Testing of the model friction units type of "tube – spacer grid" of the steam generator of the lead coolant nuclear reactor

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Abstract. Depressurization of the heat-exchange tubes is a supposed failure of normal operation of the steam generator of the lead coolant nuclear reactor in its long-term service. Most likely place of the failure is located in places of contact of the tubes with elements of spacer grid. The oscillatory motion of the tubes under impact of lead coolant determines the necessity of studying the fretting wear laws for material of the tubes. The main object of this work is to evaluate the durability of the heat-exchange tubes based on the results of fretting wear tests. These tests are performed in conditions closed to the real ones, in particular, in respect of identities of the coolant thermal properties, materials and design features of the real steam generator. To solve this problem it was developed the special tribological equipment which meets the specified requirements. This equipment enables testing of friction units of all three possible types of the contact: point, line and conformal. A brief description of the equipment design features and experimental data are presented. The experimental data serve as the basis for mathematical simulation of fretting wear calculation and evaluation of durability of the heat-exchange tubes under the conditions of normal operation.

Key Words: fretting wear test, heat-exchange tubes, steam generator.

1. Introduction

In continuous service, one of the possible causes of malfunctioning of steam generators of lead coolant reactor plant equipment is depressurization of heat-exchange tubes. The most probable place of heat-exchange tube failure is located at place of its contact with elements of spacer grid. The contact takes place in conditions of inevitable tube vibrations accompanied by friction interaction with elements of spacer grid. All these factors predetermine demand in study of fretting wear regularities for the heat-exchange tubes.

To solve this problem, a special friction test equipment "Tribometer" was developed. This equipment ensures possibility to test all the types of friction units of heat-exchange tubes with spacer grid elements complying with requirement to adequacy of thermotechnical properties of coolant, and use of the same material and design features of heat-exchange tube and spacer grid. This equipment was used to perform a series of experiments with controlled vibration velocity and load regimes. Experimental data have been obtained and processed with special mathematical model of the sample heat-exchange tube wear. As a result of the studies, the wear coefficient of heat-exchange tube material was determined. The wear coefficient serves as a base for evaluation of durability on wear for heat-exchange tubes of steam generator.

2. Experiment

2.1.Equipment, samples, and test procedure

Fig. 1 shows "Tribometer" equipment scheme. "Tribometer" equipment consists of housing, foundation plate, and supporting frame (not shown in the figure). The housing is a cylindrical vessel with flange which is pressure-proof connected with foundation plate. The foundation plate is rigidly attached to supporting frame. Inside the vessel, a cable type lever mechanism is assembled. Tested samples are attached to swinging and fixed levers of the mechanism. Each of them is fixed (welded) with removable plates which ensure precise positioning of tested samples by means of set pins. From the top through a hole in foundation plate and sealing bellows, an oscillator rod enters into the vessel. A counter sample is mounted to this rod.

Fig. 1 shows the following test schemes: two fixed spacer grid elements paired with movable sample of heat-exchange tube (scheme 1) and two fixed sample of heat-exchange tubes paired with movable flat stick which simulates the opposite side of spacer grid (scheme 2). Material of the heat-exchange tube sample was steel EP302M, while flat stick was made of steel EP302.

Radius of the sample heat-exchange tube is R=9 mm. Strip chart recording of nominally flat stick surface revealed that it has a slightly curved cylindrical shape with radius $r = 422$ mm.

To suppress corrosive activity of melted lead coolant, concentration of dissolved oxygen was ensured approximately $4{\cdot}10^{-6}$ % wt. To ensure control of efficiency of lead coolant hydrogen recovery, "Tribometr" equipment is provided with a system to supply mixture of argon and hydrogen above melt mirror. As well, there are provided means for periodic chromatographic analysis of this mixture from protective gas blanket.

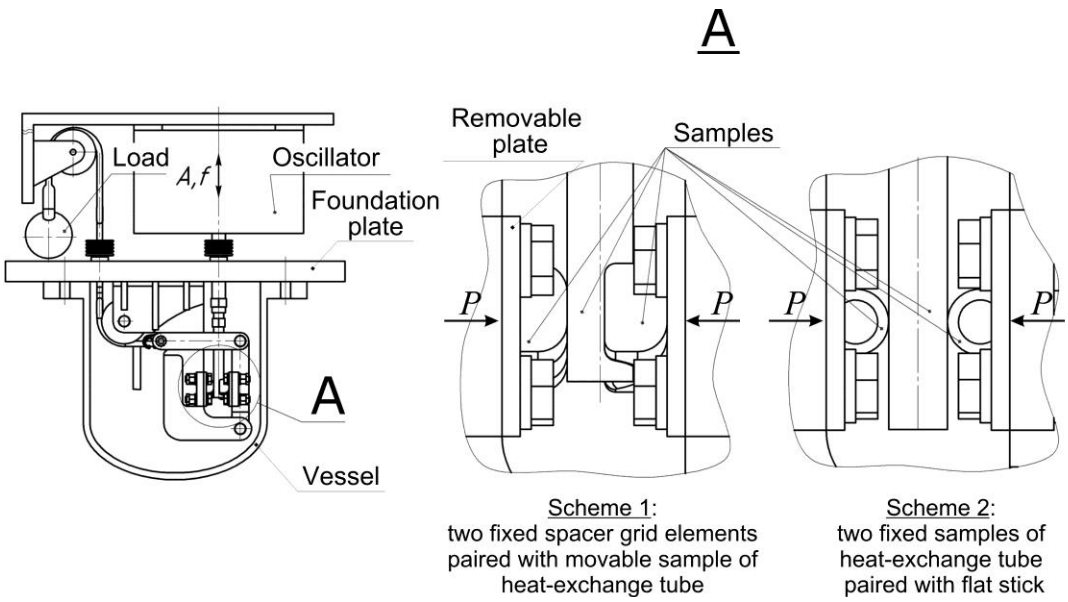


FIG. 1. Scheme of equipment for fretting wear test of pairs type of sample heat-exchange tube – spacer grid element.

Plates with attached samples of heat-exchange tube or spacer grid were installed on pins at support planes of swinging and fixed levers of loading mechanism. Correspondingly, counter sample (flat stick or tube) was rigidly attached to a movable rod of oscillator. Swinging lever with attached sample was rotating around the axle until contact of the tested samples. Suspended load was used to obtain a contact load P on the tested pair. The vessel was filled with liquid lead. Parameters of lead were similar with operating parameters of lead coolant. Using an oscillator, counter sample was driven in reciprocating movement with required amplitude and frequency.

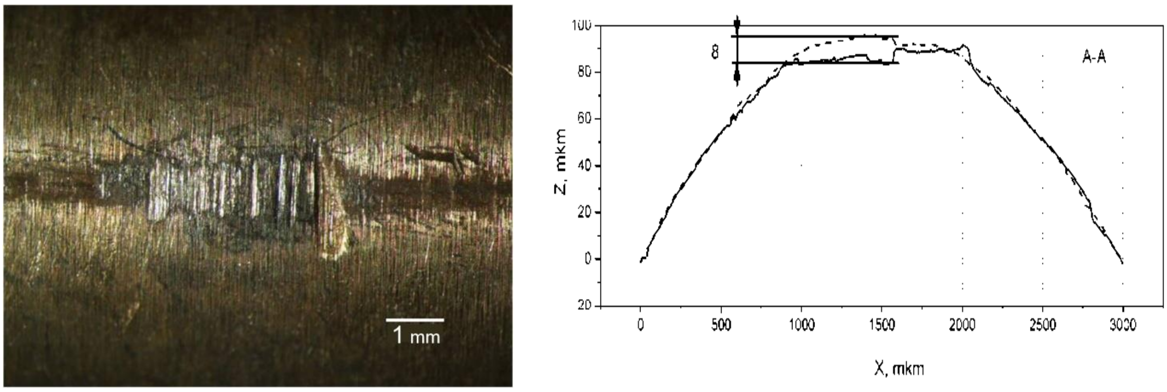
The experiment was carried out under conditions of melted (T=470°C) lead. Oscillation frequency was *f*=80 Hz, amplitude *A*=0.031 mm, and load *P*=52.8 N. When conducting the experiment, lead coolant melt temperature, oxygen concentration, amplitude-frequency characteristics, and friction force were controlled. Each experiment took $t_* = 120$ hours of continuous operations.

Upon the end of experiment, tested samples were ultrasonically cleaned and washed to remove residual lead at 65°C within 60 min. This operation was followed by sample drying in air oven at 60°C. MAHR and AMBIOS profile recorders were used to get profilograms of visually detected contact areas both in transversal and longitudinal directions.

Linear wear *W* of samples was established by method of matching profile records obtained before the test and after that. Friction area *S* was calculated by ImageJ software using graphic image of worn area. The image was made using optical microscope equipped with picture digitizer. Microscopic study was carried out using Philips SEM 505 and QUANTA 650 scanning electron microscopes equipped with digital imaging systems. EDAX micro-analyzers were used for chemical micro-analysis.

2.2.Experimental results and discussion

Fig. 2 shows wear of heat-exchange tube sample in pair with flat stick (scheme 2, Fig. 1). For the sample of heat-exchange tube the average wear value $\bar{W}$ based on three transversal cross-sections was 6 µm, max wear value was $W_M = 8$ µm, and friction area was *S*=2.7 mm^2.



a *b*

FIG. 2. Friction surface of worn sample of heat-exchange tube (a) and its transversal profile record with maximum wear $W_M = 8$ *µm (b).*

The test showed no significant wear of the stick. This is due to the fact that based on the measurement, the linear wear of stick is distributed on the larger friction area *S*=25.5 mm^2. So large area is caused by presence of the stick's additional axial movement (~13 mm) caused by deformation of sealing bellows connected with stick by means of rod of oscillator, and the deformation is caused by accident change of pressure of gas media inside operating volume above lead coolant melt surface.

After running-in period (~1 hour), friction coefficient was changing within 0.08−0.12. The main results of the heat-exchange tube sample testing are given in the Table (see below).

TABLE: RESULTS OF THE HEAT-EXCHANGE TUBE SAMPLE TEST (SCHEME 2)

Friction path l_*, m	Average wear $\bar{W}$, μm	Friction area *S*, mm^2	Contact pressure *p*, MPa	Wear rate *I*	Wear coefficient *K*, Pa^{-1}
4300	6	2.7	19. 55	$1.4 \cdot 10^{-9}$	$0.71 \cdot 10^{-16}$

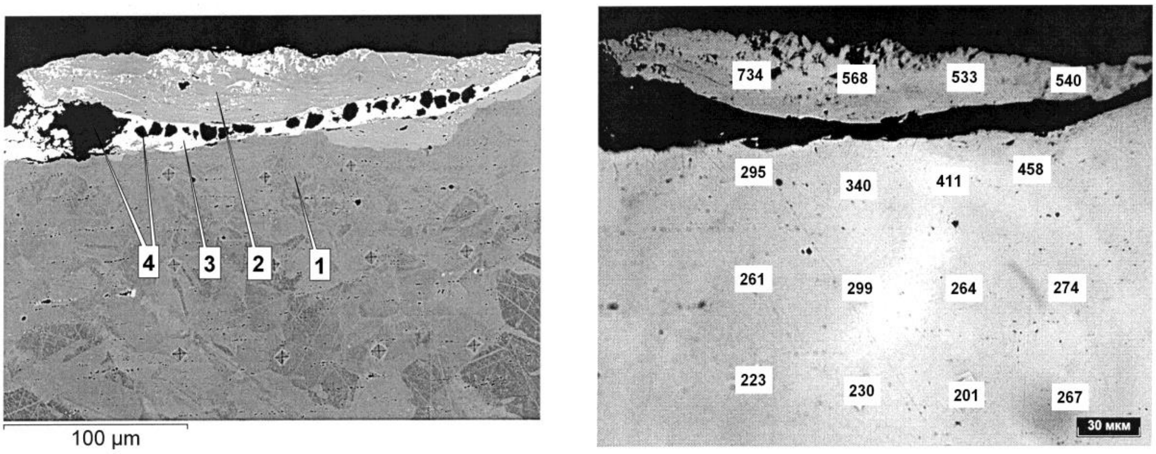
The following formulae were used to determine friction path, contact pressure, wear rate, and wear coefficient

$$l_* = 4Aft_*, \quad p = P/S, \quad I = \bar{W}/l_*, \quad K = I/p$$

and the last formula corresponds to the wear law of linear type.

Analysis of profile records and electron microscopy data of worn surface of the heat-exchange tube sample demonstrates that its surface roughens increases greatly compared to initial one. Analysis shows not only comparatively deep cracks (50 μm to 70 μm in some cases) but peaks and sharp-pointed outgrowth height of which sufficiently exceeds the height level of initial surface. These results provide some evidence for the fact that adhesion seizure processes take place on the contact of sample with stick, followed by cohesion rupture of the bonds with producing of wear particles. Material re-deformation and hardening takes place as well (Fig. 3).

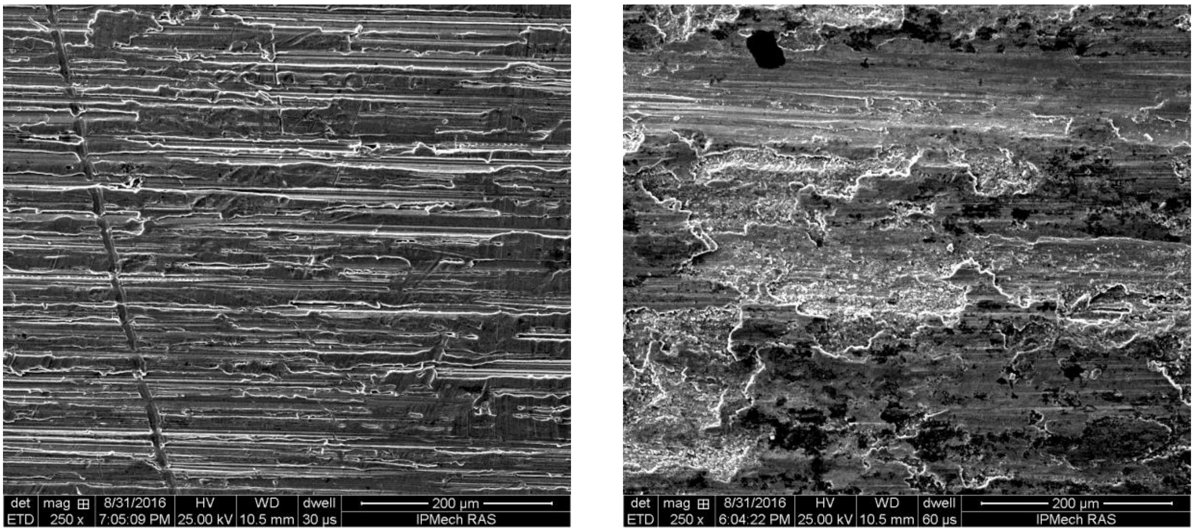
Segregated particles may behave as abrasive material being free or embedded in friction surface. Such behavior is attributable to abrasive wear which is exacerbated by the fact that the process takes place in the lead coolant corrosive medium [1].



a *b*

FIG. 3. a) A place of friction surface in cross-section of the tube sample: 1 is tube material, 2 is segregated wear particle at the surface of sample, 3 is layer of lead coolant, 4 is solid particles (metal oxides and carbides). b) Micro-hardness (HV) depth variation.

Outside friction area, the surface is covered with specific regular stripes (Fig. 4 *a*). Sufficiently homogeneous surface distribution of chemical elements complies with chemical composition declared by the steel manufacturer. Oxygen content is approximately 3% by weight. In the friction area, surface topology varies as follows: longitudinal stripes disappear, surface relief increases due to appearance of caverns and destruction spots (Fig. 4 *b*). X-ray spectrometry made it possible to establish that chemical element distribution in the friction area becomes non-homogeneous. Some spots have the same composition like areas out of friction zone. At the same time there are found spots where oxygen and carbon quantity increases rapidly (up to 20% by weight and more). For such spots it was found a great increase the content of silicium, manganese, and chrome. This provides some evidence for the fact that on the friction area of heat-exchange tube sample appear oxides and carbides of that elements.



a *b*

FIG. 4. The surface morphology of the tube sample before (a) and after (b) test.

3. Conclusions

The complex experiment - theoretical method for evaluation the wear resistance of heat-exchange tube contacting with spacer grid in steam generator is developed. The method is based on use the "Tribometer" equipment which ensures continuous fretting wear tests of all possible pairs of heat-exchange tube and spacer grid elements in liquid lead.

The paper presents results of the second (intermediate) stage of fretting wear test of heat-exchange tube coupled with backside of spacer grid sample (stick). Based on the results the wear coefficient of heat-exchange tube material is identified.

The data fill the appropriate range of parameters used in the theoretical model as a base for solution of the problem on evaluation of the heat-exchange tubes durability in steam generator.

References

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