Visual Abstract

Assessment of the strength reliability of high-temperature heat exchangers with long service life at the design stage

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ABSTRACT. The article describes a method for assessing the strength reliability of high-temperature heat exchangers with service life of several tens of thousands of hours at the design stage, when there is not enough statistical data on the operating time of elements and material properties. The method shows, how to determine the coefficients of variation for calculating reliability and build the function of the probability of failure-free operation, considering the change of the properties of the structural material over time. The method of visualizing the distribution of zones, both satisfying and not satisfying reliability criteria at the nodes of any finite element model, is also described.

KEYWORDS. Reliability; Strength; Heat-exchanger; Assessment.

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INTRODUCTION

The energy supply of high-power systems requires the use of heat exchangers (HE) for various purposes as part of a power plant.

In the case when the service life of the plants is several tens of thousands of hours, and the temperatures reach the creep temperatures of the structural material, it becomes necessary to take into account changes in the properties of materials (reduction of long-term static strength), as well as changes in the stress state of the structure (stress relaxation) over time, which is directly affects strength reliability. Thus, the substantiation of the strength reliability of HE with long service life is a rather difficult engineering task.

There are several works devoted to reliability of HE. However, in [1] the authors use statistical data on similar serial heat exchangers that have been working for a long time and determine other parameters. In work [2], the authors use a similar method in content, however, they carry out calculations in the software package and do not indicate data on the coefficients of variation and the principle of their choice. In [3], considered a technique for analyzing the reliability of complex mechanical systems at the design stage, however, the authors consider other aspect of this problem.
In this paper, the authors consider a method for determining the coefficients of variation for calculating the reliability of complex systems, such as HE, at the design stage.

OBJECT OF STUDY

As an example, considered a shell-and-tube type HE with a cylindrical body in which a tube packet (TP) is enclosed. The tubes in packet are connected to the tube boards by welding.
In the general case, the structure is under the influence of pressure drops in various cavities and under the influence of high temperature fields distributed according to a certain law both - along the length of the structure and in the radial direction along HE sections. The thermal isolation of the casing and the tube package is carried out using a bellows (Fig. 1). All parts are made of steel 08Cr16N11M3 (Russian classification).

THE STRUCTURAL MODEL AND THE FINITE ELEMENT MODEL

Fig. 2 shows the finite element model (FEM) built in the «Fidesys» software package. Fig. 3 shows the distribution of the temperature field in the heat exchanger.

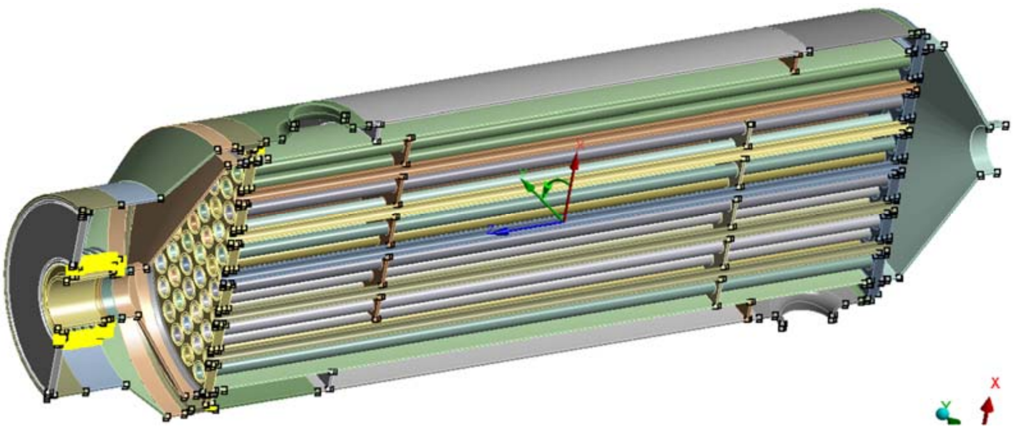

Figure 1: Structural model of HE

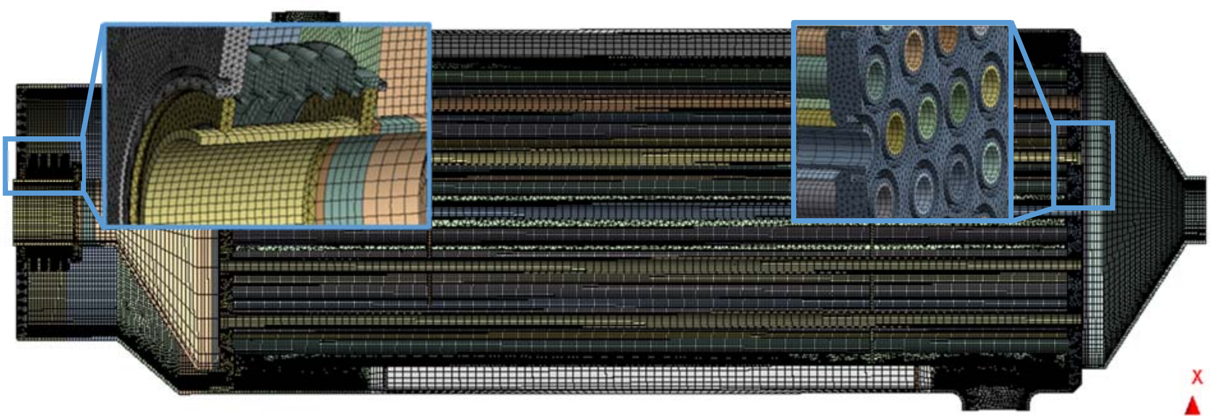

Figure 2: Variant of finite element model of the HE

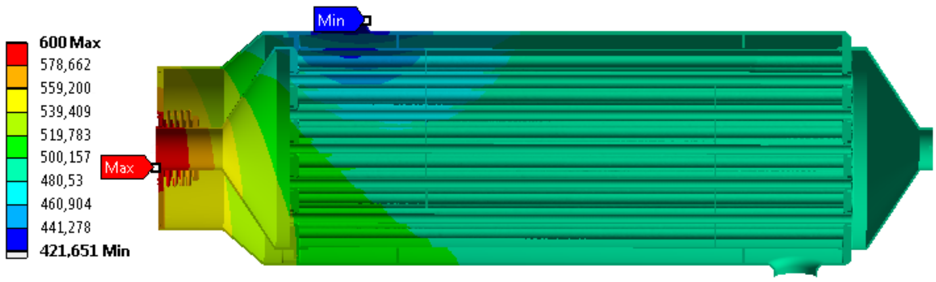

Figure 3: Temperature field applied to HE, °C

ESTIMATION OF LONG-TERM STATIC STRENGTH CONSIDERING THE EFFECT OF STRESS RELAXATION

The study of the stress state of the structure using the FEM showed the presence of high stresses in the compensator, σ = 200 MPa (Figs. 4, 5), which exceeds the long-term static strength R_{mt} for the material used at a temperature of 600 °C, and a resource of 1×10^5 hours: $R_{mt} = 80$ MPa, however, does not exceed the limit of short-period (about tens of hours) long-term static strength R_{lts} according to [4]: $R_{lts} = 273$ MPa.

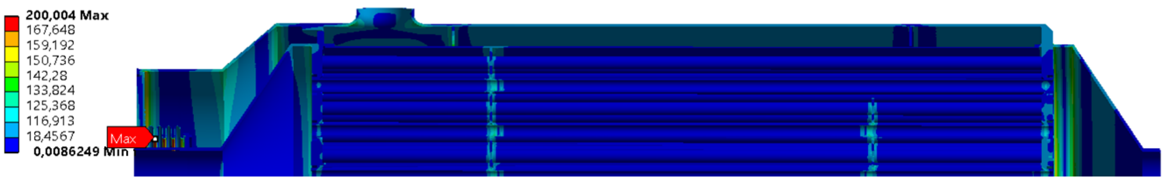

Figure 4: Calculation results. Fragments with the highest stresses, MPa.

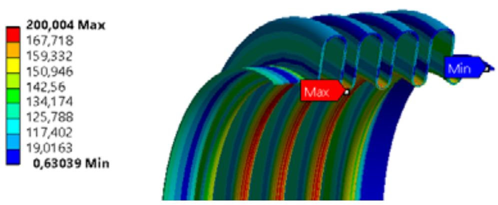

Figure 5: Calculation results. Compensator of temperature displacements, MPa

To calculate the relaxation process, the equation of steady creep was used in the form proposed by Shesterikov S. A. and Yumasheva M. A. [4], which best way describes the experimental data for the considered steel:

$$\dot{\varepsilon}_{cr} = A\left(\frac{\sigma}{R_{lts} - \sigma}\right)^{n} \tag{1}$$

where

R_{lts} - the limit of short-period long-term static strength according to [4], for 600 °C: R_{lts} = 273 MPa;

σ – the calculated stresses in the element under study, MPa;

A and n – temperature-dependent constants obtained by processing the results of steel creep tests;

on which based method of processing of experimental data in [4]:

$$\lg(t_p) = D + 17\cdot\lg(R_{lts}) - n\cdot\lg\left(\frac{\sigma_A}{R_{lts} - \sigma_A}\right) \tag{2}$$

where

σ_A – the applied stress in experiment;

t_p – time to sample failure

and

$$D = \lg\left[t_p \left(\frac{\sigma_A}{R_{lts} - \sigma_A} \right)^n R_{lts}^{-17} \right] \tag{3}$$

In accordance with [4], after processing the test results of 08Cr16N11M3 steel, for 600 °C:
$A = 2.0725\times10^{-6}$
and
$n = 2.238$.
Based on relation (1), the relaxation equation is obtained following way. If the total strain (elastic + creep) is constant, then it can be argued that the strain rate is zero:

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{cr} = 0 \tag{4}$$

Equation for elastic strain:

$$\dot{\varepsilon}_{el} = \frac{\dot{\sigma}}{E} \tag{5}$$

and Eqn. (4) takes the following form:

$$\frac{\dot{\sigma}}{E} + A\left(\frac{\sigma}{R_{lts} - \sigma} \right)^n = 0 \tag{6}$$

or

$$\frac{1}{E} \cdot \frac{d\sigma}{dt} + A\left(\frac{\sigma}{R_{lts} - \sigma} \right)^n = 0 \tag{7}$$

After transformation of Eqn. (7), the relaxation equation is obtained:

$$t(\sigma) = -\frac{1}{AE}\int_{\sigma_0}^{\sigma} \left(\frac{R_{lts} - \sigma}{\sigma} \right)^n d\sigma \tag{8}$$

where

E – the Young's modulus of steel at the corresponding temperature, for 600 °C: $E = 1.63\times10^5$ MPa;

σ_0 – the stress at the initial instant of time.

The relaxation curve for the initial stresses σ_0 = 200 MPa and the long-term strength curve are presented in Fig. 6. It can be seen that the relaxation curve lies below the long-term strength curve constructed from the values from [5] over the entire considered time period.
Formally, a comparison of these curves is enough to satisfy the criteria of long-term static strength, however, in the general case, the magnitude of the acting stresses, considering relaxation, is a random variable. Also, a random variable is the value of the long-term static strength, therefore, to assess functional reliability, the use of probabilistic methods is necessary.

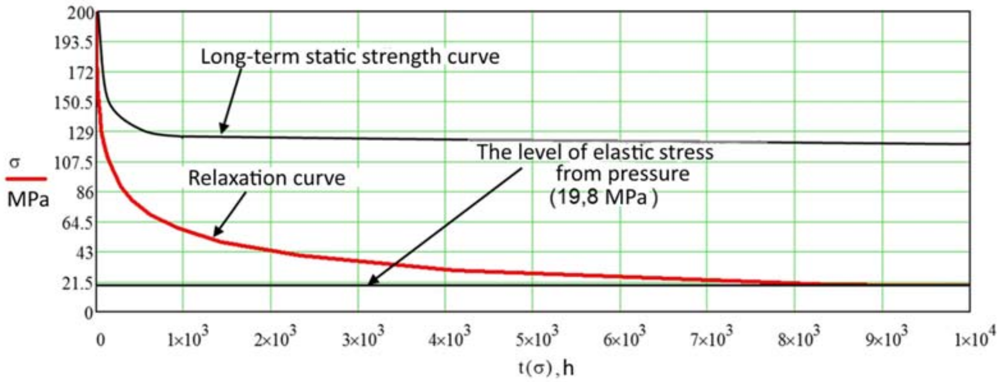

Figure 6: Relaxation and long-term strength curves for 08Cr16N11M3 steel for the initial stress of 200 MPa and the temperature of 600 °C.

RELIABILITY ASSESSMENT

Method

In the general case, the strength reliability is determined through the probability of failure-free operation *P*, which is gotten by integrating the probability density function $p(\Psi)$ of the difference of random variables R - alleged failure stresses, with the mathematical expectation $\langle R\rangle$ and F - of the calculated stresses, with the mathematical expectation $\langle F\rangle$: $p(\Psi) = p(R-F)$ (Fig. 7), in the interval determining the failure-free operation, on which the values of $R \geq F$, i.e. from 0 to +∞.

$$P = \frac{1}{\sqrt{2\pi}\sigma_{\Psi}} \int_{0}^{+\infty} exp\left[-\frac{\left(\Psi - \langle\Psi\rangle\right)^2}{2\sigma_{\Psi}^2}\right] d\Psi \tag{9}$$

where

Ψ – the integration variable;

σ_{Ψ} – standard deviation of a random variable Ψ, according to the rule of summation of random variables, the square of which σ_{Ψ}^2 is equal to the sum of the variances $D_R = \sigma_R^2$ and $D_F = \sigma_F^2$: $\sigma_{\Psi}^2 = \sigma_R^2 + \sigma_F^2$ [6], from where

$$\sigma_{\Psi} = \sqrt{\sigma_R^2 + \sigma_F^2} = \sqrt{\left(\nu_R \cdot \langle R\rangle\right)^2 + \left(\nu_F \cdot \langle F\rangle\right)^2} \tag{10}$$

where

ν_R and ν_F are the object of the investigation - are the coefficients of variation of the random variables R and F;

$\langle\Psi\rangle$ - the mathematical expectation of a random variable, in this case, the meaning of the mathematical expectation difference $\langle\Psi\rangle = \langle R\rangle - \langle F\rangle$.

To take into account the change in the reliability characteristics over time, use the relaxation curve as a function describing the change in the calculated stresses $\langle F\rangle(t)$, and the long-term strength curve as a function describing the change in the stress of the alleged failure $\langle R\rangle(t)$, and obtain $\langle\Psi\rangle(t) = \langle R\rangle(t) - \langle F\rangle(t)$.

Then can be built (for example, in MATLAB or Python) a three-dimensional function of probability density over time, taking into account the change in time of all its parameters (Fig. 8) [7, 8] and the function of changing the probability of failure-free operation over time (Fig. 9).

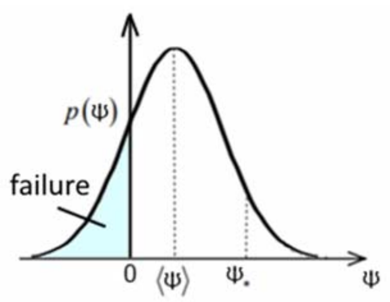

Figure 7: Example of probability density $p(\Psi)$

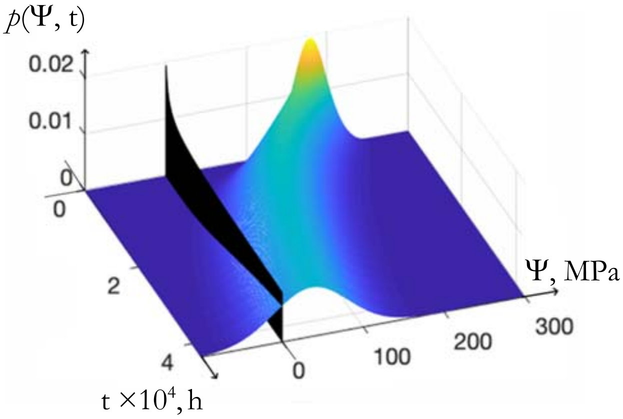

Figure 8: Example of probability density dependence function on time

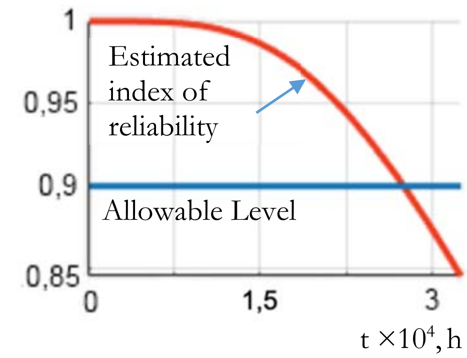

Figure 9: Example of function of the dependence of the reliability indicator on time

Determination of coefficient of variation

The determination of the coefficients ν_R and ν_F is a key problem in the probabilistic assessment of reliability, because there are no general methods for their determination for cases where there are no statistical data from which it would be possible to determine the variances of the D_R, D_F values and standard deviations σ_R and σ_F.

The best way to determine the value characterizing the deviation of the failure stresses from the mathematical expectation is to test the steel samples that are supposed to be used and obtain data on the scatter of values, and then determine the coefficient of variation of material properties based on them, but it is often not available.

In this case, the coefficient of variation for welded joints can be included in the value as a term, according to [9]: $\nu_{wld} = 0.05$, which characterizes the deviations associated with the peculiarities of changing the properties of the material in the welding area.

As the second term characterizing the deviations of the properties of the material, can be taken the value of the coefficient of variation of the properties of the material, equal to 0.1, from the Russian regulatory document "GOST 25.504 "Calculations and strength tests. Methods for calculating fatigue resistance characteristics."

The final coefficient of variation for the allowable stresses will be determined as the sum of these terms:

$$\nu_R = 0.1 + 0.05 = 0.15 \tag{11}$$

Next, it is necessary to determine the coefficient of variation ν_F for the stresses obtained as a result of the load, which determines the possible deviation of the load value from the calculation. This coefficient cannot be found in the literature and the main question becomes - how to determine and justify its value.

Considering that stresses are determined as a result of calculations, it would be logical to use the error of the methods by which these calculations were performed as the coefficient of variation. For "manual calculation", can be considered the error associated with cutting off the decimal places. Using the FEM, a number of test calculations can be performed on

simple problems and compared with the exact analytical solution. From experience can be said, that as a rule, with proper preparation of the model, the FEM error does not exceed 5-6% (i.e., a variation coefficient of ν_F = 0.05 or 0.06 can be used), however, the calculation error for a complex model may increase due to the influence of other mathematical factors (such as an increase in stresses in the zones of "mathematical concentrators"), which will require the use of a posteriori estimation methods for the error of FEM calculation and the use of data obtained on their basis.
In calculating the FEM, the following method can also be used. In this calculation, there is an element whose reliability is the subject of research - a compensator. Using the method of submodeling, this element is "cut out", after which the problem is solved many times with mesh refinement with each new calculation until the asymptotic convergence of the results is obtained. On example of compensator from previous section we get following results (see Tab. 1).

Number of elements by thickness	2	3	4	5	6	7
Stress in the compensator, MPa	200	175.3	179	170.6	169.7	170.1

Table 1: The results of FEM calculations for the strength of the compensator

After that, using data from Tab. 1, can be calculated the sample average value, which is taken as the mathematical expectation

$$\langle F \rangle = \frac{1}{n}\sum_{i=1}^{n}\sigma_i = 177.45 \text{ MPa} \quad (12)$$

selective (unbiased) variance as

$$D_F = \frac{1}{n-1}\sum_{i=1}^{n}\left(\sigma_i - \langle F \rangle\right)^2 = 135.31 \text{ MPa}^2 \quad (13)$$

and get $\sigma_F^2 = D_F$. From where:

$$\nu_F = \sqrt{\sigma_F^2 / \langle F \rangle^2} = \sqrt{135.31 / 177.45^2} \approx 0.065 \quad (14)$$

Accordingly, the more results after the solution is established, the higher the accuracy and less ν_F, which is not required in this formulation of the problem. On the contrary, in order to obtain a more conservative result, it is necessary to obtain the minimum and maximum value of the calculated stresses for the model under study in order to determine the calculation error "relative to oneself" for further calculation of the values necessary for assessing reliability $\langle F \rangle$ and ν_F necessary for assessing reliability.
As variation coefficient of load ν_F for structures that will subsequently be subjected to mechanical tests, can be taken the total error rounded up for all metrological characteristics of the equipment on which loading conditions will be implemented. Such information is usually contained in the certificate of verification of equipment and this value can be about 3.5% (i.e., a variation coefficient of 0.035 can be used). If it is impossible to obtain data of ν_F other way, this approach can be considered quite acceptable.
In the general case, the coefficients ν_R and ν_F can also depend on time; however, it is rather difficult to justify the function of their change without sufficient statistics on the properties of the material.

RESULTS OF RELIABILITY ASSESSMENT

In the case of designing complex structures, it is necessary that simple elements (parts) had a reliability indicator equal to 1 (in the mechanical sense, when we get as a result of the calculation 0.999999…. - an infinite number of nines after the decimal point).

Using the method from "Reliability Assessment" section of this article, to assess the reliability of the compensator taking into account the values of the coefficients, can be obtained the field of nodes of the FE-model of the compensator with estimates of the satisfaction of the reliability criterion. After the FEM calculation, data on the coordinates of the nodes and the values of the Von Mises stresses in these nodes can be downloaded from any software package. Further, using algorithms written in MATLAB (or in another language), can be implemented the estimates from "Reliability assessment" paragraph, and then load the converted results back into the software package (if it allows it) or implement graphical construction through the function "scatter3(X,Y, Z, D, D, 'o', 'filled')" from MATLAB, where X, Y, Z are the vectors of the coordinates of the nodes, and D are the values of the reliability estimates. As a result, it is possible to obtain a visualization of areas whose reliability does not meet the requirements at any of the time points of the resource, for example, less than 0.9999, as shown in Fig. 10 (zones with P <0.9999 at a certain time point of the resource are highlighted).

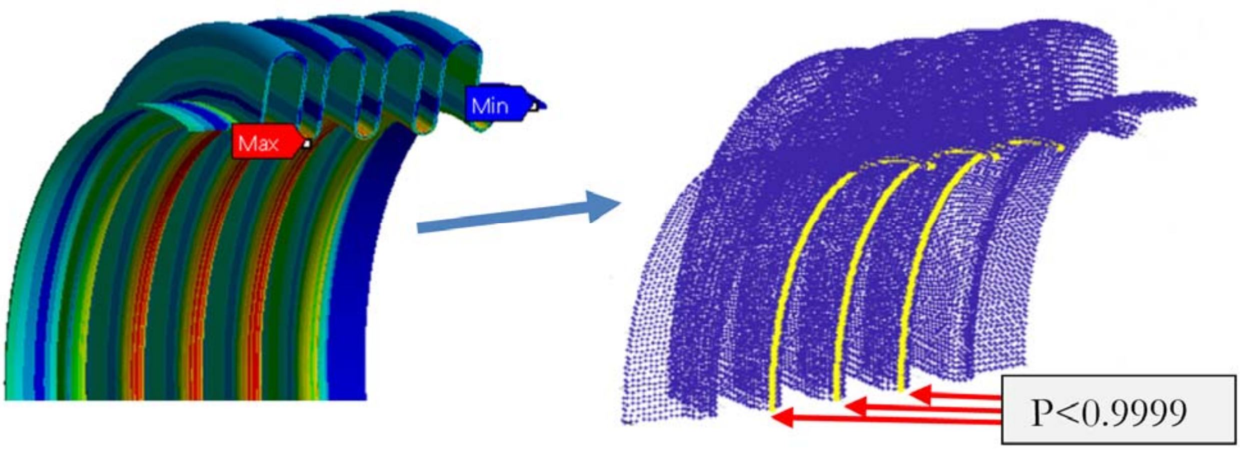

Figure 10: Nodal reliability assessment by FE model in MATLAB

Having received the results of the reliability assessment in this form, they can be used to build algorithms for automatic optimization of the structure with a change in the geometric and physical parameters of the model.

CONCLUSION

The reliability assessment method given in this article is a convenient tool for assessing the reliability of structures at the design stage when there are no statistical data on operating hours and it is necessary to take into account the change in material properties and load over the service life.

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