Experimental determination of the pressure drop and temperature fields in the working section of the fuel assembly model with microfuel

S V Mirnov1,2, A T Komov1, A N Varava1, A V Dedov1, A V Zaharenkov1, Yu V Smorchkova1 and I A Tupotilov1

1General Physics and Nuclear Fusion Department, National Research University "Moscow Power Engineering Institute", 14 Krasnokazarmennaya Street, Moscow, Russia
2Division of Tokamak Reactors Physics, JSC “SRC RF TRINITI”, 12 Pushkovykh street, Troitsk, Moscow, Russia

E-mail: ZakharenkovAV@mpei.ru

Abstract. The paper describes an experimental stand and a working area on a model of fuel assembly with microfuels cooled by a single-phase coolant flow at high pressures. The experiments were carried out in a wide range of operating parameters of the coolant coolant pressure \( p = (2 \div 7) \) MPa; mass flow rate of the coolant \( G_{\text{water}} = (0.05 \div 0.5) \) kg/s. The experiments were carried out on the working area of the body, which is made of high-temperature ceramics. The results of pressure losses and temperature distribution of balls along the length and radius of the filling are obtained. It is shown that the hydraulic resistance coefficient obtained on the basis of experimental data is in good agreement with the Bogoyavlensky formula. Significant temperature stratification is observed along the radius of working section.

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 use of fuel in the form of spherical microfuel in VVER-type reactors can significantly increase the safety of nuclear power plants. 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 microtules have a low thermal inertia [2]. Their shells do not have seams, they are strong and resistant, reliably retain fission products, and can work with large degrees of fuel burnup. Microtel can be overloaded without stopping the reactor.

The microfuel production process illustrates well their high resistance to high temperature and in a corrosive environment. First, spherical particles are obtained from uranium dioxide, at a temperature of 1500 °C methane is pumped through a layer of such particles. In this case, a "fluidized bed" is formed, in which the particles are coated with soot layers during the decomposition of methane. At
such a high temperature, this carbon black, called pyrographite, is very durable. Then, a gas containing silicon is pumped through the "fluidized bed", upon decomposition of which spherical particles are coated over soot with a layer of silicon carbide. This is followed by boiling of such balls in a mixture of nitric and sulfuric acid, as a result of which uranium particles are removed from their surface, and balls with a defective coating dissolve. Micro-fuel rods showed high performance when tested for many months in a water coolant at a temperature of 350°C, when tested in a pair with a temperature of 1000°C and in a flue gas environment at a temperature of 1500°C.

A fairly large number of works have been devoted to the study of hydrodynamics and heat transfer in ball filling, but the experiments in these works were carried out in narrow ranges of operating parameters, which leads to the need for additional studies in this area.

The purpose of this work is an experimental study of hydrodynamics and heat transfer at work sites, which are a cylindrical filling of ball elements.

2. The description of the test section

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 ÷ 16.0) MPa. The circuit is made of stainless pipes (08X18H10T), with dimensions determined on the basis of strength and hydrodynamic calculations. A detailed description of the stand elements is given in [3].

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. General view of the working area (a) and the layout of thermocouples in the cassette are presented (b) in the figure 1.
Figure 1. (а) 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; (b) diagram of the cassette and the cross section of thermocouples installation.

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.

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 \( p = (2 \div 7) \text{ MPa} \); mass flow rate of the coolant \( G_{\text{water}} = (0.05 \div 0.5) \text{ kg/s} \); temperature at \( T = (20 \div 150) \text{ °C} \).

Figure 2 shows the dependences of the hydraulic resistance of ball filling (measured in the course of the experiment by the Bogoyavlenskiy formula) on the Reynolds number \( \xi = f(\text{Re}) \) for one mode (\( T = 100\text{°C} \)). Light markers correspond to pressure \( p = 3 \text{ MPa} \), and black markers correspond to \( p = 6 \text{ MPa} \).
Figure 2. The dependence of the hydraulic resistance of ball filling on the Reynolds number at 3 and 6 MPa: ■, □ – Bogoyavlenskiy formula; ♦, ◊ – ξ 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.

At the first stage, experimental research on heat transfer consisted in determining the temperature field inside the spherical filling. For this, several series of experiments were carried out with the following operating parameters of the coolant: $p = 3.0$ MPa; mass flow rate of the coolant $G_{water} = (0.05 \div 0.5)$ kg / s; inlet temperature at $T = (20 \div 100)$ °C. The purpose of these experiments was to study the regularities in the distribution of the temperature of the liquid and balls in the given geometry of the cassette. Figure 3 and 4 shows the variation of the surface temperature of the balls along the length of the working section.

It is good from the graphs that an increase in the flow rate of the coolant significantly reduces the temperature of the spherical filling, while stratification of the thermocouple readings along the radius of the working section is observed. In this case, there is an unambiguous trend showing that the temperature of the balls at the periphery is somewhat lower than in the center, which may be due to the better flow of the coolant around the latter.
Figure 3. Dependence $T = f(x)$ of the temperature of the balls on the coordinate of the installation of thermocouples in the backfill ($N_{el} = 25.0$ kW, $T = 60^\circ$C): 1 – $G = 0.15$ kg/c; 2 – $G = 0.20$ kg/c; 3 – $G = 0.45$ kg/c.

Figure 4. Dependence $T = f(x)$ of the temperature of the balls on the coordinate of the installation of thermocouples in the backfill ($G = 0.15$ kg/c, $T = 60^\circ$C): 1 – $N_{el} = 1.2$ kW; 2 – $N_{el} = 6.8$ kW; 3 – $N_{el} = 11.1$ kW; 4 – $N_{el} = 25.0$ kW.

4. Conclusions
At present, most of the engineering problems related to the design and manufacture of spherical microfuel have been resolved. Russia has its own technology for the manufacture of such microfuel, as
well as an experimental and industrial base for their production. However, a number of unsolved problems remain in the field of hydrodynamics and heat transfer in a spherical bed. The work carried out by various scientific teams made it possible to obtain significant material and calculated ratios, however, a comparison of calculations based on the equations obtained in these works shows a significant discrepancy between them. The results of experimental studies obtained in this work make it possible to supplement the experimental data previously obtained by other researchers, as well as to estimate the pressure loss and heat transfer coefficient in the working sections with different geometries. The possibility of conducting experimental studies with the parameters of the coolant corresponding to those of the reactor is, of course, extremely useful. As a result of this work, it is shown that in the case of a single-phase coolant flow regime:

- • hydraulic resistance of a cassette with ball filling is well described by the well-known Bogoyavlensky formula;
- • the temperature field in the backfill is non-uniform over the cross section;
- • the first experiments showed that an increase in the temperature of the coolant at the inlet to the working section leads to the formation of steam bubbles on the surface of the balls, which will lead to a significant unevenness of the temperature distribution over the cross section of the ball filling.

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