Experimental study of fluid dynamics in the pebble bed in a radial coolant flow

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Abstract. The results of experimental studies of pebble bed hydrodynamics are presented. For the first time experimental data on the pressure loss in a radial flow of fluid through the pebble bed was obtained. Experiments were carried out in the liquid flow rate ranging from 0.09 to 0.4 kg / s, fluid temperature is 20ºC.

1. Introduction

In recent years, the problem of improving the efficiency and safety of nuclear power plants becomes urgent. One solution to this problem is to use the microfuel fuel assemblies (MF FA), immediately cooled by single-phase or two-phase coolant [1,2]. The design of MF FA for VVER reactors was proposed in [1]. In such an assembly microfuel is placed between the perforated covers. To minimize pressure losses radial flow of coolant was proposed. Despite the fact that the MF FA geometrical parameters is fully consistent with the traditional assemblies, their implementation on a large scale in nuclear energy is unlikely.

However, now interest in small nuclear power is increasing. In Russia, this interest is primarily related to the need of development of remote regions. Also, low-power nuclear station can solve the problems associated with increasing the energy security of critical facilities, such as industrial facilities with continuous production, urban infrastructure, etc., providing the vital needs of the city.

However, for low-power stations wide spreading it is extremely important to provide a reliable radiation safety in case of accidents. So high temperature resistance, high integrity and good retention of fission products within microfuel up to temperatures of about 1600 ° C are of particular importance. In [3] and other works microfuel tests for strength and corrosion resistance were described. We regard options of microfuel consideration for the use of low-power reactors to be very interesting and promising.

One of the difficulties, arising in the implementation of microfuel in nuclear power plants, is the lack of knowledge of heat-hydraulic characteristics in the pebble bed with internal heat release. Quite a lot of works are devoted to the study of hydrodynamics and heat transfer in pebble bed, but the experiments in this work were carried out in narrow ranges of operating parameters, which leads to the need for more research in this area. In addition, there are no experimental studies of heat transfer and hydrodynamics in the pebble bed in a radial flow of coolant in the literature.

2. The experimental facility

2.1. The hydraulic circuit

The studies were conducted in an open hydraulic circuit, the circuit is shown in Fig. 1. The distilled water, which is in the tank (1) was used as an operating fluid. The circulation of the coolant is carried out by multistage centrifugal pump Grundfos CRNE 1-4 (2). Water from the tank is pumped through a filter (3) to the working area (6) and flows back to the tank. As the volume of water in the tank is large enough, in the experiments in the circuit water temperature does not change significantly.
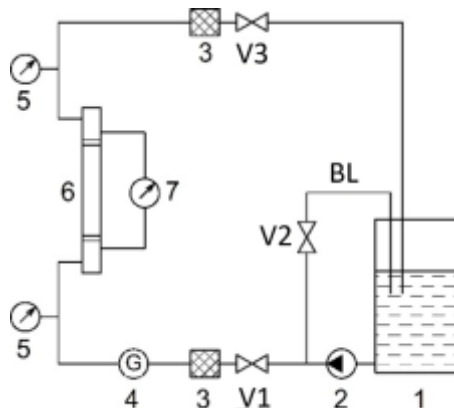

Fig.1. Hydraulic circuit

Flow control was carried out in two ways: step by step by using a frequency regulator that is installed on the pump and smoothly via the bypass line (BL) and the valves (V1, V2). Measurement of flow through the working portion was performed by an electromagnetic flowmeter (4) Vzlet EM Profi-212.

For pressure measurement in the work area exemplary arrow manometers (5) on the inlet and outlet of the working area and the differential pressure sensor (7) Elemer 100 are used.

Experimental set is designed for the following operating parameters: temperature in the circuit is 20 °C to 180 ° C, the pressure in the circuit is up to 1.0 MPa, the coolant flow rate is (0,01-0,50) kg /s.

2.2. Working area

The working area diagram (WA) is shown in Fig. 1. WA is made of material which is transparent to high-frequency radiation, as the further experiments are suggested to be carried out by the heating of the pebble bed via high-frequency generator. Pebble bed (3) is placed between the inner (2) and outer (4) perforated covers. Balls of 2.0 mm diameter are made from steel grade AISI 420. Perforated inner cover has a conical shape, in order to ensure a steady flow rate adjustment of pebble bed. The cover is made of abs plastic using 3D printing. The outer cover is a perforated tube made of polycarbonate. Perforation of the covers was performed by drilling, hole diameter 1.5 mm.

The geometric parameters of the working arrea are the following: inlet diameter (the diameter of the base of the cone) is 11 mm, the wall thickness of the cone (the inner perforated cover) is 2 mm, the diameter of the outer perforated cover is 47 mm, wall thickness is 1,5 mm, the diameter of the outer pipe (6) is 54 mm, wall thickness is 3 mm. The height of the filling is 100 mm.

To minimize pressure losses in such a construction, the flow through the pebble bed should be close to the radial. To do this, we should define inner and outer covers' perforation parameters. Determination of perforation options was performed on the basis of numerical simulation results in the software package ANSYS Fluent. During the simulation, it was found that a steady height perforations of covers shows unsatisfactory results. Therefore, the covers were divided into three sections and for each section we determined the coefficients f living section and number of holes. Covers' perforation parameters are shown in table 1.
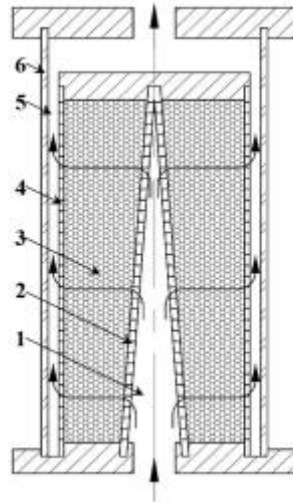
Fig.2. The working area diagram

Table 1. Covers' perforation parameters

| | Inner cover | | Outer cover | |
	f	Number of holes	f	Number of holes
Lower section	0,299	350	0,113	400
Middle section	0,395	250	0,148	390
Upper section	0,471	200	0,148	390

3. Experimental data

The porosity of the pebble bed was determined by gravimetric method and is estimated to be 0.385. According to the results of multiple weighing on laboratory scale portions of 100 balls was determined their mass, as all the balls are calibrated, difference with the weighing results is not more than 1%. Further, we know the mass of one ball and a set of balls from the work area, their number and we can calculate the volume. The porosity of the pebble bed was determined using the formula:

$$\varepsilon = 1 - \frac{V_p}{V}$$

V – the volume of the working area section, where the pebble bed placed, V_p– the volume of balls.

Experiments to determine the pressure loss was conducted in the range of flow rate from 0.09 to 0.4 kg /s at 20 ° C fluid. The range of Reynolds numbers ($Re = Ud/\nu$, U is the superficial velocity, d is the diameter of the ball, ν is the kinematic viscosity) was 1800 – 8400. Initial experimental data is shown in Fig. 3 by points. For the development tests of the method of measuring the experimental values were compared with the results of numerical simulations performed in ANSYS Fluent. The simulation results are presented in Fig. 3 by a solid line. The discrepancy between the results does not exceed 12%. Unfortunately, it is not possible to compare the experimental data with known equations for the pebble bed hydraulic resistance because all available in the literature equations are designed to flow through the pebble bed, located in the circular cross-section tube and give overestimated results.
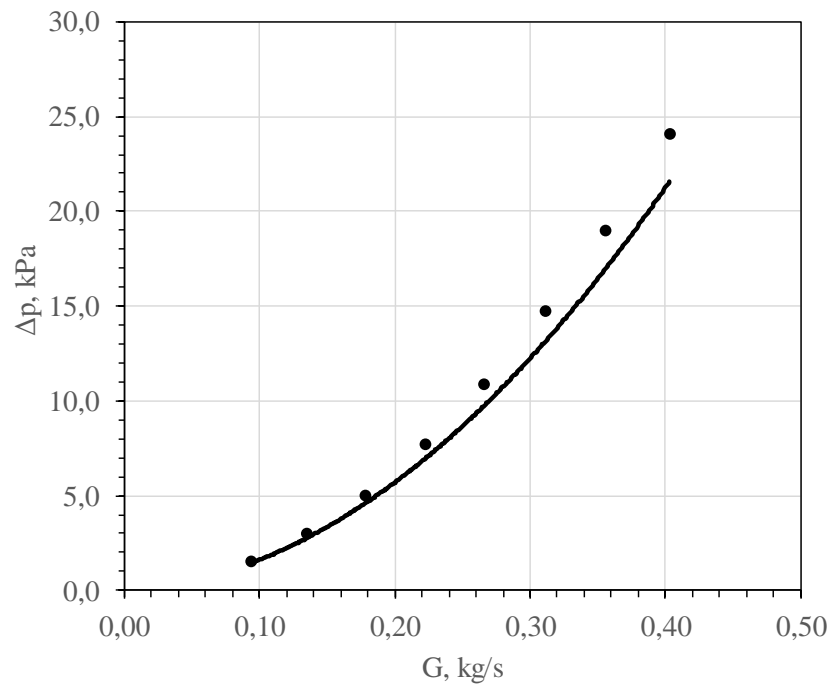
Fig.3. The pressure loss relation on the mass flow rate

For comparison in Fig. 4 shows the results of this work and the dotted line presents the experimental data obtained earlier [4] for the pebble bed, located in the circular tube with axial flow of liquid. The porosity and height of the pebble bed, as well as operating parameters of the experiments in [4] were similar to this article. We can see that the pressure loss by organizing the radial flow through the pebble bed is significantly reduced. This confirms the necessity of radial flow when using ball fillings in nuclear power installation.
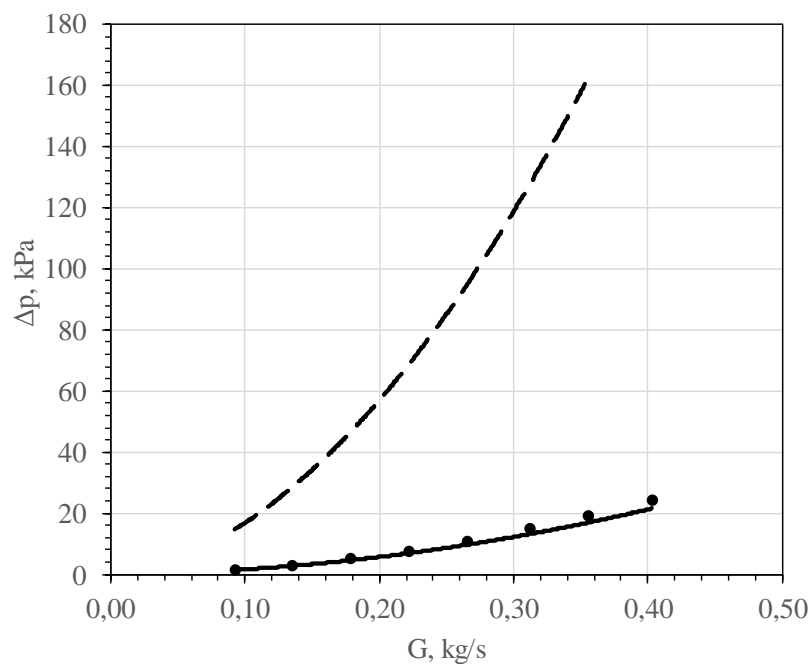

Fig.4. The pressure loss relation on the mass flow rate

4. Conclusion

Experimental data on the pressure losses in the pebble bed in a radial flow of coolant was first obtained, despite the fact that numerical modeling of such geometries was conducted previously and it was applied to a microfuel fuel assemblies for nuclear reactors. Thereby, currently the accuracy of the data is only possible to estimate by comparison with the simulation results, as calculated ratios presented in the literature allow us to determine the hydraulic resistance ball fillings with an axial flow.

References

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