Design parameters of heat exchange equipment optimization

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Abstract. The dynamics of straight tubes bundles in heat exchangers, in cross flow of coolant, is considered. The proposed mathematical model allows to determine quantity values which are fundamental in assessing the wear vibration intensity in contact points of tubes with intermediate supports taking into account gap values between tube and support. Tube vibration data obtained by application of this mathematical model (sliding path, contact tubes load in gaps, strain, response frequency structure) allow optimization of design parameters (gaps in intermediate supports, supports number and their location along the tubes length) and operational parameters of heat exchange equipment.

Heat exchanger (HE) is one of the most important components of power equipment. This unit transfers heat energy from coolant to water to produce high pressure and temperature steam. HE has a close tubes arrangement of pipes in bundle, high temperatures, significant flow rates of coolant, a large number of intermediate supports (spacer grids) in which tubes under conditions of assembling are installed with diametrical gaps. The greatest danger from intense oscillations hydrodynamic excitation is the case of cross flow around the tube bundle. This type of flow is often found in various heat exchangers as it is structurally simple and easily implemented constructively and beneficial in terms of thermal and hydraulic installation processes. In tube vibrations process inside the plane support gap, attrition can occur, and the removal of material from surfaces of both the tube and spacer grid in the gap. In the case of sufficiently intense fretting wear tube through wiping can occur and undesirable leakage in the HE will take place. Fretting wear caused by vibration is a significant source of HE damage and accidents not inferior in this respect even corrosion. The study of wear processes carried out in our country and abroad showed that among the factors determining the wear rate, an important role is played by the tube movement type in the gap [1]. The movement can be accompanied by direct blows normal to the support surface and oblique blows with slippage. These modes can’t be analyzed without taking into account the gaps between the tube and support and the required support number. It is obvious that designing HE problem becomes multi-parametric and multi-criteria, and significantly nonlinear according to object operation (gaps presence in supports).

The mathematical model (MM) proposed by authors allows to calculate the dynamic response of multi-support tube bundle with gaps element. In this case, hydrodynamic excitation, depending on cross flow velocity, includes vortices separation from tubes and their hydrodynamic connection with each other. Coefficients of hydroelastic connection between tubes were determined analytically from flow around the cylinder profiles problem solution [2, 3].

Detailed mathematical model of HE tube bundles vibration is presented in [2, 3]. The computational scheme is shown in Fig. 1. Equations for rods bending vibrations are used to describe
tubes in the bundle vibrations. In this case, the hydromechanical excitation takes into account the vortex separation, inertial and hydroelastic connection between the bundle tubes. Reactions of intermediate supports are introduced into the right parts of equations as impulse forces [3].

\begin{equation}
\begin{bmatrix}
\dddot{S} \\
\dot{S} \\
\end{bmatrix} + \begin{bmatrix}
C \\
K \\
\end{bmatrix} \begin{bmatrix}
\ddot{S} \\
\dot{S} \\
\end{bmatrix} + \begin{bmatrix}
M \\
K \\
\end{bmatrix} \begin{bmatrix}
S \\
\dot{S} \\
\end{bmatrix} = \begin{bmatrix}
F \\
\end{bmatrix},
\end{equation}

where \([M], [C], [K]\) mass, damping and stiffness matrices respectively, \(\{S\}, \{F\} – \) generalized displacement and external load vectors. Matrices \([M], [C], [K]\) have dimension \(2k \times 2k\), where \(k\) is the tubes number [3].

Tube row elements make the orbital motion, and direct impact model at contact with spacer grids is not acceptable. The paper considers an oblique impact model with normal and tangential force reaction components in supports [2, 3].

In contact interaction description in the normal direction energy dissipation at impact is not taken into account and the expression for normal forces is taken as follows:
\[ R_{ii}^d(t) = -C[r_{ii}(t) - \delta_{ii}] \cdot \eta[r_{ii}(t) - \delta_{ii}] \]  

(2)

where \( r_{ii}(t) \) – radial tube displacement in the \( l \)-th support, \( \delta_{ii} \) – clearance in \( l \)-th support, \( \eta[r_{ii}(t) - \delta_{ii}] \) – Heaviside function (realized in the program by conditional operators).

Dry (solid) friction hypothesis is used to calculate tangential forces of oblique impact i.e. tangential force is connected with normal force and is directed against motion:

\[ R_{ii}^t = f_r R_{N}^i, \]

where \( f_r \) – dry friction coefficient is assumed to be 0.2 [3].

The total reaction for the \( i \)-th tube in the first intermediate support is determined by geometric forces summation:

\[ R_{ii} = R_{N}^i + R_{ii}^d. \]

To solve the dynamic problem (1) Wilson method of step-by-step integration is applied. In research strategy for tube systems dynamics constructive parameters such as diametrical gap between the tube and the intermediate support, supports number and location are considered to have the greatest influence on the wear. Next, as a first group factors result dynamic factors are considered: type of tube movement, tube deflection influenced by flow, frequency and amplitude of impact forces in contact. The main parameters of design resource estimation are: tubes in intermediate supports vibration wear, bending stresses and their value changes from plus to minus frequency in vibration process.

According to Kragelsky I V function [4], removed material volume in the friction path \( L \) can be represented as:

\[ V_L = K_B F_N L, \]

where, \( K_B \) vibration wear coefficient, \( F_N \) – normal contact force between tube and support, \( L \) – friction path.

For a given form of resulting defect (scar), the equivalent depth of vibration wear is determined by expression:

\[ H_B^e = \frac{K_B F_N L}{\pi d_b K^e}, \]

where \( b_K^e \) the equivalent defect width, i.e. the average support width.

In this paper, contact force values \( F_N \), the tube path while touching the support in time unit \( L \), is determined from a numerical experiment according to the above algorithm

\[ P_{wear} = \frac{F_N L_c}{\pi d}, \]

(4)

where \( L_c \) – friction path in 1 second.

This parameter minimizing will increase the structure service life.

The strength condition under various cyclic loads is determined from formula [1]:

\[ \sum_{i=1}^{k} \frac{N_i}{[N_0]} = a \leq [a_N], \]

where \( N_i \) – \( i \) type cycles number during operation; \( k \) – total number of cycle types; \( [N_0] \) – allowable number of type \( i \) cycles; \( a \) – accumulated fatigue damage, the limit value of which \( [a_N] = 1 \).

The number of allowed cycles, in our case, depends on bending vibrations amplitude and their change frequency. As our calculations have shown oscillation process for these nonlinear systems is complex. Overlay of natural oscillations frequencies and exciting forces frequencies takes place, the frequency composition of response depends on gap size in intermediate supports and their arrangement. The discrete Fourier transform method is applied to find the oscillation frequencies. On Figura 3a, b as an
example, we can see the dependence of radial oscillations amplitudes and frequency composition, respectively.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Graphs for $V=1.14 \text{ m/s}$, $=0.01 \text{ mm}$.}
\end{figure}

(a) time dependence of radial oscillation amplitudes;
(b) dependence of oscillation frequencies.

Based on the above as a quality criterion in fatigue strength calculation we take amplitude of bending stresses maximum value in oscillations process in corresponding directions:

$$P_\sigma = \max(\sigma_{x,y}^{\text{bend}})$$

As a quality criteria for this design, we choose vibration wear criterion (4) and fatigue criterion for bending vibrations amplitude (5):

$\Phi_1$ – maximum friction path in one second of tube movement $L_C$, m/s;
$\Phi_2$ – maximum normal (linear) impact force in $F_N$ support, N/m;
$\Phi_3$ – maximum bending stress along the X axis $\sigma_x$, Pa;
$\Phi_4$ – maximum bending stress along the Y axis $\sigma_y$, Pa.

These parameters are determined by the numerical implementation of proposed tube bundles vibration mathematical model taking into account gaps in intermediate supports. At the first optimization stage it is fair to take into account equivalence of the accepted quality parameters to increase HE resource concerning fretting wear and tubes fatigue strength. Figure 4 shows dependence of quality parameters on gap size in intermediate supports and on cross flow velocity.

The above results of numerical experiments show that one of the qualitative criteria optimization is not sufficient for reliable statement on increasing the system resource and you multi-parametric and multi-objective optimization is essential. Moreover, as a result of this multidimensional optimization (under given parameters and criteria), we obtain compromise multidimensional regions of both the best and the worst considered structural parameters values. An important factor is the need for a significant number of experiments. The effective technologies of processing the results of computational experiments (CE) include the PLP-search method [5, 6]. The essence of PLP-search is that the result of conducting $N_0$ computational experiments randomization a set of values $\{\Phi_{ijk}\}$ is formed where $\{\Phi_{ijk}\}$ where the average value of the $k$-th quality criterion at the $i$-th level of the $j$-th parameter of the $k$-th criterion. All criteria needed to be minimized. These criteria argument is vector
of variable parameters $\alpha$, which includes: length from the tube to $l$-th support, $m$, radial gap in radial support, respectively, $m$.

**Figure 4.** Quality criteria dependence on the size of gaps and cross-flow velocity:

a) Friction path per time unit dependence on the radial gap and velocity of approach coolant flow for series $q = 1.63$;

b) Normal force dependence on the radial gap and velocity of approach coolant flow for series $q = 1.63$;

c) Bending stresses dependence on radial gap and coolant flow velocity for $q = 1.63$ series.

The formalized problem statement is as follows:

1. The initial area $G_0(\alpha)$ changes in parameters affecting the system quality is set.

2. Criteria system of operating device quality of is set $\{\Phi_k = \Phi_k(\alpha, \alpha \in G(\alpha), k = 1, K\}$. 

3. By the statistical evaluation influence of $\alpha_j$ parameters on the quality criteria and graphical analysis the concentration areas $G_k(\alpha)$ of the minimum values for each criterion $\Phi_k(\alpha)$ are determined and the parameter area containing a compromise solution is identified.

In Figura 5 (as an example) the compromise areas search results for a square bundle consists of 9 tubes with 5 spacer supports fragment at a fixed approach flow velocity, $V=0.125$ m/s are presented in graphical form. Graphical results in Figura 5 are shaded rectangles located on the axes of tube length $L$ change and radial gap $\delta_l$ between tube and support in this connection:

- rectangles of bright colors are source (basic, original) boundaries region of structural parameters changes (search area);
- rectangles of dark color represent optimal values of investigated (varied) structural parameters areas boundaries in terms of fatigue strength and tube wear

**Figure 5.** Compromise areas for a tube bundle with five spacing supports.
Conclusions:
1. The proposed method allows with required probability to identify important parameters for designing (engineering), exploitation and resource forecasting, for studied processes and different types of tube systems (with different numbers of supports, gaps and spans values between them) at preliminary calculations stage.
2. To determine gaps average values which significantly affect this type of systems vibration reliability, which in turn, allows us to recommend their realizable allowable values.
3. This method lets you notice that with the cross liquid flow rates increase there is distribution of distances between the supports up to probability influence predominance on the selected quality criteria in comparison with the gaps choice. This circumstance requires study of the support location influence on a given length tube on researched (studied) criteria in comparison with their orderly (regular) location.
4. Carried out computational experiments analysis of statistical and graphical results allows us to recommend compromise solutions for areas of each supports number on a given tube length search at a fixed cross flow rate.

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