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Unlocking Circular Economy Opportunity Through Tube-Induced Vibrations Mitigation in Shell and Tube Heat Exchangers

Dhawi A. Al-Otaibi[1]

[1]Equipment Consulting Services Department, Saudi Aramco, Dhahran, Saudi Arabia

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Abstract: Shell and tube heat exchangers are core components in a wide variety of industrial systems, from power generation and petrochemical processing through HVAC and desalination facilities. Strong in structure and efficient in thermals, these devices are vulnerable to flow-induced vibrations (FIV) that lead to tube wear, fatigue failure, and compromised performance. This paper provides an overview of tube-induced shell and tube heat exchanger vibrations due to physical forces, their analytical, numerical, and experimental modeling, and current-day state-of-the-art design and mitigation techniques. A multi-disciplinary approach with a focus on fluid mechanics, structural dynamics, and heat transfer is emphasized throughout. Moreover, a case study is presented to show the impact of stiffening the tubes to mitigate FIV.

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I. INTRODUCTION

Shell and tube heat exchangers (STHEs) are perhaps the most commonly used form of heat exchanger in industry due to their ease of maintenance, mechanical strength, and versatility. The largest persistent issue in their operation and design is tube sensitivity to dynamic instabilities due to fluid flow, particularly on the shell side. The flow caused by vibration can lead to some of the forms of mechanical degradation such as fretting wear of supports, fatigue failure, and tube-to-tube contact, which can lead to costly repair, production shutdown, or failure.

The tube bundles of a STHE consist of thin, flexible tubes, which normally have high flow velocities and intensities of turbulence. Under frequencies of fluid flow that are in synchronization with the natural frequencies of the tubes, resonance is feasible, causing the excessive amplitude of vibrations. Thus, an important comprehension of the interaction between the structural response and flow dynamics is necessary for guaranteeing the safe and efficient operation of these exchangers.

II. FLOW-INDUCED VIBRATION (FIV) MECHANISMS

Tube vibrations in STHEs are caused by intricate interactions between the fluid forces and structural properties of the tubes. The most important mechanisms of FIV are:

- *Turbulent Buffetting:*

Turbulent buffeting is caused by random pressure fluctuations in the turbulent wake of flow over the tubes. It is a broadband excitation process, where fluctuating fluid forces excite a wide range of frequencies. Although energy at any frequency is small, if the turbulent energy spectrum overlaps with the natural frequency of the tube, it can cause vibration.

- *Vortex Shedding:*

When a fluid passes over a cylindrical tube, alternating vortices are shed from both sides and create a periodic side force on the tube. The frequency of vortex shedding fs is given by the Strouhal relation:

fs= St* (v/d)

Where:

• St = Strouhal number (typically ~0.2),
• v = fluid velocity,
• d = tube diameter.

When fs is equal to the tube's natural frequency, resonance occurs with significant amplitude vibrations.

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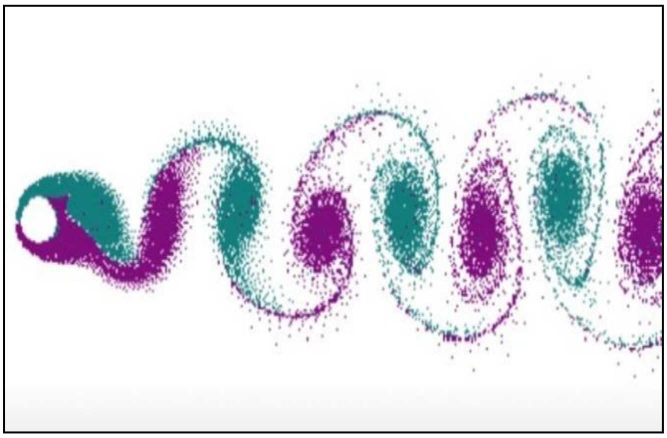
Fig 1 Tube Vortex Shedding (en.wikipedia.org)

➢ *Fluidelastic Instability:*

Fluidelastic instability (FEI) is a damaging potential mechanism of self-exciting, self-sustained vibrations. Contrary to vortex shedding, FEI occurs as the fluid energy input exceeds the damping capability of the tube. It exhibits geometry-, pitch-, and flow velocity-sensitive tube array geometry. The reduced velocity vr is a major nondimensional parameter; it is utilized to calculate and define it as follows:

$vr= v/(fn*d)$

Where fn is the natural frequency. FEI generally occurs when vr is greater than a critical value (typically ~10–15 in inline arrays and ~30–50 in staggered arrays).

➢ *Acoustic Resonance:*

Pressure waves induced by flow in some heat exchangers, particularly those with constricted geometries, may resonate with acoustic modes of the shell. This relatively rarer phenomenon serves to couple tube vibrations with structural modes and thus increase them.

Acoustic vibration mostly occurs in heat exchangers of large shell diameters, typically over 49 in. (1.25 m). It rarely matches the natural frequency of tubes; therefore, accompanying tube vibration or tube damage is seldom a problem. Acoustic vibration is most often observed when the shell side fluid is a gas or a vapor. However, acoustic vibration has been observed in shell side condensers where liquid volume fraction of the two-phase, liquid/gas mixture did not exceed about 15 percent.

The prediction of the occurrence of acoustic vibration in shell-and-tube heat exchangers is not precise. It occurs when resonance develops and due to complex nature of resonance, its prediction is controversial and subject to interpretation. However, acoustic vibration is preventable through conservative design, and corrective measures including installation of "de-resonating" or "detuning" baffles.

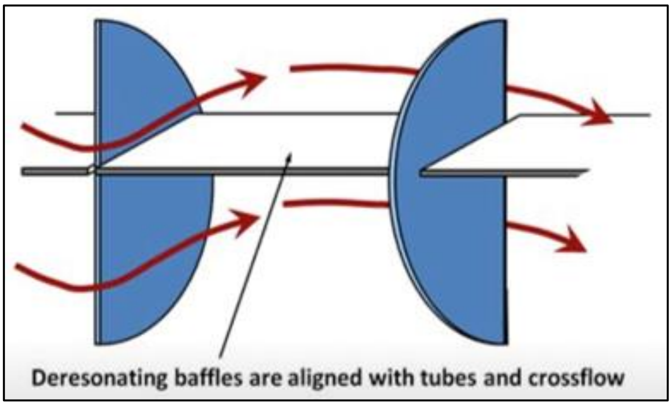

Fig 2 De-Resonating Baffle for Acoustic Vibration

Table 1 presents a summary of these vibration mechanisms for single tube and tube bundles for liquid, gas and liquid-gas two-phase flow respectively. Of these four mechanisms, fluid-elastic instability is the most damaging in the short term, because it causes the tubes to vibrate excessively, leading to rapid wear at the tube supports. This mechanism occurs once the flow rate exceeds a threshold velocity at which tubes become self-excited and the vibration amplitude rises rapidly with an increase in flow velocity.

Table 1 Vibration Excitation Mechanisms (Pettigrew, et al., 1997)

Cross Flow	**Vortex Shedding**	**Fluid-Elastic Instability**	**Turbulent Buffeting**	**Acoustical Resonance**
Liquid	x	*	x	o
Gas	o	*	x	*
Two- Phase	o	*	*	o

Where;

Vibration Unlikely: o
Vibration Possible: x
Vibration Most Important: *

➢ *Governing Parameters*

The following parameters are commonly governing FIV.

- *Structural Parameters:*

✓ Natural frequency and mode shapes of tubes (determined by tube material, length, diameter, and boundary conditions).
✓ Damping (structural and hydrodynamic).
✓ Tube support geometry (number and baffle spacing, antivibration bar presence).
✓ Tube-to-baffle hole clearance.

- *Flow Parameters:*

✓ Cross-flow velocity and direction (shell-side or tube-side).
✓ Fluid density and viscosity.
✓ Turbulence intensity and spectrum.
✓ Reynolds and Strouhal numbers.

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➢ *Analytical and Numerical Modeling:*

- *Analytical Approaches:*

Classical analytical methods treat the tubes as Euler-Bernoulli beams with fluid forcing and damping terms. The most basic model is:

$m\ddot{x}+c\dot{x}+kx= F(t)$

Where

m = unit mass per unit length,
c = damping coefficient,
k = stiffness,
F(t) = flow-induced force (may be random or periodic).

Analytical models are restricted to simplified flow conditions and geometries but are sufficient for initial design.

- *Empirical Correlations and Design Codes:*

Design codes such as ASME VIII Div. 1 Appendix A and TEMA R, C, B provide experimental correlations for critical velocity, natural frequencies, and support spacing to prevent FIV. For instance, TEMA provides recommendations to prevent vortex shedding resonance by doing:

$fs \neq fn$ and $v < vc$

- *Computational Fluid Dynamics (CFD):*

CFD is employed to solve the flow fields about the tube bundle, which gives:

✓ Velocity and pressure field prediction,
✓ Vortex shedding modes,
✓ Tube force spectra.

High-resolution CFD (e.g., LES, DNS) can resolve transient and turbulence effects but requires great computational effort.

- *Finite Element Analysis (FEA):*

Used in modal analysis of tube bundles. It offers:

✓ Natural frequencies and mode shapes,
✓ Stress and strain distributions,
✓ Dynamic load response.

➢ *Experimental Methods*

✓ Following Loop Testing: Scaled models tested under simulated flow conditions under controlled conditions.
✓ Modal Testing: Experimental modal analysis (EMA) used to define natural frequencies, damping ratios, and mode shapes.
✓ Field Monitoring: Strain gauges and accelerometers placed in industrial environments to measure and examine vibration modes.

➢ *Mitigation Strategies*

- *Design Modifications:*

✓ Alter tube layout: Staggered arrays have higher critical velocities for FEI.
✓ Increase support density: Reduce unsupported span to raise natural frequency.
✓ Use antivibration bars: Effective for transverse modes.

- *Flow Modifications:*

✓ Reduce fluid velocity by design or operation.
✓ Fit flow straighteners or vortex suppressors.
✓ Refine baffle design (e.g., helical baffles for less turbulent flow paths).

- *Material Selection:*

✓ Greater-damping tubes (e.g., elastomer-coated or composite tubing).
✓ Optimized tube stiffness-to-mass ratio.

➢ *Case Study: FIV In 30 Year Carbon Steel Reboiler*

This case is one of the oldest operating reboilers with flow induced vibration defects. The reboiler is running for almost 30 years. The defect details are shown in below inspection table. The following is the equipment operating and construction data.

- Material: CS SA-516 Gr.70/ SA-179 tubes
- ID: 1575 mm (60 inches)
- Design Condition: 0.5MPa (75 psi) & 260 ˚C (500 ˚F)
- Tube Type: U-bend unsupported at tangent line
- Year of construction: 1994

Fig 3 Inspection Data.

III. ANALYSIS RESULTS & RECOMMENDATION

The study was done on U-tubes reboiler running in hydrocarbon gas. Failure of the tubes were recurrent on a reboiler. Fluidelastic instability was indicated by vibration monitoring. Redesign of baffle spacing and the addition of antivibration bars mitigated the FIV and tubes damage which extended operating life of the reboiler. Below table compare the original design with the enhanced one using HTRI software.

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Table 2 Analysis Results

Factors	Original Design	Enhance Design	Remarks
Baffles at the U-bend	No	Yes	Required
Gap Velocity / Critical Gap Velocity	1.0435	0.2036	Shall be < 1.0
Vortex shedding frequency ratio	Ok	Ok	Shall be < 0.5

IV. CONCLUSION

Tube-induced vibrations in shell and tube heat exchangers are a multi-disciplinary problem across fluid dynamics, structural mechanics, and thermal design. With rising flow velocities and process intensities being encountered in contemporary systems, vibration-proof heat exchanger designs are an increasing need. An interpretation process spanning analytical, computational, and experimental approaches is required to forewarn, prevent, and counter these vibrations. Continuous development in materials, modelling, and monitoring is instrumental in maintaining safety and effectiveness in these vital industrial components.

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Dhawi A. Al-Otaibi, P.Eng. is a heat exchangers engineer working with Saudi Aramco. He has over 25 years of experience in the thermal design, revamping and troubleshooting of heat exchangers and in the design of heat exchanger networks. He has written several articles and presented many papers at technical symposia. He received BS and MS degrees in heat transfer and thermofluid science from King Fahad University of Petroleum & Minerals and since then he has contributed to several heat exchangers engineering activities.