Experimental studies of temperature pulsations during the process of mixing non-isothermal coolant flows in nuclear reactor equipment components

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Abstract

One of the most important scientific and technical tasks of the nuclear power industry is to assure the reactor equipment life and reliability under random temperature pulsations. High-intensity temperature pulsations appear during the process of mixing non-isothermal coolant flows. Coolant thermal pulsations cause corresponding, sometimes very significant, fluctuations in the temperature stresses of the heat-exchange surface metal, which, added to static loads, can lead to fatigue failure of equipment components.

The purpose of this work was to conduct an experimental study of the temperature and stress-strain states of a pipe sample under the influence of local stochastic thermal pulsations caused by the mixed single-phase heat coolant flows.

To solve the set problems, an experimental section was created, which made it possible to simulate the process of mixing non-isothermal coolant flows accompanied by significant temperature pulsations. The design of the experimental section allowed us to study the thermohydraulic and life characteristics of pipe samples made of austenite steel (60×5 mm). Some tools were developed for measuring the pipe sample stress-strain state and the coolant flow temperature field in the zone of mixed single-phase media with different temperatures. The measuring tools were equipped with microthermocouples and strain sensors.

As a result, we obtained experimental data on temperature pulsations, time-averaged temperature profiles of the coolant flow in the mixing zone as well as statistical and spectral-correlation characteristics of thermal pulsations. Based on the results of measuring the relative strains, the values of fatigue stresses in the mixing zone were calculated.

In addition, some devices and methods were elaborated to measure the temperature and stress-strain states of the pipe sample under the influence of local stochastic thermal pulsations. The developed experimental section provided thermal-stress loading of the metal surface at a high level of alternating stress amplitudes causing rapid damage accumulation rates. The results were included in the database to verify the method for assessing the fatigue life of structural materials for nuclear power plants as applied to austenite steel 12Cr18Ni10Ti under the influence of random thermal cyclic loads.

Keywords

Equipment life, temperature pulsations, coolant, temperature field, stress-strain state

Introduction

The equipment of stationary and marine nuclear reactor plants exposed to thermal stresses is subject to various deterioration mechanisms affecting the strength properties of structural materials and leading to its early life expiration (Abib et al. 2013, Chapuliot et al. 2005, Faidy 2002). The danger is represented by alternating thermal stresses caused by temperature pulsations. Temperature pulsations are steady-state random processes, in which the equipment life expiration occurs by the mechanism of high-cycle thermal fatigue (Sudakov and Trofimov 1980, 1989). A high level of temperature pulsations is characteristic of the processes of mixing nonisothermal coolant flows, which are widespread in nuclear reactor equipment. An urgent problem is temperature pulsations in transportable nuclear reactors, which are characterized by high thermal-stress density due to a significant decrease in their physical data (Budov and Dmitriev 1989).

Existing normative methods for assessing the reactor equipment life characteristics neither take into account the real laws of its thermal-stress loading, nor provide sufficient accuracy for damage accumulation calculations; therefore, this approach is rightly considered excessively conservative (NP-054-04 2004, Jhung 2013). Life tests of full-scale structures in normal conditions are not suitable due to the extreme complexity, high cost and long duration. In this regard, it seems appropriate to use a computational-experimental approach to assessing the longevity (useful life) of nuclear reactor equipment under random thermal cyclic loads, including the use of computational fluid dynamics (CFD) and stress-strain state modeling programs (Mahaffy et al. 2007, Smith 2010, Smith et al. 2010, 2015) as well as mathematical models of the fatigue damage accumulation process in the structural material.

This most quickly occurs at high values of the amplitude and number of loading cycles (Wakamatsu et al. 1995, Beaufils 2011, Courtin 2013). However, in the domestic and foreign literature there are no comprehensive experimental data on a single-phase coolant mixing at temperature drops of more than 100 °C (Miyoshi et al. 2016, Braillard and Edelin 2009, Chen et al. 2014, Kamide et al. 2009). Therefore, it was an important task to develop an experimental section for simulating the process of mixing coolant flows accompanied by significant temperature pulsations.

Currently, JSC Afrikantov OKBM is developing a methodology containing numerical simulation technologies using supercomputers to assess the effect of random thermal cyclic loads on the life characteristics of materials of the RITM-200 transportable nuclear reactor. As part of this work, the scientific team of the “Steam Generating Systems” Research Laboratory (“SGS” RL) at the NNS-TU Nuclear and Thermal Stations Department conducts life tests of experimental models, the preparatory stage of which was the study of the temperature field and the stress-strain state (SSS) in the thermal-stress loading zone.

The article presents the results of the preparatory tests focused on the characteristics of temperature pulsations in the coolant mixing zone as well as the stress-strain state of the experimental sample material.

Description of the experimental facility

Experimental studies were carried out on the modernized FT-80 thermophysical facility (Dmitriev et al. 2006): its technical characteristics provide operating conditions corresponding to modern nuclear reactors. The experimental facility includes the following main components:

- coolant circuit;
- cooling circuit of the main coolant circuit equipment;
- reactor coolant makeup system;
- power supply system; and
- instrumentation system.

The equipment and pipelines of the facility are made of austenite steel 12Cr18Ni10Ti. High purity water was used as a coolant. The coolant circuit of the facility has five parallel channels for installing experimental models.

Description of the experimental section

The experimental section (Fig. 1) is a tee-branch consisting of the main 60×5×286 mm and peripheral 9×1,5 mm pipes and detachable joints. The pipes are made of steel 12Cr18Ni10Ti, which is used in reactor engineering. A diffuser is made in the guide flange. The slope angle of the peripheral pipe relative to the main one is 18°. The distance from the cut of the peripheral pipe to the inner wall of the main one is 7 mm. The main pipe is an experimental model (sample) subjected to temperature loading. Local loading of the inner sample wall is carried out by supplying a cold coolant flow from the peripheral pipe to the hot coolant flow.

Due to the detachable joints, both experimental and measuring models can be installed on the experimental section. The following measurement models were used in this work:

- model for measuring the temperature field (MMTP) and
- model for measuring the stress-strain state (MMSSS).

The material and dimensions of both models and samples are identical. The MMTP is equipped with a set of eight micro-thermocouples (t1–t8) made of KTMS cable in a stainless capillary with an individual calibration characteristic (Fig. 2). The calibration error is ±0.2 °C. To reduce the
thermal inertia of the thermocouples, the junction is made on the surface of the stainless capillary, and the sensitive part of the sensor is rolled to a diameter of no more than 0.5 mm (Kuschewski 2015). The thermocouples are installed in the central part of the pipe along the lower generatrix of the inner surface at a distance of 10 mm from each other. The sensors are oriented perpendicular to the main flow and spaced 1 mm away from the inner wall surface. Thermocouple t3 is located under the front edge of the peripheral pipe relative to the main flow direction. The MMSSS is equipped with eleven strain sensors and three thermocouples mounted on the outer surface of the model. The error in measuring the relative strain is ±44·10^{-6}. The location zone of the sensors for the measuring models was selected so as to fully cover the proposed localization of the coolant mixing zone.

### Experiment

For a reliable assessment of the durability of objects exposed to thermal-power impacts, it was necessary to study the complex processes of fatigue damage accumulation in structural materials of the equipment under simulated full-scale loading conditions, i.e.:

- pressure in the coolant circuit = 10 MPa;
- temperature range of the hot coolant flow (Th) = 283 °C–287 °C;
- temperature range of the cold coolant flow (Tc) = 35 °C–62 °C;

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\begin{align*}
\text{Th} & = 283 \text{ °C–287 °C}; \\
\text{Tc} & = 35 \text{ °C–62 °C}; \\
\end{align*}
\]

The coolant flow rates were taken on the basis of the equality of the axial velocity components in order to create a quasi-stable vortex structure in the mixing region. \( Th \) was selected on the basis of the maximum possible temperature gradients of coolants, characteristic of the reactor equipment exposed to thermal stresses. The resulting high-intensity temperature pulsations made it possible to obtain alternating stresses in the model material, providing fast rates of damage accumulation.

Coolant temperature pulsations in the MMTP were registered and recorded in the steady-state facility operation. The operating parameters were measured using transducers of temperature, pressure, differential pressure/temperature, and flow installed on the underwater sections of the experimental models. Technical characteristics of the sensors of the facility instrumentation complex are presented in Table 1.

### Findings

The experimental temperature realizations (Fig. 2) determined the statistical (Figs 3, 4) and spectral-correlation (Fig. 5) characteristics of the temperature field in the mixing zone. In Figs 4, 5, the coordinates of the MMTP thermocouples were marked along the x-axis. As a defined zero, a point spaced 10 mm away from Thermocouple t1 location was taken.
The maximum intensity of temperature pulsations (mean square deviation) $\sigma_t$ (Chapuliot et al. 2005) was registered by Thermocouple t4. The largest range of thermal pulsations was 120 °C. The characteristic spectrum of temperature pulsations in the zone located under the peripheral pipe cut had a peak in the frequency range of 0.4–0.5 Hz.

According to the results obtained on the MMSSS, the stress-strain state of the sample was calculated. The maximum stress value in the loading area was 152 MPa.

The results presented in the work were obtained at $T_h = 285 ^\circ C$, $Re_h = 5.15 \cdot 10^4$, $T_c = 35 ^\circ C$, $Re_c = 1.08 \cdot 10^3$.

**Conclusion**

An experimental facility was designed and constructed to study the fatigue damage accumulation kinetics in the material of the experimental models as a result of loading by temperature pulsations due to mixed non-isothermal coolant flows. The loading of the experimental models with temperature pulsations was simulated with coolant parameters similar to the standard parameters of a nuclear reactor steam generator cassette. As a result of the experimental work,

- experimental data were obtained on the temperature field in the mixing zone; and
- the stress-strain state of the experimental sample was determined.

The results were included in the database to verify the method for assessing the fatigue life of structural materials for nuclear power plants as applied to austenite steel 12Cr18Ni10Ti under the influence of random thermal cyclic loads.

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