The experimental facility for investigation of MHD heat transfer in perspective coolants in nuclear energetics.

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Abstract. Paper presents the current results of work conducted by a joint research group of MPEI–JIHT RAS for experimental study of liquid metals heat transfer. The team of specialists of MPEI–JIHT RAS put into operation a new mercury MHD facility RK-3. The main components of this stand are: a unique electromagnet, created by specialists of the Budker Institute of Nuclear Physics (BINP), and a sealed liquid-metal circuit. The facility will be explored lifting and standpipe flow of liquid metal in a transverse magnetic field in channels of different forms. For the experiments on the study of heat transfer and hydrodynamics of flows for measuring characteristics such as temperature, speed, pulse characteristics, probe method is used. Presents the first experimental results obtained for a pipe in a transverse magnetic field. During the experiments with various flow parameters data was obtained and processed with constructing temperature fields, dimensionless wall temperature distributions and heat transfer coefficients along the perimeter of the work area. Modes with low frequency pulsations of temperature were discovered. The boundaries where low frequency temperature fluctuations occur were defined in a circular tube.

1. Introduction
The flow and heat transfer of liquid metal in the tokamak is under the influence of strong magnetic fields and large heat loads to the divertor and blanket. In other words, convection MHD heat transfer in a tokamak is in a significant joint influence of mass forces of various natures – the electromagnetic force and the buoyancy forces associated with thermo-gravitational convection (TGC). A significant effect of thermogravitational convection (TGC) on heat transfer applies primarily to heavy liquid metal coolants because of their singularities of the thermophysical properties of TGC in these environments is developing stronger than in the liquid sodium. This can lead to abnormal and even emergency situations during the work of heat exchange systems.
To study the operating parameters under which there may be such an emergency situation, it is necessary to creating new experimental setups, which simulating flow of liquid metal in conditions close to real in the perspective nuclear and thermonuclear plants.
2. Experimental facility

New experimental facility-RK-3[4], created specifically for the study of the above flow regimes of LM is a closed mercury circuit (figure 1). Peristaltic pump (10) pumping the working fluid in the pressure tank (1) from the storage reservoir (9), after that liquid flows through the test section (2), which is a vertical pipe. Then working fluid passes through two heat exchangers "pipe in pipe" type (4) and the valve (5), allowing to smoothly adjust the flow rate in the installation. Heat exchangers are used to provide thermal stabilization of the working fluid as it is heated due to supply of heat in the test section of installation. Next, the liquid flows through the electromagnetic flowmeter (6). Electromagnetic valves are used for flow direction changing: mercury either goes directly into the storage tank (9) or enters the weighing system, which purpose is calibration different types of flow meters. The measuring probe is entered in the flow from the end of the test section through the flange (3). In addition to the electromagnetic flowmeter (6) the flow value is determined by the turbine flowmeter (11). Pressure sensor (12) determines the value of possible pulsations of the pressure of mercury entering in the test section from the pressure tank.

![Figure 1. Schematic diagram of mercury stand. 1 – pressure tank, 2 – test section, 3 – flange mount probe, 4 – heat exchangers type "pipe in pipe", 5 – valve, 6 – electromagnetic flowmeter, 7 – connection of the weighing system, 8 – electromagnetic valve, 9 – storage tank of working liquid, 10 – peristaltic pump, 11 – turbine flowmeter, 12 – pressure sensor](image-url)
3. The automation system of the RK-3

The automation system (AS) of the RK-3 were established according with the modern concept of building information-measuring and control systems [9], providing trunk-modular architecture AS, open meets international standards. While a hardware SA have been created it were used mainly instrument PXI, SCXI, CompRIO and other production by company National Instruments (NI). Software AS was based on NI LabVIEW development tools.

The AS of the stand can be divided into two coupled parts: the automated system of scientific researches (ASSR) and the automated system stand control (ASC).

The ASSR should ensure effective and qualitative carrying out of experiments on the facility, performing the following:
- the control of the measuring probes coordinate mechanism;
- suppression of the interference with normal and common type on measuring lines;
- measurement of sensors and transducers signals, as in the mode of the serial poll and the parallel synchronous mode;
- formation and storage arrays of the primary experimental data;
- statistical processing and analysis of primary data, definition of operating parameters, integral and local characteristics of hydrodynamics, heat transfer, the other studied variables;
- presentation of results in tabular or graphical form and other forms;
- the possibility of a public demonstration of the experiment process on the screens and monitors;
- the possibility of remote experiments over computer networks.
The lower level of ASSR is the physical quantity sensors with analog outputs (thermocouple signals, signals of standard levels 0-5V, 0-10V, 0-20mA, 4-20mA and smart sensors with transmitters of information to be output to the standard serial interfaces such as RS-232, RS-485, CAN). The sensor signals commutate on terminal blocks of ASSR, then they served on standard measurement units CompactDAQ. These blocks operate under the control of the upper-level computer, ensure coherence of levels or signals between the sensors and the measuring modules and transfer of experimental data to the operator terminals and users of the test stand. The use of trunk-modular architecture blocks allows to reconfigure ASSR of the facility efficient and simple, and also conduct scaling and prototyping of various ASSR subsystems.

ASC is built on the basis of the typical blocks by standard NI CompactRIO, ensures the normal trouble-free operation of the stand, controls regular and pre-crash condition of the stand, and enables both automatic and manual control elements of the infrastructure of the stand.

There are 5 levels of the stand condition:
- Regular functioning
- Warning.Minor deviations.
- Warning.Serious problems.
- Critical situation. There is a risk of equipment damage.
- Critical situation. There is a threat to the safety of personnel.

The system record control protocols and monitors the status of the stand, operator’s commands, events, triggers decisions, etc.). The system enables data exchange with user terminals and other subsystems on the local network via TCP/IP Protocol. Polling frequency of the sensors is determined by the characteristic time of the process, the ASC provides the required sampling rate at least 10 Hz. The time for decision shall not exceed 0.1 sec. A part of ASC is the subsystem emergency protection SEP. It is designed for 24-hours standalone from any other system monitoring options, the SEP has the algorithms of the expert system, functioning in real time. SEP maintains its own historical database alarm and warning events, ensures emergency shutdown of the stand and the alarm ASSR and stand personnel about the occurrence of pre-emergency or emergency events. First, the number of subsystems serviced SEP includes subsystem of monitoring the concentration of mercury vapor, the cooling system of the magnet, the system of ventilation and air-conditioning space of the stand, the state of the power supply of the stand.

Products CompactRIO offer high performance and flexibility, and also allow you to create custom measuring systems. NI CompactRIO combines a real-time processor and reconfigurable FPGA that allows you to create a standalone embedded and distributed applications, as well as industrial modules I/O with built-in aligning the signals, the possibility of direct connection of sensors and hot-plug. Standard units ASC retain their operability in a wide temperature range (-40 ...+70 degrees) and at different levels of supply voltage.

Software user level, as well as the control modules embedded systems is developed in the graphical programming environment NI LabVIEW. Using of NI LabVIEW allows the development, modernization and using of all software blocks on the basis of the unified technological platform, provides the possibility of collective access to the virtual devices and user panels of virtual instruments booth, including in remote computer access technology for the ALP UD.

ASSR and ASC stand allow zoom installation model blocks CompactRIO, CompactDAQ and other international standards (GPIB, VXI, PXI, SCXI, etc.). Thus, the chosen technology of virtual devices allows increasing the functionality of ASSR and ASC for almost any desired number of channels and signaling types of the sensors-transducers.

4. Experimental data.
Automation system and accompanying equipment allows us to conduct experiment autonomous for a long time. A research of heat transfer was done in the downward mercury flow affected by a transverse magnetic field and homogeneous heating. Temperature fields were measured and three-dimensional pictures of temperature intensity fluctuations distribution were obtained using different modes, such as
when exposed to a magnetic field and without it. The studied section is located at a distance of $z/d=37.4$ from the beginning of the heated zone of the work area.

In Figure 2 it is shown the temperature field obtained at operating conditions $Re = 11 \cdot 10^3$, $Gr = 8.0 \cdot 10^7$ with various Hartmann numbers. It shows that the imposition of the magnetic field leads to the appearance of zones of deteriorated heat transfer, and therefore to the inhomogeneity in the temperature distribution of the wall.

![Temperature field](image1)

**Figure 3.** Temperature field in the test section. $Re=11 \cdot 10^3$, $Gr=8.0 \cdot 10^7$, a) $Ha=0$, b) $Ha=1300$, c) distribution of temperature wall in cross section, $Ha=1300$.

There is complete suppression of temperature fluctuations in the experiment when $Ha=1300$.

In the experimental study of the MHD heat transfer has been detected modes, in which low-frequency pulsations of temperature were observed. The type of all detected pulsations except separately stipulated cases is the form of breakdowns.

Next the results of experiments with modal parameters: $Re=11 \cdot 10^3$, $Gr = 8.0 \cdot 10^7$, different numbers $Ha$ (coordinates of the probe: $X=0$, $Y=0$) is presented. In figure 5 it is shown examples of the temperature pulsations under these operating conditions. Under these operating conditions the low frequency pulsations are observed already at $Ha=150$. Further, with increasing the Hartmann number the presence of low frequency pulsations is retained. At $Ha=500$ periodicity of the pulsations is noticeably reduced; this tendency continues with increasing Hartmann number. At $Ha=500$ for the time interval 100 seconds can be seen only one peak, because the period of low-frequency pulsations is 260 seconds. This means
that these modes require a longer sampling time to fully explore this effect. Suppression of temperature fluctuations is observed when $Ha=525$ and above.

Figure 4. Intensity of temperature pulsations with different Hartmann numbers $Re=11\cdot10^3$, $Gr=8.0\cdot10^7$, $R=0.65$.

In figure 5 it is shown how much time is needed to stabilize for the mode with influence of magnetic field. It can be noted, that modes with high Hartmann number require more sampling. This fact is the cause for further experiments with longer time to measurement.
During experiments, it received full suppression by the magnetic field of low-frequency pulsation with the anomalous intensity. These results expand the modern view of the MHD heat transfer processes and the influence of TGC. However, in order to study this effect fully, it is necessary to increase the sampling time in experiments to measure of temperature pulsation. In the future, the authors of this work expect such experiments, because the experimental stand allows to carry out such measurements for a long time.

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