RESEARCH ARTICLE

A heat transfer tube wear reliability analysis method based on first-order reliability method

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Abstract

The heat transfer tube is one of the most essential components of the nuclear power plant as the boundary between the first and second circuit pressures. The wear between the heat transfer tube and the support plate or the anti-vibration strip is one of the essential reasons for its failure. Based on a heat transfer tube wear analysis method, combined with the reliability analysis theory, the calculation scheme of tube wear failure probability is proposed in this paper. In the analysis and calculation process, the key factors affecting the reliability are determined, including the baffle thickness $B$ and the aperture difference $C_e$. In the manufacturing process, these key factors can be controlled, which is instructive for engineering practice.

Keywords: reliability; failure probability; steam generator; wear

List of symbols

\begin{itemize}
  \item $A_t$: The cross-sectional area of the tube
  \item $A_i$: The cross-sectional area enclosed by the inner wall of the tube
  \item $A_0$: The discharges fluid area of the tube
  \item $B$: Baffle thickness
  \item $C_e$: The difference between the outer diameter of the tube and the inner diameter of the baffle hole
  \item $C_m$: The additional quality factor of the tube
  \item $D$: The outer diameter of the tube
  \item $F_n$: The fluid elastic force of the nth-order mode
  \item $f_n$: The nth-order natural frequency
  \item $F_{SR_n}$: Fluid elastic stability ratio of the nth-order mode
  \item $h$: Wear depth
  \item $j$: Index for each node in the finite element model
  \item $K$: Wear coefficient
\end{itemize}

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L : The support thickness
Lm : Characteristic span length
Le : Effective length of the modal
m : Total mass per unit length
mj : The actual mass of the structure at node j per unit length
mr : The reference mass of structural per unit length
n : Index for each vibration mode of the model
Pf : Failure probability
\( t \) : Wear time
th : Tube thickness
\( \dot{U}_c \) : Critical flow rate
\( \dot{U}_{cn} \) : The critical velocity of the transverse flow in the nth-order mode
\( \dot{U}_{en} \) : The sufficient velocity of the transverse flow in the nth-order mode
\( U_j \) : The transverse flow velocity of the external flow field at node j
V : Wear volume
W : Wear power
\( W_r \) : Frequency-dependent empirical constant
Z : The performance function
\( \alpha \) : Fluid elastic stability constant
\( \beta \) : Reliability index
\( \Delta z_j \) : Half of the sum of the lengths of two adjacent cells to which node j belongs
\( \delta_n \) : The nth logarithmic decay rate
\( \mu_z \) : The arithmetical mean of the performance function Z
\( \xi_n \) : The damping ratio of the nth-order mode
\( \rho \) : The fluid density
\( \rho_i \) : The fluid density in the tube
\( \rho_j \) : The fluid density of the external flow field at node j
\( \rho_o \) : External fluid reference density
\( \rho_t \) : The density of metal tubes
\( \sigma_z \) : The standard deviation of the performance function Z
\( \phi_{jn} \) : Modal displacement at the node j of the nth-order mode
\( \phi^*_n \) : The biggest modal displacement of the nth-order mode

1. Introduction

In the past few decades, the global supply of fossil energy has been relatively stable. Still, the key technological breakthroughs and the demand for ecological, environmental protection have accelerated the energy revolution from a fossil energy era to a new one. As a clean and efficient modern energy, nuclear energy has become an essential means for countries to alleviate the energy crisis. As the hub of primary and secondary circuits, the steam generator is one of the vital equipment in the pressurized water reactor nuclear power plant. The heat transfer tube is an essential component of the heat exchange of the first and second circuits of the pressurized water reactor and the integrity of the pressure boundary of the primary channel (Dvoršek, Cizelj, & Mavko, 1998; Wang, Chen, Chen, Gao, & Li, 2019).

Many studies have shown that (Gupta, Kumar, Sahoo, Sahu, & Sarangi, 2017; Basavarajappa, Shankarappa, Jayanna, & Lare, 2019; Muhammad, Tamour, Muhammad, Hayat, & Wei, 2019) in the heat transfer tube of the steam generator, the flow of the fluid causes the tube bundle to vibrate, and friction is repeated between the two contact materials. Therefore, friction and wear are generated between the tube and the anti-vibration structure. Also, it is impossible to altogether remove the vibration of the tube at the support position, so there will always be some form of wear in tubes (Xin et al., 2016). As a result, the tube is local wall-thinning or even broken, which reduces the service life (Li, Lu, Xin, & Shoji, 2018), endangers the safety of the nuclear power plant and leads to catastrophic failure (Lee, Kim, Kang, & Chung, 2001; Kwon, Jeung, Chung, Yoon, & Park, 2011), bringing substantial economic losses and environmental disasters. Therefore, it is of considerable significance to study the wear behavior of heat transfer tubes and improve the safety and economy of nuclear power plants.

At present, the research on the wear of nuclear power equipment materials mainly focuses on fretting wear, etc. The fretting wear that occurs in a restricted position between the tube and the support frame is one of the main failure modes of the heat transfer tube. Fretting wear mainly includes adhesive wear, wear, delamination, material transfer, and oxidation. It is the accumulation of damage at two contact surfaces subject to relatively small amplitude oscillations.

Several studies have been mentioned in many articles related to fretting wear, especially for the fretting wear of heat transfer tubes. The effects of different materials [affected by particle size carbides and hardness, surface hardness (Budinski, 2013)] and different mechanical parameters [displacement amplitude (Lim, Oh, & Lee, 2003), the normal force (Lim et al., 2003; Huang, Wang, Li, Zhu, & Zhang, 2017), temperature (Gue’rout & Fisher, 1999; Lee et al., 2001; Lee, Kim, Kim, Park, & Kim, 2003; Hong & Kim, 2005; Yun et al., 2014; Mi et al., 2016; Lai, Gao, Tang, Guo, & Zhang, 2018), frequency (Dick, Paulin, Caillaud, & Fouvry, 2006; Van Peteghem, Fouvry, & Petit, 2011), environmental PH (Wang, Lu, Li, & Shoji, 2016), etc.] on the fretting wear behavior of tubes were studied.

Besides, Lim et al. (2003), Che and Lei (2013), and Jeong, Cho, and Lee (2005) studied the fretting wear coefficient K under various test conditions. Leonard, Sadeghi, Shinde, and Mittelbach (2012) used the Archard and dissipated energy wear theories to predict
wear, wear scar shape, and wear pressure curves. Experiments conducted by Rogers and Pick (1976, 1977) in air and water with and without gap support verify the results of computer technology prediction analysis of multi-span single-tube devices. The life of the tubes is predicted based on the expected support impact force, and the existing experimental fretting wear data.

In most applications, fretting wear is often modeled using Archard or dissipative energy equations. The Archard equation was proposed in the 1950s and is still the most commonly used theory. The dissipative energy approach is a recent development and is being recognized as a theory of fretting wear analysis (Leonard et al., 2012).

The prediction and evaluation of tube life is an essential part of ensuring the safe operation of heat transfer tubes. The work rate model is a widely used predictive model, which was proposed by Frick, Sobek, and Reavis (1984). Through continuous improvement, some new models are developed, such as Markov stochastic process model (He et al., 2019), and a work rate model based on the Archard wear equation.

Calculation of wear volume $V$ by the most widely used Archard wear physical model is done as below:

$$V = K F_n L,$$  \hspace{1cm} (1)

where $V$ is the wear volume, $F_n$ is the normal contact force between the foreign objects and the tube, $L$ is the sliding distance, and $K$ is the wear coefficient.

Fluid traction, additional mass, and vibration damping are the primary input conditions for transient dynamic analysis. Then, the normal contact force $F_n$ and total sliding length in the Archard model $L$ are calculated by transient dynamics analysis. Finally, the wear volume of the heat transfer tube $V$ was calculated based on the wear coefficient $K$ between the tube material and the foreign substance.

According to the Archard model, the wear amount $V$ produced by the contact point per unit time is proportional to the wear power $W$ of the point, which can be simply expressed as the following formula.

$$V = K W$$ \hspace{1cm} (2)

$$W = W f_i D F_n$$ \hspace{1cm} (3)

$$F_n = C_f \rho_0 D U_{en}^3 \left( \frac{C_t}{D} \right) \left[ 1 - \frac{U_{en}^2}{U_{cr}^2} \right] L_e$$ \hspace{1cm} (4)

The research in wear and tear of tubes focuses on flow-induced vibration, tube and support material wear characteristics, wear degree prediction, and device structure design and improvement. Also, a large number of wear behavior studies, such as wear volume and wear depth, were performed to predict the life of tube wear behavior.

However, when these simplified mechanical models are used to solve the tube wear problem, there are some limitations. The details of the simulated dynamic behavior in the complex structure are not entirely consistent with the experimental measurement behavior. There is a certain conservative margin in the measurement and analysis of wear volume.

The previous studies have not seen relevant reports on the sensitivity analysis of wear depth to essential parameter variables and the solution of failure probability of tube wear in the service cycle. To ensure the heat exchanger requirements, it is not allowed to set too many conservative margins in the design. It is necessary to conduct in-depth research on various parameters, including wear and analysis of wear behavior. The finite element method, such as ABAQUS, is used to calculate and analyze the tube model. Then, the flow elastic excitation force and wear amount are calculated. The finite element model is established according to the typical U-shaped heat exchanger structure in Fig. 1 and based on the average flow field data in Table 1. According to the flow data and actual
support conditions in the flow-induced vibration evaluation results of the heat exchanger, the tubes susceptible to flow-induced vibration are screened.

The flow elastic force is calculated by sequentially removing the active support, and the tube wear is analyzed by exploring the method of tube wear analysis and establishing the wear evaluation system of tubes during the life span. Combined with the reliability calculation method of tube wear, the wear failure probability and wear life of tube are discussed. The main influencing factors affecting the life of the tube are obtained, and the rationality of the life prediction is enhanced.

2. Steam Generator Tube Wear Analysis Method

2.1 A fluid elastic instability analysis method

The fluid elastic instability caused by the fluid flexible excitation is the self-excited vibration phenomenon after the flowing fluid is coupled with the vibration of the tube. When a heat transfer tube in the tube bundle is instantaneously displaced from its original equilibrium position, the flow field is changed, and the balance of forces on adjacent tubes is broken, so that they are also replaced and vibrated. When the flow velocity reaches a specific value, the work done by the fluid elastic force on the tube system is higher than the work consumed by the damping function of the tube system. At this time, the reaction amplitude of the tube will rapidly increase. It cannot converge (ASME, 2008); even if there is a small increase in the flow rate, it will cause a sudden rise in the vibration of the tube, so that collisions will occur between adjacent tubes. Fluid elastic instability is the result of strong coupling between structure and fluid. To avoid fluid elastic instability, the fluid elastic stability ratio $FSR_n$ in all modes should be satisfied:

$$FSR_n < 1.0,$$

where $FSR_n$ is defined as:

$$FSR_n = U_{en}/U_{cn},$$

in which, $U_{en}$ is the effective velocity of the transverse flow in the nth-order mode, $U_{cn}$ is the critical velocity of the transverse flow in the nth-order mode, and $U_{en}$ and $U_{cn}$ are calculated according to (7) and (8), respectively (Han, Zuo, Qin, & Zhang, 2014):

$$U_{en} = \sqrt{\sum_{j=1}^{N} \left( \frac{\rho_o \phi_{jn} \Delta z_j}{m_j} \right)^2},$$

$$U_{cn} = a f_n \sqrt{\frac{m_j}{\rho_o D^2}},$$

In (7), $\rho_j$, $U_j$ are the fluid density and transverse flow velocity of the external flow field at the node $j$, respectively. $\rho_o$, $\Delta z_j$ represent external fluid reference density and half of the sum of the lengths of two adjacent cells to which node $j$ belongs. $\phi_{jn}$ represents modal displacement at the node $j$ of the nth-order mode. $m_j$, $m_o$ denote the actual mass of the structure at node $j$ and the reference mass of structural per unit length. In (8), $\alpha$ is the fluid elastic stability constant, takes 4.5 (Tang et al., 2016), $f_n$ is the nth-order natural frequency, and $\delta_n$ is the nth-order logarithmic decay rate. $\delta_n = 2 \pi \xi_n$, $\xi_n$ represents the damping ratio of the nth-order mode.

$m_j$ and $m_o$ are calculated according to (9) and (10):

$$m_j = A_T \rho_j + A_A \rho_i + C_m A_T \rho_j,$$

$$m_o = A_T \rho_i + A_A \rho_i + C_m A_T \rho_i.$$

In (9), $A_T$, $A_A$, and $A_T$ are the cross-sectional area of the tube, the cross-sectional area enclosed by the inner wall of the tube, and the discharges fluid area of the tube. $\rho_j$ and $\rho_i$ represent the density of metal tubes and fluid density in the tube, respectively. $C_m$ denotes an additional quality factor, which is conservatively taken as 2.8 (Kim & Lee, 2001).

The critical damping ratio $\xi_n$ in each model is calculated according to the following equation (Pettigrew, Rogers, & Axisa, 2011):

$$0.6% < \xi_n = \frac{1460 \rho D^2}{m f_n} \left( \frac{L}{L_m} \right)^{0.5} + 0.5 \left( \frac{L}{L_m} \right)^{0.5} < 3.0%.$$

In (11), $m$ is total mass per unit length, $L_m$ is the characteristic span length, $L$ is the support thickness, and $\rho$ is the fluid density.
2.2 Heat transfer tube wear calculation method

The amount of wear for tubes is a function of time and can be calculated according to the Archard wear theory. The following three types of input parameters are mainly involved in wear calculation: the wear coefficient of the tube and the support material (depending on the type of material and motion); the wear power associated with the magnitude of the normal force and the slip motion; and the relationship between the wear depth at the contact surface and the wear volume (related to the geometry). The wear volume of the tubes and baffles after a specific running time can be calculated according to (12).

\[ V = \int K(WR)dt \]  

In (12), \( V \) and \( K \) are respectively the wear volume of tubes or baffles and the wear factor determined by the experiment. For the calculation of the wear coefficient of tubes (Rogers, Taylor, & Pettigrew, 1984; Song, 2000; Kim & Lee, 2001; Pettigrew et al., 2011), set \( K = 21 \times 10^{-5} \text{m}^2/\text{N} \cdot \text{t} \) is the operation hours. \( WR \) denotes the wear power, which can be calculated as follows.

\[ WR = W_f \int dF_n \]  

In (13), \( W_f \) represents the empirical constant related to structure frequency. \( F_n \) indicates the fluid elastic force under transverse flow excitation, which can be calculated as follows (Langford & Connors, 1991).

\[ F_n = \rho_0 U^2 c_n \frac{4\pi}{a^2} \left(1 - \frac{U_n^2}{U_e^2}\right) L_e \]  

In (14), \( c_n \) is the difference between the outer diameter of the tube and the inner diameter of the baffle hole. \( L_e \) is the modal effective length, which can be calculated as follows:

\[ L_e = \sum_{j=1}^{N} \left( \frac{m_i}{m_k} \left( \frac{\varphi_{jn}}{\varphi_{kn}} \right)^2 \Delta z_j \right) \]  

where \( \varphi_{jn} \) represents the biggest modal displacement of the nth-order mode. If the finite element analysis of the mode shape does include the step of normalization, \( \varphi_{jn}^* \) will be equal to 1.

Considering that the tube passes through the circular aperture of the baffle, the wear is manifested by a uniform annular thinning of the tube surface, and the wear depth \( h \) can be calculated from the wear volume:

\[ h = \frac{V}{\pi DB} \]  

where \( B \) is the baffle thickness. Considering that wear can occur on one side of the heat transfer tube, when calculating the wear depth, conservatively use the following formula instead of (16).

\[ h = \frac{2V}{\pi DB} \]  

2.3 Reliability analysis and calculation method

The reliability of structure is related to many random variables, and the relationship between the variables is not only the addition or subtraction, which makes the calculation process of the random process large and time consuming. The calculation of reliability is more complicated. The reliability analysis methods mainly include first-order reliability method, second-order reliability method, Monte Carlo simulation method, and probability finite element method in the field of mechanical and structural reliability. First-order reliability method is one of the most commonly used methods for reliability analysis and calculation. The international standard "General Principles of Structural Reliability" and the first-level and second-level structural reliability design standards in China, such as "Unified Standard for Reliability Design of Engineering Structures" and "the Unified Standard for Reliability of Building Structures," are also recommended to adopt first-order reliability method. First-order reliability method was initially calculated based on the linear performance function and the second moment of the independent normal random variable.

As an important boundary of the primary and secondary circuits, the heat transfer tube not only bears the pressure difference and temperature difference between the two sides but also is affected by fluid vibration load and environmental corrosion, making the heat transfer tube the weakest link in the pressure boundary of the entire primary circuit. In order to avoid the leakage of nuclear material in the primary circuit, it is judged whether or not the pipe plugging is required according to the relevant pipe plugging criteria. For degraded heat transfer tubes, experiments and analysis should be used to determine the maximum allowable thinning. Since the current tube plugging criterion is based on wall thickness, it is particularly important to determine the wear volume and depth in the heat transfer tube wear calculation. The heat transfer tube wear is mainly reflected in the wall thickness. Under operating conditions, in order to avoid excessive wear and tear of the pipe in the thickness direction, the performance function is usually set to the difference between the thickness and the wear depth of a certain proportion. This ratio is usually around 10%. For the sake of conservativeness in this article, a safer ratio of 8% is selected as an example. So, we assume that the performance function is \( Z = 0.08 \pi h - \pi \), where \( h \) is the tube wall thickness. The primary variables are subject to a normal distribution or a lognormal distribution, and each of the essential variables is statistically independent of each other. The statistical mean \( \mu_X \) and the standard deviation \( \sigma_X \) of the performance function \( Z \) can be calculated from the 1st moment and the 2nd moment of the underlying random variable \( X_i \), thereby determining the reliability index \( \beta \) value of the state equation.
The first-order partial derivative of the wear depth h to the parameter is as follows. 

\[
\frac{\partial h}{\partial B} = -\frac{2K W f_n t F_n}{\pi B^2} 
\]

(18)

\[
\frac{\partial h}{\partial K} = -\frac{2W f_n t F_n}{\pi B} 
\]

(19)

\[
\frac{\partial h}{\partial W} = -\frac{2K f_n t F_n}{\pi B} 
\]

(20)

\[
\frac{\partial h}{\partial C_e} = \frac{8KW f_n t}{B\alpha^2} - \rho f n U_2^2 - 1 \left( \frac{U_2}{U_{\text{cr}}} \right)^2 L_e 
\]

(21)

\[
\frac{\partial h}{\partial \alpha} = -\frac{12KW C_e f_n t F_n}{B\alpha^2} - \rho f n U_2^2 L_e 
\]

(22)

Considering the change of the diameter D of the structure, the frequency f_n and the damping of modal calculated by the finite element method will be all changed, and the equivalent transverse flow velocity U_{\text{cr}}, the critical flow velocity U_{\text{cr}}, and the effective modal length L_e are all changed. The derivative of the wear depth is difficult to express by its mathematical formula. According to the probability finite element theory, the first-order partial derivative of the wear depth h to the diameter D can be calculated by the different methods. 

\[
\frac{\partial h}{\partial D} = \lim_{D \to 0} \frac{h(D + \Delta D) - h(D)}{\Delta D} = \lim_{D \to 0} \frac{2V}{\pi D(D + \Delta D)B} 
\]

(23)

The average value of wear depth h:

\[
\overline{h} = \frac{2KW f_n t F_n}{\pi B} 
\]

(24)

The standard deviation of wear depth h:

\[
\sigma_h = \sqrt{\frac{\partial h}{\partial B}^2 + \frac{\partial h}{\partial K}^2 + \frac{\partial h}{\partial W}^2 + \frac{\partial h}{\partial C_e}^2 + \frac{\partial h}{\partial \alpha}^2} \left( \frac{\partial h}{\partial D} \right)^2 
\]

(25)

\[
\mu_z = 0.08\overline{h} - \overline{h} 
\]

(26)

\[
\sigma_z = \sqrt{\frac{\partial h}{\partial B}^2 + \frac{\partial h}{\partial K}^2 + \frac{\partial h}{\partial W}^2 + \frac{\partial h}{\partial C_e}^2 + \frac{\partial h}{\partial \alpha}^2} \left( \frac{\partial h}{\partial D} \right)^2 
\]

(27)

Reliability index:

\[
\beta = \frac{\mu_z}{\sigma} 
\]

(28)

Failure probability:

\[
P_f = \Phi (-\beta) 
\]

(29)

### 3. Calculation Model Examples Analysis

In this paper, we mainly consider the tubes near the inlet and outlet of the heat exchanger. The general structure of the heat exchanger is shown in Fig. 1. Since the fluid flow load is also largely due to the high flow rate, it is expected to generate a large amount of wear.

#### 3.1 Model input parameters

The heat transfer tube material is 304L stainless steel with a size of 9.525 × 0.889 mm. Considering that the fluid outside the tube does not boil, the fluid density inside and outside the tube is 1000 kg/m³. And the equivalent density of the heat transfer tube calculated is 16845 kg/m³, according to equation (9). The following table gives the results of the flow-induced vibration evaluation of the heat exchanger based on HTSE, special software for thermal-hydraulic analysis of heat exchangers.

#### 3.2 Model simplification method and finite element model

Considering that the cold water on the shell side flows into the heat exchanger through the inlet nozzle, it will flow to the outlet nozzle. The elbow zone of the U-shaped heat transfer tube is a dead zone and is not subjected to the vibration load of the shell side flow. Therefore, the calculation of the tube wear is only for the straight tube section, and the elbow section is equivalent to the straight tube extension section. The maximum fluid elastic stability ratio of the heat exchanger under normal operating conditions, that is, the maximum value of the ratio of the average cross-flow velocity to the critical flow velocity, is 0.3, so that the heat exchanger does not undergo fluid elastic instability. According to equation (14), when the flow elastic stability ratio is less than 1, the flow elastic force F_n is less than 0, that is, no wear occurs.

The heat transfer tube is simplified into a beam and select fixed constraint between the heat transfer tube and the integrated tube box, and the contact between the tube and the baffle (or support plate) is simply supported, as shown in Fig. 2. Figure 3 shows the flow field flow rate at each span of the heat transfer tube. The simple support of the tube at the position of the baffle is removed sequentially, and four finite element models are established, as shown in Fig. 4. The flow elastic stability ratio of the tube near the anti-vibration baffle under the condition that the four-layer baffle fails in the sequence is calculated. The wear of the baffle plate is calculated when the flow elastic stability ratio exceeds 1.
Figure 2: Finite element model of heat transfer tube.

Figure 3: The corresponding flow rate of each cross-section of the heat transfer tube.

Figure 4: The finite element model of the heat transfer tube support is sequentially removed.

Figure 5: Finite element mesh and central nodes.

Table 2: Analysis of the stability of the stream after removal of the 1st support.

| Order | Frequency (Hz) | Equivalent flow rate (mm/s) | Damping ratio | Critical flow rate (mm/s) | Flow elastic stability ratio |
|-------|----------------|-----------------------------|---------------|---------------------------|----------------------------|
| 1     | 34.76          | 674.10                      | 0.018         | 858.92                    | 0.785                      |
| 2     | 60.17          | 663.10                      | 0.011         | 1143.28                   | 0.580                      |

Figure 5 shows the central nodes of the tube finite element model. The model uses a first-order beam element model. First, the endpoints of tubes and the baffle support points are numbered 1–6 as critical nodes. Then, fill each span in turn, a total of 108 nodes.

3.3 Results

The calculation results after removing the four supports, in turn, are shown in Tables 2 to 5. It can be seen from the data that removing the support of the 1st baffle and the 2nd baffle to tubes, respectively, will not wear at the contact. The support of the tubes of the 3rd baffle plate and the 4th baffle plate are removed, respectively. The calculated flow elastic stability ratio of each step is greater than 1. In the following, the modes of the two linear flow elastic stability ratios greater than 1 are defined as mode A and mode B. This indicates that the tubes will wear at the contact with the 3rd and 4th baffles, and the wear calculation results of these two points will be discussed later.

Table A1 gives the dimensionless mode displacement of second-order mode instability.

The main calculation results are given in Table 6. The wear depth of the heat transfer tube in contact with the 3rd baffle plate reaches 0.0122 mm after 60 years, which accounts for 1.4% of the wall thickness of 0.889 mm. The wear depth at the contact with the 4th baffle plate reaches 0.0016 mm after 60 years, which accounts for 0.17% of the wall thickness. Both of them are less than 10% of the wall thickness. It can be seen that the tube wear caused by flow-induced vibration is small. After removing the 3rd baffle and the
**Table 5:** Analysis of the stability of the stream after removal of the 4th support.

| Order | Frequency (Hz) | Equivalent flow rate (mm/s) | Damping ratio | Critical flow rate (mm/s) | Flow elastic stability ratio |
|-------|----------------|-----------------------------|---------------|---------------------------|-----------------------------|
| 1     | 6.99           | 627.80                      | 0.030         | 221.05                    | 2.841                       |
| 2     | 45.48          | 936.76                      | 0.014         | 987.74                    | 0.948                       |

**Table 3:** Analysis of the stability of the stream after removal of the 2nd support.

| Order | Frequency (Hz) | Equivalent flow rate (mm/s) | Damping ratio | Critical flow rate (mm/s) | Flow elastic stability ratio |
|-------|----------------|-----------------------------|---------------|---------------------------|-----------------------------|
| 1     | 26.93          | 546.41                      | 0.023         | 752.58                    | 0.726                       |
| 2     | 60.52          | 644.85                      | 0.011         | 1146.80                   | 0.562                       |

**Table 4:** Analysis of the stability of the stream after removal of the 3rd support.

| Order | Frequency (Hz) | Equivalent flow rate (mm/s) | Damping ratio | Critical flow rate (mm/s) | Flow elastic stability ratio |
|-------|----------------|-----------------------------|---------------|---------------------------|-----------------------------|
| 1     | 16.11          | 934.39                      | 0.029         | 509.49                    | 1.834                       |
| 2     | 43.96          | 571.86                      | 0.015         | 970.39                    | 0.589                       |

**Table 6:** The main calculation results.

| Main parameters                      | Third support point (mode A) | Fourth support point (mode B) |
|--------------------------------------|------------------------------|-------------------------------|
| Modal effective length $L_e$         | 523.97 mm                    | 200.41 mm                     |
| Equivalent flow rate $U_e$           | 849.45 mm/s                  | 570.91 mm/s                   |
| Critical flow rate $U_c$             | 634.09 mm/s                  | 275.11 mm/s                   |
| Aperture difference $C_e$            | 0.405 mm                     | 0.405 mm                      |
| External fluid reference Density $\rho_o$ | $1 \times 10^{-9}$ t/mm³ | $1 \times 10^{-9}$ t/mm³     |
| Fundamental frequency $f$            | 16.11 Hz                     | 6.99 Hz                       |
| Wear coefficient $K$                 | $2.1 \times 10^{-8}$ MPa⁻¹  | $2.1 \times 10^{-8}$ MPa⁻¹    |
| Frequency-dependent empirical constant $W_f$ | 0.005                      | 0.005                         |
| Outer diameter $D$                   | 9.525 mm                     | 9.525 mm                      |
| Baffle thickness $B$                 | 6 mm                         | 6 mm                          |
| Wear time $t$                        | $1.892 \times 10^3$ s (60 years) | $1.892 \times 10^3$ s (60 years) |
| Fluid elastic excitation force $F_n$ | 0.0421 N                     | 0.0126 N                      |
| Wear volume $V$                      | 1.099 mm³                    | 0.143 mm³                     |
| Wear depth $h$                       | 0.0122 mm                    | 0.0016 mm                     |

4th baffle support respectively, the fundamental frequencies of the two are 16.11 and 6.99 Hz, respectively, and the corresponding flow elastic stability ratios are 1.34 and 2.08, respectively.

Although the flow elastic stability ratio is higher and the tube instability is more severe under the condition of removing the 4th baffle support, the maximum position of the tube vibration mode is the curved tube area with a flow velocity of zero. At the same time, the fundamental frequency of the tube drops to 6.99 Hz, which also dramatically reduces the total number of vibrations during the 60-year lifetime. This causes the maximum wear of the tube to occur in contact with the 3rd baffle.

We use the mean first-order reliability method to calculate the reliability index and failure probability of tube wear and propose an analysis method of tube wear reliability. The sensitivity of wear depth to various influencing factors is analyzed, and the failure probability of tubes in two cases is compared.

The wall thickness of the tube is 0.889 mm. We assume that the probability distribution type of each variable is a normal distribution. The characteristics of each random variable for calculating the wear depth are shown in Table 7. The sensitivity analysis of the tube wear calculation was carried out by the mean first-order second-moment method. The sensitivity results of the wear depth for each variable are shown in Table 8. The reliability calculation results are shown in Table 9. In mode A, the ratio of the mean value of the performance function to the standard deviation is relatively small, that is, the reliability index value is relatively small. Therefore, compared with mode B, the failure probability in mode A is relatively large.

From the previous equations (25)–(28), we can see that the reliability index $\beta$ is affected by the standard deviation $\sigma_z$. The change in the standard deviation of each parameter will affect the reliability. So, the size of $\sigma_z$ will affect the reliability index. The effect of each variable on $\beta$ in both modes is shown in Table 10.

Based on Table 7, different standard deviation values are taken out to investigate the influence of the parameters on the failure probability. As shown in Table 11, the standard deviation of baffle thickness $B$ was increased from 0.05 to 0.35 in the step of 0.05. The
standard deviation of aperture difference \( \sigma \) was increased from 0.07 to 0.1 in the step of 0.005, and the standard deviation of fluid elastic stability constant \( \alpha \) was increased from 0.1 to 0.4 in the step of 0.05.

The abscissa of the graph has undergone the min–max normalization process. Figure 6 shows that in mode A, which occurs in the position between the tube and the third baffle, the standard deviation of the fluid elastic stability constant \( \alpha \) has a more significant influence on the failure probability of the tube than other variables: the failure probability remains around \( 8.824 \times 10^{-5} \). As the standard deviation of the parameter distribution increases, the failure probability increases gradually. To our surprise, the baffle thickness has little effect on reliability.

Figure 7 shows that in mode B, which occurs in the position between the tube and the fourth baffle, relative to the baffle thickness, the standard deviation of the aperture difference \( C_e \) and the fluid elastic stability constant have a significant influence on the failure probability of the tube: the failure probability remains around \( 1.806 \times 10^{-6} \). As the standard deviation of the parameter distribution increases, the failure probability increases gradually. To our surprise again, the baffle thickness also has only a little effect on reliability.

Recognized development of artificial intelligence is an effective way to optimize and screen engineering design according to theoretical prediction (Deng, Liu, Xu, Zhao, & Song, 2020). Considering the difference in processing accuracy, with the improvement of processing technology, the influence of various variables on the probability of failure will be reduced. In the practical application of the project, spending more on the thickness of baffle to improve the process level is not suggested, because the impact of the thickness of baffle on the failure probability is basically unchanged. The suggestion is to make some improvements in the aperture difference; improving the processing technology will reduce the failure probability of heat transfer tube.

Compared with the wear amount, the failure probability is used as a reliability reference index for tube wear analysis, which state of the tube during the lifetime can be described more objectively and directly. Through the tube wear reliability analysis, we can obtain the key factors that affect the wear amount of the heat transfer tube during the lifetime.
4. Conclusion

A reliability analysis method is proposed in the paper, which can be applied to wear reliability analysis of heat transfer tube structures. The method based on Archard wear theory and vibration evaluation results, and the outer heat transfer tube near the shell side inlet and outlet nozzle are taken as the research object. First, the vibration and the amount of wear at the point of contact with the baffles are analyzed. Combined with the reliability calculation method, the failure probability of tube wear is discussed, and the main influencing factors affecting the life of the tube are obtained, which further enhances the rationality of the tube life prediction. The following conclusions can be drawn:

(i) Considering the reliability calculation method, extending the deterministic wear analysis to the probabilistic failure analysis. The failure probability of the tube improves life prediction during the service period.

(ii) The diameter \( D \) of the tube is not a critical factor affecting failure probability. The key factors, baffle thickness \( B \) and aperture difference \( C_e \), can be controlled during the production and manufacturing, which is instructive for engineering practice. And the fluid elastic stability constant \( \alpha \) needs to be determined more accurately during the experiment.

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Appendix

Table A1: Dimensional mode displacement with wear mode.

| Node number | X coordinate (mm) | Flow rate (mm/s) | Dimensionless mode displacement |
|-------------|-------------------|-----------------|--------------------------------|
|             |                   |                 | Mode A     | Mode B     |
| 1           | 0                 | 913             | 0.00000    | 0.00000    |
| 2           | 448               | 720.5           | 0.00000    | 0.00000    |
| 3           | 958               | 528             | 0.00000    | 0.00000    |
| 4           | 1468              | 907.5           | 0.99780    | 0.00000    |
| 5           | 1916              | 643.5           | 0.00000    | 0.60930    |
| 6           | 2133              | 0               | -0.88230   | 1.00000    |
| 7           | 20.364            | 913             | 0.00039    | -0.00004   |
| 8           | 40.727            | 913             | 0.00144    | -0.00015   |
| 9           | 61.091            | 913             | 0.00306    | -0.00031   |
| 10          | 81.455            | 913             | 0.00514    | -0.00052   |
| 11          | 101.818           | 913             | 0.00757    | -0.00076   |
| 12          | 122.182           | 913             | 0.01024    | -0.00104   |
| 13          | 142.545           | 913             | 0.01304    | -0.00132   |
| 14          | 162.909           | 913             | 0.01587    | -0.00161   |
| 15          | 183.273           | 913             | 0.01862    | -0.00189   |
| 16          | 203.636           | 913             | 0.02119    | -0.00215   |
| 17          | 224               | 913             | 0.02347    | -0.00238   |
| 18          | 244.364           | 913             | 0.02535    | -0.00258   |
| 19          | 264.727           | 913             | 0.02674    | -0.00272   |
| 20          | 285.091           | 913             | 0.02752    | -0.00280   |
| 21          | 305.455           | 913             | 0.02760    | -0.00282   |
| 22          | 325.818           | 913             | 0.02687    | -0.00274   |
| 23          | 346.182           | 913             | 0.02524    | -0.00258   |
| 24          | 366.545           | 913             | 0.02260    | -0.00231   |
| 25          | 386.909           | 913             | 0.01886    | -0.00193   |
| 26          | 407.273           | 913             | 0.01391    | -0.00143   |
| 27          | 427.636           | 913             | 0.00765    | -0.00079   |
| 28          | 467.615           | 528             | -0.00878   | 0.00090    |
| 29          | 487.231           | 528             | -0.01870   | 0.00193    |
| 30          | 506.846           | 528             | -0.02953   | 0.00305    |
| 31          | 526.462           | 528             | -0.04103   | 0.00424    |
| 32          | 546.077           | 528             | -0.05295   | 0.00548    |
| 33          | 565.692           | 528             | -0.06506   | 0.00675    |
| 34          | 585.308           | 528             | -0.07712   | 0.00801    |
| 35          | 604.923           | 528             | -0.08889   | 0.00925    |
| 36          | 624.538           | 528             | -0.10010   | 0.01044    |
| 37          | 644.154           | 528             | -0.11070   | 0.01156    |
| 38          | 663.769           | 528             | -0.12020   | 0.01258    |
| 39          | 683.385           | 528             | -0.12850   | 0.01347    |
| 40          | 703               | 528             | -0.13540   | 0.01423    |
| 41          | 722.615           | 528             | -0.14060   | 0.01481    |
| 42          | 742.231           | 528             | -0.14400   | 0.01520    |
| 43          | 761.846           | 528             | -0.14530   | 0.01537    |
| 44          | 781.462           | 528             | -0.14430   | 0.01530    |
| 45          | 801.077           | 528             | -0.14080   | 0.01497    |
| 46          | 820.692           | 528             | -0.13470   | 0.01435    |
### Table A1: Continued

| Node number | X coordinate (mm) | Flow rate (mm/s) | Mode A | Mode B |
|-------------|-------------------|------------------|--------|--------|
| 47          | 840.308           | 528              | −0.12560 | 0.01342 |
| 48          | 859.923           | 528              | −0.11350 | 0.01216 |
| 49          | 879.538           | 528              | −0.09808 | 0.01053 |
| 50          | 899.154           | 528              | −0.07921 | 0.00853 |
| 51          | 918.769           | 528              | −0.05670 | 0.00612 |
| 52          | 938.385           | 528              | −0.03036 | 0.00329 |
| 53          | 977.615           | 528              | 0.03453  | −0.00376 |
| 54          | 997.231           | 528              | 0.07278  | −0.00790 |
| 55          | 1016.846          | 528              | 0.11430  | −0.01234 |
| 56          | 1036.462          | 528              | 0.15860  | −0.01700 |
| 57          | 1056.077          | 528              | 0.20520  | −0.02179 |
| 58          | 1075.692          | 528              | 0.25370  | −0.02661 |
| 59          | 1095.308          | 528              | 0.30360  | −0.03139 |
| 60          | 1114.923          | 528              | 0.35440  | −0.03604 |
| 61          | 1134.538          | 528              | 0.40580  | −0.04047 |
| 62          | 1154.154          | 528              | 0.45750  | −0.04459 |
| 63          | 1173.769          | 528              | 0.50840  | −0.04832 |
| 64          | 1193.385          | 528              | 0.55880  | −0.05158 |
| 65          | 1213              | 528              | 0.60810  | −0.05428 |
| 66          | 1232.615          | 528              | 0.65580  | −0.05633 |
| 67          | 1252.231          | 528              | 0.70170  | −0.05777 |
| 68          | 1271.846          | 528              | 0.74540  | −0.05816 |
| 69          | 1291.462          | 528              | 0.78650  | −0.05777 |
| 70          | 1311.077          | 528              | 0.82480  | −0.05639 |
| 71          | 1330.692          | 528              | 0.85990  | −0.05395 |
| 72          | 1350.308          | 528              | 0.89160  | −0.05036 |
| 73          | 1369.923          | 528              | 0.91960  | −0.04553 |
| 74          | 1389.538          | 528              | 0.94370  | −0.03939 |
| 75          | 1409.154          | 528              | 0.96380  | −0.03184 |
| 76          | 1428.769          | 528              | 0.97960  | −0.02282 |
| 77          | 1448.385          | 528              | 0.999090 | −0.01223 |
| 78          | 1488.364          | 528              | 1.00000  | 0.01452 |
| 79          | 1508.727          | 528              | 0.99710  | 0.03082 |
| 80          | 1529.091          | 528              | 0.98910  | 0.04883 |
| 81          | 1549.455          | 528              | 0.97600  | 0.06844 |
| 82          | 1569.818          | 528              | 0.95780  | 0.08960 |
| 83          | 1590.182          | 528              | 0.93440  | 0.11220 |
| 84          | 1610.545          | 528              | 0.90600  | 0.13620 |
| 85          | 1630.909          | 528              | 0.87270  | 0.16150 |
| 86          | 1651.273          | 528              | 0.83460  | 0.18800 |
| 87          | 1671.636          | 528              | 0.79180  | 0.21560 |
| 88          | 1692              | 528              | 0.74460  | 0.24430 |
| 89          | 1712.364          | 528              | 0.69310  | 0.27390 |
| 90          | 1732.727          | 528              | 0.63750  | 0.30450 |
| 91          | 1753.091          | 528              | 0.57810  | 0.33590 |
| 92          | 1773.455          | 528              | 0.51510  | 0.36810 |
| 93          | 1793.818          | 528              | 0.44890  | 0.40100 |
| 94          | 1814.182          | 528              | 0.37970  | 0.43450 |
| 95          | 1834.545          | 528              | 0.30780  | 0.46860 |
| 96          | 1854.909          | 528              | 0.23550  | 0.50320 |
| 97          | 1875.273          | 528              | 0.15730  | 0.53820 |
| 98          | 1895.636          | 528              | 0.07931  | 0.57360 |
| 99          | 1935.727          | 0                | −0.07780 | 0.64420 |
| 100         | 1955.455          | 0                | −0.15640 | 0.67940 |
| 101         | 1975.182          | 0                | −0.23570 | 0.71460 |
| 102         | 1994.909          | 0                | −0.31560 | 0.75010 |
| 103         | 2014.636          | 0                | −0.39590 | 0.78560 |
| 104         | 2034.364          | 0                | −0.47660 | 0.82130 |
| 105         | 2054.091          | 0                | −0.55750 | 0.85700 |
| 106         | 2073.818          | 0                | −0.63860 | 0.89270 |
| 107         | 2093.545          | 0                | −0.71980 | 0.92850 |
| 108         | 2113.273          | 0                | −0.80110 | 0.96420 |