Application of full-scale strain studies results for determining the equipment internal surfaces damages during rapid changes of coolant temperature

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Abstract. The method for metal damage determining for the inner surfaces of power equipment exposed to the coolant with a rapidly changing temperature is considered. Due to the impossibility of deformations and temperatures direct measurement for the inner surface, a calculation-experimental algorithm is proposed based on processing the results of strain measurements obtained for the outer surface in geometrically homogeneous and non-uniform zones of the structure. To qualify the functions for changing stresses and temperatures on the inner surface, in this paper, it is proposed to use the algorithm based on solving inverse problems of mechanics. The recovered functions of the temperature stresses temporal variations for the interface zone of the pipeline and the nuclear power plant body are presented.

1. Introduction
The most important element of modern power generating plants (nuclear and thermal power units, steam and gas plants) is the coolant circulation circuits, which serve to transfer heat from the energy source to heat exchangers and steam generators for the subsequent conversion of thermal energy into mechanical and further - into electrical. The unsteadiness of the heat transfer temperature processes and the turbulence of the coolant flows inside the circuit lead to temperature fluctuations on the inner surfaces, causing constant changes in the stresses on the metal surface and, as a consequence, the risk of fatigue macro-cracks and exhaustion of the structure resource. Figure 1 shows typical functions of changing the temperature state of NPP elements with emerging “sawtooth” temperature stresses that can affect the cyclic strength and life of the structure.
Methods for determining the stress state of structural elements developed at IMASH RAN [1] on the basis of computational or experimental modeling of their loading conditions under certain a priori specified operating conditions. Another method of determining the stress state [2] is to conduct full-scale tests to obtain experimental information under real operational loading. In some cases, this method does not allow to identify the most dangerous conditions in the critical zones because of the distance from the measuring points (for example, because of the location of the measuring points on the outer surface, not on the inner one). For these cases, a method [3] based on the solution of the inverse problem of the theory of thermal conductivity was developed. It allows to recover the history of changes in the thermal stress state on the inner surface of the structure. Unfortunately, given the random nature of the coolant temperature change, this method does not always lead to a sufficiently stable solution of the operator equations used.

In this paper we consider the case of periodic (cyclic) changes in temperature stresses, for which a stable solution, based on the application of methods for solving inverse problems of thermal conductivity and thermoelasticity is possible. To solve the problem, we use the measured values of stresses arising on the outer surface of the pipeline.

2. Research method
During pre-commissioning tests and in the initial operational period of NPP power units, temperature stresses may occur in the connecting pipelines caused by the influence of coolant with a cyclically changing temperature. In particular, such phenomena occur in the injection pipeline of the VVER-1000 pressure compensator and the pipeline connecting the pressure compensator to the main circulation circuit. The reason for cyclic changes in temperatures and associated stresses in the walls of the pipeline is the periodic movement of the coolant rates with variable temperature, arising during the operation of the control systems of the power unit. The greatest stresses associated with this phenomenon occur on the inner surface of the structure, inaccessible to direct measurements. To solve the problem of identification of these stresses, the following can be used:
- experimentally obtained functions of the outer surface temperature change;
- measured (discrete) stress values at the points of the outer surface;
- readings of pressure and temperature sensors in the circulation circuit.
In general, the determination of the stress-strain state from the specified initial data is a complex inverse problem, and the tolerances of the results of its solution are too large. Therefore, to determine the damage introduced into the material of the inner surface of the structure, the general problem is proposed to be divided into several particular issues, and the damage introduced for each of them shall be determined. The total damage can be determined by the hypothesis of linear summation of damage taking into account the sequence of changes in the loading parameters. To implement this algorithm, the total stresses shall be determined independently for the following categories:

- pipeline homing stresses caused by limitations of its movements;
- stresses caused by static pressure in the circulation circuit and its pulsations caused by the operation of circulation pumps;
- stresses caused by a radial temperature drop through the wall thickness;
- stresses associated with high-frequency fluctuations of coolant flows with different temperatures.

2.1. Homing stresses recording
Homing stresses are caused by longitudinal forces and bending moments acting in the pipeline sections, and should be excluded from the total stresses when solving the inverse problem of thermoelasticity in paragraph 2.3 in the case of using the values of meridional stresses as initial data. Determination of these stresses by calculation based on the temperature distribution in the pipeline leads to significant tolerances due to the lack of initial data. Therefore, it is advisable to use experimental data obtained with the help of strain gauges, additionally installed in several sections of the pipeline. The method of application of this approach is presented in the work [3] more detailed. The stresses measured by these additional strain gauges can also be used to construct a general history of structural loading, including under operating conditions that are not associated with cyclic thermal loading by the coolant.

2.2. Determination of stresses caused by static pressure in the circulation circuit
Stresses caused by internal pressure in the circuit must be taken into account in solving the inverse problem of thermoelasticity, even if only the values of stresses occurring in the circumferential direction are used as input data. There occur no difficulties when recording these components [2], while both the calculation algorithm and experimental data obtained during hydraulic tests of the structure can be used. If the internal pressure in the circuit changes, it is necessary to synchronize the moments of the pressure and voltage measurements or to make adjustments due to the non-synchronicity of the measurements. Unfortunately, this approach cannot be applied to exclude the influence of high-frequency pressure pulsations in the circuit from the initial data of the inverse problem due to the insufficiency of the experimental results.

2.3. Determination of stresses caused by radial temperature drop in the wall
To determine these stresses, it is possible to use the solution of the inverse heat conduction problem [1], where the measured temperatures of the outer surface are used as input data, and the solution is the heat flow and heat flow patterns in the structure. The obtained heat flow patterns are used to calculate stresses in the pipeline by numerical methods. Figure 2 shows the simulation results of the stress change function on the inner and outer surfaces of the VVER-1000 pipeline obtained from temperature measurements on the outer surface. The initial data for the stress calculation are the recovered functions of the coolant temperature change shown in figure 2.
Figure 2. Measured temperature values on the outer surface of the NPP pipeline (°C, below,) and recovered: coolant temperature (°C) and circumferential stresses (MPa) on the inner surface of the structure.

The solution of the problem according to this algorithm is not always stable due to the effect of temperature smoothing on the outer surface and requires additional verification by solving a number of direct problems and comparing the results with the results of measurements. This process involves considerable time and intellectual resources and does not always allow you to set the range of tolerances of the results. Therefore, it is advisable to use in the absence of strain gauges on the outer surface of the pipeline.

More stable is the solution of the inverse problem of thermoelasticity in which the initial data are the measured values of stresses, and the unknown - the temperature of the inner surface. The equation solved in this case is as follows:

\[ \int_{0}^{t} d\tau \int_{L} G_{ij}^{O}(s,x,t-\tau)T(x,\tau)dL(x) = \sigma_{ij}^{*}(s,t) \]  \hspace{1cm} (1)

where \( T \) is for temperature, \( t \) is for current time, \( G_{ij}^{O}(s,x,t-\tau) \) - Green's functions for stress, \( \sigma_{ij}^{*}(s,t) \) - measured stress values.

The solution of the inverse problem, i.e. the determination of the heat flow pattern from equation (1) is possible if the stress components are caused only by the loading of the pipeline by the radial heat flow pattern, and do not contain components associated with other loading factors defined in accordance with paragraphs 2.1 and 2.2. The advantage of this approach is the absence of inaccuracy of the initial data associated with the effect of the thermal lag of temperatures on the outer surface. The measured stresses are almost synchronous with changes in the temperature of the inner surface, so the solution of the issue is more stable than in the first case.

In this paper, we propose a method to accelerate the process of finding a stable solution to the issue, based on the use of the harmonic function of the change in the temperature of the inner surface in a steady state. For this purpose, the solutions obtained from the solution of the inverse problem of thermoelasticity are considered in the class of harmonic functions having a period of change in time coinciding with the period of change of stresses on the outer surface of the pipeline. The amplitudes of these functions are unknown factors selected according to the criterion of the greatest compliance with
the measured values. The criterion of conformity is taken to correspond to the norm in the space $L_2$ (minimizing the sum of squares of the differences between the measured and calculated stresses.) The process of selecting the best solutions is rapidly converging and leads to the coincidence of the calculated stresses and temperatures with the measured ones (within the range of possible tolerances).

The proposed algorithm is applied to the analysis of cyclic temperature loads arising in the connecting pipeline of the VVER-1000 pressure compensator. The obtained results are presented in figure 3; the maximum discrepancy between the calculated and measured temperatures was: for temperatures 7°C (about 3%); for voltages – 2.5 MPa (less than 10%).

![Figure 3](image_url)

**Figure 3.** Simulation results of stress change functions on the inner surface of the VVER-1000 feed water pipeline obtained from measurements of stresses and temperatures on the outer surface of the pipeline:

1-temperature of the outer surface (measurement); 2 - the temperature of the inner surface (calculation); 3-circumferential stresses on the outer surface (calculation); 4-stresses on the outer surface (measurement)

The initial data for the calculation of stresses on the inner surface are the recovered functions of the coolant temperature change. In turn, for construction of temperature of the coolant are used: solution of the inverse problem of thermal conductivity (by known values of temperatures on the outer surface) and the inverse problem of thermoelasticity (by known values of stresses on the outer surface).

2.4. Record of damages caused by pressure pulsations and fluctuations of coolant flows with different temperatures

Pressure pulsations in the pipeline caused by the operation of circulation systems usually do not make a significant contribution to the damage of the pipelines, and the stresses caused by them approximately correspond to the measurement tolerance, that is, they are at the noise level. For their evaluation, precision strain gauges can be used, but practically there is no need for such studies. As for the temperature fluctuations of the coolant, they are not recorded by external temperature sensors but can be reflected in the readings of strain gauges in the form of high-frequency non-harmonic fluctuations of the stress components. When specifying the initial data for solving inverse problems, these fluctuations should be filtered out, but taken into account when assessing the damage to the inner surface of the pipeline. To do this, the voltage fluctuations measured on the outer surface shall be replaced by harmonic functions having the same amplitude and frequency corresponding to the maximum fluctuation frequency. The obtained harmonic functions can be used as input data for solving
the inverse problem of thermoelasticity and determining the dynamic component of stresses on the inner surface according to the above-mentioned algorithm.

3. Conclusions and results
As a result of the carried out researches we developed the algorithm for recording of the pipelines internal surfaces metal damage caused by emergence of the coolant temperatures cyclic changes. The proposed algorithm is based on the solution of inverse problems of thermal conductivity and thermoelasticity under the assumptions of the independence of individual loading processes. The obtained results of determining the stresses and temperatures for the connecting pipeline VVER-1000 have tolerances not exceeding 10% in determining the stresses and 3% in determining the stresses on the inner surface.

References
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