Study of heat exchange and hydrodynamics on the model of fuel assembly with microfuels

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Abstract. The design of the working section was developed and the hydraulic circuit of the TVS-MPEI experimental bench was modernized to study hydrodynamics and heat transfer in a fuel assembly with microfuel. Experimental studies were carried out to determine the pressure loss and hydraulic resistance coefficient of a cylindrical ball filling with the following operating parameters of the coolant: \( p = (2 \div 7) \) MPa, \( G = (0.05 \div 0.5) \) kg/s. The technology of installation, output and sealing of thermocouples at the work site has been developed. The first experimental data on the temperature distribution inside the ball filling were obtained.

1. Introduction

Improving safety is one of the main tasks in the operation of nuclear installations. Nuclear energy faces a number of major problems, such as nuclear and radiation safety of reactors, competitiveness with thermal power plants equipped with combined-cycle plants, reproduction of nuclear fuel, long-term safe and inexpensive storage of radioactive waste [1].

The need to comply with constantly growing requirements for the safety systems of nuclear reactors entails a growing cost of nuclear power plants (NPPs). Quite long ago, a solution implying the use of fuel assemblies on the basis of micro fuel elements (MF FAs) was developed, which allows essentially safer operation of nuclear reactors to be obtained [1, 2].

The ball microfuel consists of a fuel core coated with a protective sheath. The shells separate fuel and coolant and provide retention of fission products of nuclei [1]. Due to their small size (diameter 0.6–4.2 mm), microfuel elements have a high specific surface area and are characterized by a low fuel temperature in the center of a fuel element. Spherical microfuels have a low thermal inertia [2]. Their shells do not have seams, they are strong and resistant, retain reliably fission products, and can work with large degrees of fuel burnup. Microtel can be overloaded without stopping the reactor.

Microfuel manufacturing technology was developed for high-temperature gas-cooled reactors in the 1960s. In high-temperature reactors, ball fuel rods in normal conditions operated at a temperature of 1500 °C [3] and at the same time effectively retained fission products. In emergency conditions, they retained this ability at a temperature of 2000 °C. Recent studies have shown that microfuel cells with shells made of pyrocarbon and silicon carbide can be used in VVER reactors. They have the necessary corrosion resistance in a water and water-steam coolant in the VVER operating mode and
emergency conditions, in supercritical water parameters, and are compatible with reactor materials. Nuclear and radiation safety, even in such a dangerous accident as the separation of the bottom of the reactor vessel, is ensured by the removal of heat by the surrounding air due to its natural circulation through the core.

Micro fuel elements are placed into such an assembly between perforated jackets and are directly streamlined by coolant. To minimize the pressure loss, radial flow of coolant is arranged. In their external geometrical parameters, MF FAs are fully identical with the conventional FAs with fuel rods. In [4,5] and in other publications, the concept of using micro fuel elements in water-cooled water-moderated reactors is further developed, and tests of micro fuel elements for strength and corrosion resistance are described. The results from investigations into hydrodynamics and heat transfer for axial flow of fluid through pebble beds are reported in quite a number of publications, e.g., in [6,7], however, there are few systematic studies in a wide range of operating parameters, up to reactor parameters, in the scientific literature.

The purpose of this work is an experimental study of hydrodynamics and heat transfer in working sections, which are cylindrical filling of ball elements in the following range of operating parameters: coolant pressure \( p_{cp} = (2 \div 7) \) MPa; mass flow rate of the heat carrier \( G_{\text{water}} = (0.05 \div 0.5) \) kg / s; temperature \( T = (20 \div 150) \) °C. The results presented in the work are one of the stages of a set of studies aimed at experimental substantiation of the use of microfuel in nuclear power.

2. The description of the experimental stand

In 2010, an experimental stand was put into operation at the Department of Physics and Nuclear Physics for the study of hydrodynamics and heat transfer in ball fillings and fuel assemblies TVS-MPEI. The stand is universal both in technical characteristics and in the possibilities its application for studying the thermohydraulic characteristics during the flow of the coolant in channels of various geometries and with different heating systems.

The hydraulic circuit was modernized at the stand with the aim of installing a working section in it – a large-scale model of ball filling. The technological characteristics of the bench correspond to the operational parameters of real VVER-1000-type plants (pressure up to 16 MPa, temperature up to 350°C).

The hydraulic circuit is a closed single-circuit hermetically tight circulating system filled with distilled water, with a working pressure range of \((0.1 \div 16.0)\) MPa. The circuit is made of stainless pipes (08X18H10T), with dimensions determined on the basis of strength and hydrodynamic calculations. The circuit includes pumps, shut-off and control valves, heat exchangers, heaters and a working section. The water circulation in the circuit is carried out by a centrifugal pump TCEN-149, providing a nominal flow rate of \(8 \text{ m}^3/\text{h}\) of coolant.

The working section is a cylindrical filling of ball elements. The body of the working section is made of high-strength alundum ceramics. In these experiments, microfuel is modeled by metal balls with a diameter of 2 mm, and volumetric heat release is achieved by induction heating of the switchgear. The backfill is securely fixed in the cassette, through specially designed clamping devices. A sketch of the working section design is shown in figure. 1.
Figure 1. The work area design sketch: 1 – radiolucent ceramic body of the work area, 2 – perforated grill for holding ball fill, 3 – pressure spring, 4 – thermocouple seal assembly, 5, 6 – inlet and outlet pipes.

To conduct thermophysical measurements, nine thermocouples of the HA type were prepared, which were placed at various points along the height and radius of the ball filling. The temperature of the coolant inside the ball filling is measured by five chromel-alumel cable thermocouples, the remaining four are sealed into the walls of metal balls, forming a measuring element. The manufacture of such a measuring element was carried out as follows: on a laser spot welding machine, which is equipped with a high magnification digital microscope, a through hole was shot through the ball. A thermocouple was placed in this hole, and the hole was sealed with high-temperature soldering with solder, forming reliable contact with the wall of the ball. figure. 2a shows a sketch of an element meant for measuring the temperature of a metal ball, figure. 2b shows a diagram of the cartridge with the locations of the thermocouples.
3. Experimental study results

A series of experiments was carried out on pressure loss at the working section, the filling height was 180 mm. The experiments were carried out with the following operating parameters: coolant pressure \( p = (2 \div 7) \) MPa; mass flow rate of the coolant \( G_{\text{water}} = (0.05 \div 0.5) \) kg/s; temperature at \( T = (20 \div 150) \)°C.

The purpose of these experiments was to obtain the dependence of the coefficient of hydraulic resistance of the ball on the flow parameters. Figure 3 shows the dependences of the pressure loss on the switchgear on the calculated mass flow rate \( \Delta p = f(\rho U) \) at 3 (a) and 6 (b) MPa.

Figure 2. a) Scheme of measuring the temperature of a metal ball.
b) Diagram of the cassette and the cross section of thermocouples installation.
Figure 3. Dependence of pressure losses on the mass velocity of the coolant at 3 (a) and 6 (b) MPa at the inlet to the switchgear: ♦ – $T = 30^\circ$C, ▲ – $T = 150^\circ$C.

Figure 4 shows the dependences of the hydraulic resistance of ball filling (measured in the course of the experiment by the Bogoyavlenskii formula) on the Reynolds number $\xi = f(Re)$ for one mode ($T = 100^\circ$C). Light markers correspond to pressure $p = 3$ MPa, and black markers correspond to $p = 6$ MPa.

Figure 4. The dependence of the hydraulic resistance of ball filling on the Reynolds number at 3 and 6 MPa: ■, □ – Bogoyavlenskii formula; ♦, ◊ - $\xi$ determined from experimental data.

As follows from these data, the influence of the coolant pressure is very significant in the flow with low velocities ($Re < 3000$) and is gradually smoothed out at higher flow rates. In flow regimes with
small Re numbers, calculations according to the Epiphany formula give significant overestimations to the value of hydraulic resistance.

Several experiments on heat transfer were performed, their purpose was to determine the possibility of heating this working area by the selected method. The dependence of the temperature of the balls on the coordinate of the location of the thermocouples in the backfill $T = f(x)$ is plotted, the dependences are shown in figure 5.

![Figure 5. Dependence $T = f(x)$ of the temperature of the balls on the coordinate of the installation of thermocouples in the backfill.](image)

Conclusions
In this work, arrays of experimental data were obtained on pressure losses and temperature field during axial flow of the coolant through the filling of spherical elements. The dependences of pressure of losses on the mass velocity of the coolant, as well as the hydraulic resistance on the model of fuel assembly with microfuels on the Reynolds number are shown. The calculated values of the hydraulic resistance coefficient are in good agreement with this parameter calculated by the Bogoyavlensky formula in the entire range of the experimental data obtained. The possibility of simulating the internal heat release of filling spherical elements with induction heating is shown. The first estimates of the heat transfer coefficient showed the effectiveness of this design in terms of heat transfer characteristics.

To apply the obtained results in practice, it is necessary to continue detailed studies in this direction, including at high values of pressure (up to 16 MPa) and temperature (up to 300 °C) at the coolant inlet. It is also necessary to carry out systematic studies to study the influence of the geometric parameters of the ball filling in order to possibly improve its design.

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