in design of STHE. So, the flow induced vibration analysis is considered as an integral part of thermal design.

II. Vibration damage patterns

Mechanical failure of tubes resulting from flow induced vibration may occur in various forms. Damage can result from any of the following independent conditions, or combinations thereof.

A. *Collision Damage*

Impact of the tubes against each other or against the vessel wall, due to large amplitudes of the vibrating tube, can result in failure. The impacted area of the tube develops the characteristic, flattened, boat shape spot, generally at the mid-span of the unsupported length. The tube wall eventually wears thin, causing failure.

B. *Baffle Damage*

Baffle tube holes require a manufacturing clearance over the tube outer diameter to facilitate fabrication. When large fluid forces are present, the tube can impact the baffle hole causing thinning of the tube wall in a circumferential, uneven manner, usually the width of the baffle thickness. Continuous thinning over a period of time results in a tube failure.

C. *Tubesheet Clamping Effect*

Tubes may be expanded into the tube sheet to minimize the crevice between the outer tube wall and the tube sheet hole. The natural frequency of the tube span adjacent to the tube sheet is increased by the clamping effect. However, the stresses due to any lateral deflection of the tube are also maximum at the location where the tube emerges from the tube sheet, contributing to possible tube breakage.

D. *Material Defect Propagation*

Designs which were determined to be free of harmful vibrations will contain tubes that vibrate with very small amplitude due to the baffle tube hole clearances and the flexibility of the tube span. Such low level stress fluctuations are harmless in homogenous material. Flaws contained within the material and strategically oriented with respect to the stress field, can readily propagate and actuate tube failure. Corrosion and erosion can add to such failure mechanisms.

E. *Acoustic Vibration*

Acoustic resonance is due to gas column oscillation and is excited by phased vortex shedding. The oscillation creates an acoustic vibration of a standing wave type. The generated sound wave will not affect the tube bundle unless the acoustic resonant frequency approaches the tube natural frequency, although the heat exchanger shell and attached piping may vibrate, accomplished with loud noise. When the acoustic resonant frequency approaches the tube natural frequency, any tendency toward tube vibration will be accentuated with possible tube failure.

F. *Failure Regions*

Tube failures have been reported in nearly all locations within a heat exchanger. Locations of relatively flexible tube span and/or high flow velocities are regions of primary concern.

G. U-Bends

Outer rows of U-bends have a lower natural frequency of vibration and therefore, are more susceptible to flow induced vibration failures than the inner rows.

H. Nozzle Entrance and Exit Area

Unsupported tube spans adjacent to the tube sheet are frequently longer than those in the baffled region of the heat exchanger, and result in lower natural frequencies. Entrance and exit areas are common to this region. The possible high local velocities, in conjunction with the lower natural frequency, make this a region of primary concern in preventing damaging vibrations.

I. Baffle Region

Tubes located in baffle windows have unsupported spans equal to multiples of the baffle spacing. Long unsupported tube spans result in reduced natural frequency of vibration and have a greater tendency to vibrate.

J. Obstructions

Any obstruction to flow such tie rods, sealing strips and impingement plates may cause high localized velocities which can initiate vibration in the immediate vincity of the obstruction.

III. VIBRATION PREVENTION

When the vibrations are predicted at the design stage, one or more of the following steps may be taken. These either reduce the forcing frequency or increasing the natural frequency.

A. Reduce the Tube Span Length

This will increase the natural frequency as well as the cross flow velocity. The increase in the natural frequency is significant more than that in the cross flow velocity or the forcing frequency.

B. Reduce the Shell Side Fluid Velocity

This can be achieved by reducing the flow rate or changing the tube pitch and /or the layout angle. This reduces the forcing frequency.

C. Change the Baffle Type

The no tube in window design supports all the tubes at all the baffles. Hence, a change to this type of baffles will reduce the longest span and thus increase the natural frequency. Further, support plates can be used with this type of baffles (without affecting the thermal performance) to further decrease the tube span and increase the natural frequency.

D. Reduce the Shell Inlet Velocity

If the region under the inlet nozzle is suspect, use a larger nozzle diameter, impingement plate and/ or provide a jacket (distribution belt) around the shell for a larger entrance to the shell. This includes the forcing frequency.

IV. DESIGN PARAMETERS OF SHELL AND TUBE 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, baffles spacing and clearances.

Parameters	**Units**	**Ranges**
Shell side fluid		Butadiene
Tube side fluid		Ethylene glycol water
Tube side total fluid	Kg/hr	167109
Shell side total fluid	Kg/hr	65000
SHELL SIDE		
Inlet temperature	^{0}C	17
Outlet temperature	^{0}C	-5
Density of the fluid	Kg/m^3	640.35
Viscosity	cP	0.1785
Specific heat	Kcal/kg^{0}C	0.154
Thermal conductivity	Kcal/mhr^{0}C	0.114
Molecular weight		54.09
TUBE SIDE		
Inlet temperature	^{0}C	-14
Outlet temperature	^{0}C	-9
Density of the fluid	Kg/m^3	1034.5
Viscosity	cP	5.005
Specific heat	Kcal/kg^{0}C	0.849
Thermal conductivity	Kcal/mhr^{0}C	0.391
Molecular weight		21.9
Tube outer diameter	mm	22.225
Tube thickness	mm	1.651
Tube length	mm	3658
Tube pitch	mm	27.781
Tube pattern	degree	30
Shell internal diameter	mm	728.47
Shell outer diameter	mm	747.52
No. of tube side passes/shell		4
Baffle type		Single-segmental
Baffle cut	percentage	25
Baffle spacing	mm	304.8

Table 1: Design Parameters of Shell and Tube Heat Exchanger

A. Natural Frequency

All structures like bridges, tall stacks, cables between poles, beams and tube supported at the baffles in a heat exchanger vibrate when displaced momentarily from their normal position by forces acting on them. The number of cycles of vibrations per second that the structure undergoes is called natural frequency of vibrations. A structure may have an infinite number of discrete natural frequencies. The time taken per cycle is called the time period of vibration.

$$f_n = 10.838 \frac{AC}{L^2} \left[\frac{EI}{W_0}\right]^{1/2}$$

B. Factors Affecting Natural Frequency

The individual unsupported span natural frequency is affected by:

– Tube elastic and inertial properties and tube geometry.
– Span shape.
– Type of support at each end of the unsupported span.
– Axial loading on the tube unsupported span.

C. Acoustic Vibration

These are standing waves in the gas column perpendicular to the predominant shell side fluid flow and axial flow directions. The excitation frequency is dependent upon the flow path length, standing wave mode number, fluid molecular weight, compressibility, temperature, and the ratio of the heat capacity at constant pressure to that at constant volume.

The acoustic vibrations are excited when the shell side fluid is low density gas. The gas column normal to both the tube axis and the flow direction resonates

When the vortex shedding, turbulent buffeting or the natural frequency is close to the acoustic frequency of the gas column. When the natural 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 of mechanical tube $\rho_0$vibration.

D. Acoustic Frequency of Shell

Acoustic frequency is given by,

$$f_a = \frac{409}{w}\left[\frac{P_s\gamma}{\rho_0\left(1+\frac{0.5}{x_l x_t}\right)}\right]^{1/2}$$

w = Distance between reflecting walls measured parallel to segmental baffle cut, inches
P_S = Operating shell side pressure, psia
γ = specific heat ratio of shell side gas, dimensionless
ρ_0 = Shell side fluid density at local fluid bulk temperature, lb/ft^3

$$x_t = \frac{Pt}{d0}$$
$$x_l = \frac{Pl}{d0}$$

P_l = longitudinal pitch, inches
P_t = transverse pitch, inches
d_o = outside diameter of tube, inches

V. RESULTS

The table shows the Flow-Induced Vibration Analysis Results of STHE by using HTRI software. Rating horizontal Multi pass flow TEMA BEM shell with single segmental Baffles. The main parameters which affect the flow induced vibration are shown below

Description	Inlet	Center	Outlet
Tube natural frequency (Hz)	98.1	108.3	108.2
Critical velocity(m/s)	4.32	7.46	6.28
Vortex shedding ratio	0.018	0.030	0.025
Bundle cross flow velocity (m/s)	0.19	0.31	0.25
Cross flow amplitude(mm)	0.002	0.001	0.001

Fig. 2: Results

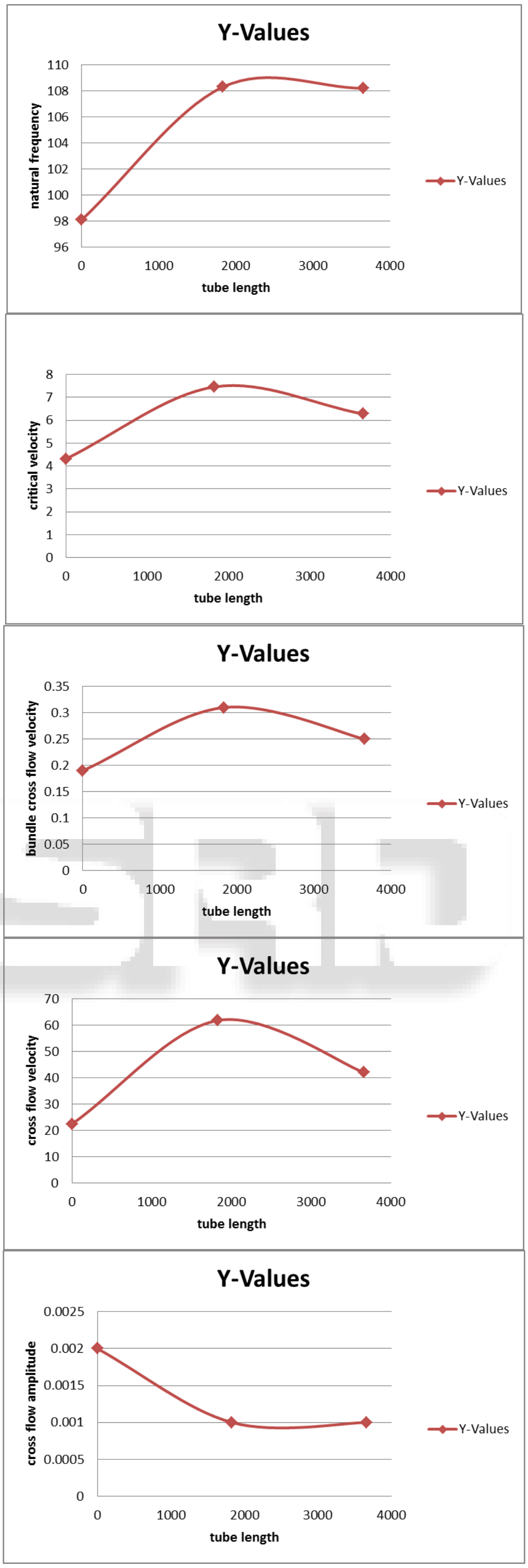

Fig. 1: Graphs

VI. CONCLUSION

From the vibration analysis of STHE it is found that the tube length has major impact on the tube natural frequency, critical velocity, vortex shedding ratio, bundle cross flow velocity, cross flow amplitude. From the table it can be concluded that mid span of the tube the tube natural frequency , critical velocity, bundle cross flow velocity and vortex shedding ratio are gradually increased to the mid span of the tube and gradually decreased mid span to end of the tube length. We finally come to the conclusion that the main parameter which largely affects the vibrations caused due to flow are dependent on unsupported tube length and varies at various locations across the tube length as unsupported tube length varies. The various other parameters which affect the flow induced vibration are critical velocity, natural frequency of tubes, cross- flow velocity and acoustic frequency.

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