Research on slipper bearings of pumps of reactor systems with lead-bismuth coolant at relatively low temperatures

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Abstract. The academic focus of the article relates to nuclear power engineering, reactor plants (RP) with heavy liquid metal coolant (HLMC) – lead and eutectic lead-bismuth. The article's purpose is to set out the goals and objectives of the research of slipper bearings for HLMC transfer pumps and to identify the problems of design and operation under these conditions based on the available experience. This experience applies both to energy reactors with high HLMC temperatures (400-550°C), and partly to acceleration-controlled systems and research reactors with HLMC temperature of about 200-350°C. The choice of the type of slipper bearing is justified for further researches of its operability in conditions of low HLMC temperatures.

1. Introduction

Currently, various RP applications are being developed in the world, including the development of acceleration-controlled systems and research reactors with a HLMC temperature of about 200-350 °C. There are also promising projects of power reactors with a coolant temperature at various points of circulation circuits from 300°C and above.

Pumping equipment plays one of the most important roles in RP circuits. Our country has unique experience of creation and operation of the main circulators (MC) of the nuclear submarines (NS) with the reactors cooled by the lead-bismuth coolant of projects 645, 705 and 705K [1]. MCP of reactor plants (RP) of projects 645 and 705K had lower hydrostatic bearings, the operation of which was ensured, inter alia, by the operation of auxiliary pumps (leak return pumps) of the reactor circuit. The MCP of nuclear submarines of project 705 was made with a cantilever arrangement of the shaft and the lower slipper bearing did not have. There is also extensive experience with hydrostatic bearings in the MCP of reactor plants BOR-60, BN-600, BN-800, where they have proven themselves well.

In the open publications, information on hydrostatic bearings operating in liquid metal coolant is insignificant and refers either to alkali metals (sodium, etc.) or to lead coolant.

In Soviet literature, the most detailed hydrostatic bearings, including for sodium pumps, are described in the work of V.M. Budov [2].

An important condition for normal operation of sliding bearings in HLMC conditions is the observance of optimal purity of coolant from impurities. Currently, there is a technology of lead-bismuth and lead coolant of RP, developed, among other things, with the participation of Nizhny Novgorod State Technical Engineering University [1]. This HLMC technology provides operability of
power contours of critical reactors of division of heavy-nuclei at operating temperatures of heat carriers 400-550°C. The main provisions of this technology are as follows:

1) Cleaning of coolant oxides (one of their main operating impurities) by treatment of coolant and circuit with reducing gas-steam mixtures.

2) Ensuring the resistance of the structural materials of the circuit due to the formation and pre-formation of oxide protective coatings on their surfaces.

3) Control (one way or another) of oxygen content in the coolant to ensure formation and deformation of protective oxide coatings.

However, such coolant transfer technology is not suitable for the conditions of acceleration-controlled systems and research reactors operating at temperatures of 200-350 °C due to the following factors:

1) Cleaning the channels of hydrostatic bearings as well as their operation in design modes is difficult, since the effective reduction of HLMC oxides by reducing gas mixtures will not occur at such temperatures (T = 200-350°C).

2) Formation of oxide protective and antifriction coatings on steel surfaces at T = 200-350°C is very unlikely.

3) It is not possible to effectively control the oxygen content of HLMC by technical means proven at high coolant temperatures for the purpose of cleaning channels and forming the necessary coatings on their surfaces.

Therefore, the team of Nizhny Novgorod State Technical Engineering University aims at experimental development of the most promising type of MCP slipper bearing transferring HLMC under the specified conditions of uncalculated operation. In order to do this, it is necessary to analyze the entire experience of operating bearings in HLMC along with analysis of the experience of the team - to choose the most promising type, conduct experimental studies in various operating modes and develop recommendations on the most optimal design versions of the bearing and its operating modes.

2. Research materials and methods

The specific properties of the high temperature liquid metal coolant affecting the operability of the slipper bearings in the conditions of the reactor circuits are as follows [1, 3, 4]:

- Traditional lubricants cannot be used in reactor circuits with HLMC due to high temperatures and the inadmissibility of contact of coolant with organic compounds. The only medium in which such a bearing can operate is the coolant itself.
- All liquid metal coolants (lead, lead-bismuth eutectic, sodium) of reactor plants have a small viscosity value and cannot be considered as lubricants in the traditional sense.
- HLMC does not wet the working surfaces of slipper bearings - adhesion operation is small; the coolant is not able to be held on contact surfaces. Bearing working surfaces as well as other loop surfaces shall have protective oxide coatings.
- Heat is released in the local contact areas of the friction surfaces, which can be effectively discharged by the liquid metal coolant, which has a favorable effect on the operation of the contact pairs.

In wall areas of structural material contact with coolant, formation of oxide protective coatings and disperse systems including impurities impregnated with coolant is possible (and mandatory). As have the experiments of Nizhny Novgorod State Technical Engineering University showed, they are both antifriction coatings, which has a favorable effect on the operation of the contact zones of the working surfaces.

The slip process in a hydrodynamic bearing implies two necessary conditions [5, 6]:

- complete wetting of shaft and bushing surfaces with lubricating fluid;
- high viscosity of lubricating fluid.

In the circuits of lead and lead-bismuth coolant, both these conditions are absent. A necessary condition for the operation of high-temperature circuits with HLMC is the formation and pre-
formation of protective oxide coatings (films) on the surfaces of structural materials. The presence of such films ensures the wettability of the oxidized surface of the HLMC, the value of the edge wetting angle of these surfaces in the protective gas medium is $\theta \approx 110 - 120^\circ$. The only medium that can be used as a liquid lubricant in hydrodynamic bearings under the conditions under consideration is a liquid metal coolant. The values of lead and lead-bismuth eutectic viscosity coefficients in the operating conditions of HLMC circuits are small and close to or less than those for water under normal conditions.

It is impossible to create operable hydrodynamic bearings operating in the medium of liquid-metal coolant of reactor circuits (sodium, lead, lead-bismuth eutectics), as confirmed both by design-theoretical and experimental methods [1].

The fundamental incapability of creating hydrodynamic bearings in HLMC, switching to the contact friction mode of hydrostatic bearings during the start-up, shutdown and emergency clogging of bearing channels with impurities particles - initiate interest in studying the operability of contact friction bearings in conditions of circuits with circulation of high-temperature liquid-metal coolants.

By contact (boundary) friction mode is meant a mode in which there is no conventional liquid or plastic lubricant wetting the friction surfaces between the friction surfaces. Under HLMC conditions, it is possible to have a layer of a disperse system (lubricant in solid phase): oxide films on the surfaces of metal structures, as well as particles of oxides or other metal compounds with gas (steam-gas) inclusions dispersed in the coolant of a wall layer impregnated with it. At the same time, periodic or constant washing of contact surfaces with a liquid metal coolant with low viscosity is possible. Under these conditions, direct contact of the "clean" surfaces of the metal surfaces of the structural materials of the contact pairs of the bearing assembly is excluded and heat generated in the contact zone is intensively removed.

Peculiarities of operating conditions of contact friction bearings in HLMC environment include the following:

- mandatory presence of oxide films (coatings) on the surfaces of structural materials of the circuit, which ensure their resistance in the HLMC medium;
- presence of a wall layer with properties different from those of heavy liquid-metal coolant;
- intensive heat removal by liquid metals of heat generated in the friction zone at high operating temperatures of HLMC in the circuit.

The use of contact friction bearings in lead and lead-bismuth coolant reactor circuits seems unlikely in view of their low durability. Their use in bench contours conditions is more attractive in view of the simplicity of the design. The Nizhny Novgorod State Technical Engineering University has experience in their operation as part of bench circuit pumps, which perform the functions of studies other than the studies of bearings (figure 1). Operation of RCP hydrostatic bearings of reactor circuits in contact friction modes is mandatory, a natural necessity, during both the start-up, shutdown and emergency clogging of channels of these bearings with solid-dispersed particles of impurities.

![Figure 1](a) External surface of shaft bushing (a) and internal surface of contact friction bearing bushing (b) after 950 hours of operation in lead medium at temperature of 480...510°C.
The most promising type of slipper bearing for RP with HLMC operating temperatures of 200-350°C is the hydrostatic bearing (HB) (figures 2, 3).

Figure 2. HB of constant throttling (a, b) and shaft bushing (c) of bench pump FT-1 with lead-bismuth coolant.

The Nizhny Novgorod State Technical University has experience in operation of HB of permanent throttling (figure 2) and slot type with double mutual throttling (figure 3) [4]. The first HB is operated as part of the centrifugal pump of the FT-1 bench with lead-bismuth coolant at temperatures of 250-450°C for more than 40 years and the pump operation time for a specific purpose of about one to two months per year. The second HB is operated as part of the axial pump of the FT-4 stand with lead coolant at temperatures of 420-450°C with a total operating time of up to 2000 hours.

Greater wear of the second HB and the shaft bushing is associated with the operation of the axial pump in large ranges of shaft speeds and with a large number of start-stop cycles. The FT-1 stand
pump worked most of the time with the standard shaft speed for it. It is also possible that the axial pump of the bench FT-1 did not develop a sufficient static head for its bearing, unlike the centrifugal pump of the bench FT-1. This aspect requires further investigation.

For further investigation, the HB with double mutual slot throttling was chosen as the most promising and having advantages over the HB of constant throttling [2].

Figure 3. HB with double mutual slotted throttling (a, b) and shaft bushing (c) of test bench pump FT-4 with lead coolant.

The bearing (figure 4) is a steel bushing approximately 2-3 times the diameter of the shaft on which the bearing is fitted. Adjustment (5) and working (2) chambers with throttle in each of them are turned out on inner wall. The number of such chambers can vary from 4 to 12 each, respectively. Each adjusting chamber is connected through throttle with groove to each working chamber. These grooves are recessed on the outer wall of the bearing. They can be welded with steel strips or closed by an outer sleeve over the entire bearing. On the inner wall of the bearing, parasitic leakage manifold (1,3) and high pressure manifold (4) are also turned from above, from below and between chambers. Hydrostatic bearing is made of Steel 40Cr13 All-union State Standard 5632-72.
HB tests as part of the experimental site on a research experimental bench with lead-bismuth coolant FT-1 NGTU under various operating modes in the medium of lead-bismuth coolant at a temperature of 200-350°C will allow the bearing to be worked out in conditions of emergency clogging of channels with oxides.

Also, the HB will be tested at various values of misalignment with the shaft and radial loads with real-time recording of heat emissions and braking moment on the shaft. It will also record wear after each test cycle.

3. Anticipated results
Upon completion of the works, it is planned to obtain the following results: the braking moment of the force developed on the shaft, the distribution of the temperature field in the bearing wall, the analysis of splines and the measurement of the change in the roughness of friction surfaces under various operating modes, including after life tests. These results will provide conclusions and recommendations for the design, production and operation of the hydrostatic bearing.

During the tests, it is likely that it is impossible to control the oxygen content in the HLMC at temperatures of 200-350°C, and therefore the operation of the HB with clogged channels is a «dry» friction mode. To overcome this circumstance, it is possible during the experiment to develop a method for maintaining the coolant technology, which is a useful side result.

4. Conclusion
Theoretical and experimental justification of selection of optimal slipper bearing for further experimental investigation in RP conditions with lead-bismuth coolant with temperatures of 200-350°C is presented. At these temperatures, it is difficult to control the oxygen content of the HLMC, which means that the operating mode of the bearing with clogged channels is most likely, which can lead to significant wear and tear. This circumstance makes it necessary to impose more stringent requirements for the reliability and durability of bearing supports and for maintaining the coolant technology.

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