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The study of the temperature field in pebble beds with volumetric heating and radial flow of coolant

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Abstract. The paper presents the results of an experimental and numerical study of hydrodynamics and heat transfer in a pebble bed with internal volumetric heat release. An experimental setup was designed to investigate the hydrodynamics and heat transfer at the radial flow of a single-phase coolant. The pebble bed was set from 2.0 mm diameter sphere made of AISI 420 steel. The internal heat release model in the pebble bed is provided by high-frequency induction heating, whereby the thermal power of the high-frequency installation is 20 kW. The experiments were carried out in the range of mass flow rates of 0.1 - 0.6 kg/s. The test section simulates the fuel assembly of a nuclear reactor with microfuel. Pebbles are placed between the inner and outer perforated covers. Radial coolant flow is achieved to minimize pressure losses. The inner cover is cone-shaped and is the dispensing manifold for the coolant. The conical shape of the cover provides a uniform flow rate of the cooling liquid along the length of the test section. The temperature distribution in the pebbles were recorded.

Introduction

Recently, there have been more pressing issues about improving the energy efficiency and safety of nuclear power plants. One of the ways to solve this problem is to use a fuel assembly with microfuel (FA MF) directly cooled by a coolant [1,2]. The design of FA MF for VVER reactors was proposed in [1]. In such an assembly, the microfuel is placed between the perforated covers. Radial coolant flow is used to minimize pressure losses. Despite the fact that the geometric parameters of FA MF correspond entirely to traditional assemblies, their implementation on a large scale in nuclear power is hardly possible.

Also, there is an increasing interest in small-scale nuclear power engineering. It seems very interesting and promising to consider the use of microfuel for low-power reactors.

However, one of the difficulties that arise with the introduction of microfuel in nuclear power plants is the insufficient study of thermal-hydraulic characteristics of pebbles with internal heat release. There are no records of experimental studies on heat transfer and hydrodynamics in pebbles with radial flow coolants and internal heat release in literature.

In addition, it is necessary to resolve the issue on the choice of an optimal assembly design for low-power nuclear power plants. It is most convenient to solve such a problem using numerical simulation methods. The methods and mathematical models used in numerical calculations require verification using experimental data.

Experimental setup

Hydraulic circuit. The study was carried out on an open hydraulic circuit, which diagram is shown in Fig. 1. Distilled water was used as the working fluid, it is located in the tank (1). Circulation of the



coolant is carried out by a multistage centrifugal pump Grundfos CRNE 1-4 (2). The water from the tank is injected by the pump through the filter (3) to the test section (PY) and flows back to the tank. The hydraulic circuit is equipped with a preheater (5) and a heat exchanger (10).

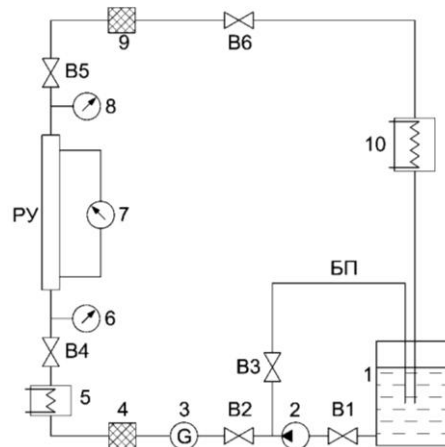


Figure 1. Hydraulic circuit

Consumption control was carried out in two ways: stepwise with the help of a frequency controller installed on the pump, and smoothly by means of a bypass line (БП) and valves (B2, B3). The flow rate through the test section was measured by an electromagnetic flowmeter (3) of the Vzlyot brand EM PROFI-212 model. To measure the pressure in the test section, the standard arrow gauges (6, 8) at the input and output of the test section and the differential pressure sensor (7) Elemer-100 were used. The experimental setup is designed for the following mode parameters: temperature in the circuit from 18 °C to 180 °C, pressure in the circuit up to 1.0 MPa, coolant flow rate (0.01-0.60) kg/s.

Test section. The plan of TS is shown in fig. 2.

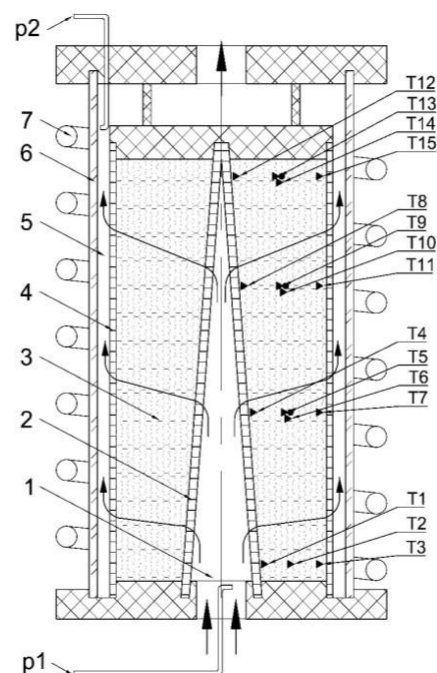


Figure 2. Diagram of the test section

The pebbles (3) are placed between the inner (2) and outer (4) perforated covers. The pebbles are filled up to a height of $H = 100$ mm. The coolant in such a design is fed into the dispensing manifold (1), washes over the pebbles and enters the collection manifold (5). The prefabricated collector is formed by an outer perforated cover and tube (6), which simultaneously performs the functions of external sealing of the working section. The diameter of the perforated outer cover is 47 mm, the diameter of the tube (6) is 54 mm. To ensure a uniform flow rate along the height of the pebbles, the inner perforated cover is cone-shaped. The diameter of the inlet is 15 mm. The cover is made of abs plastic using 3d printing. The perforated outer cover is a polycarbonate tube. The covers were drilled and the perforated holes were 1.5 mm in diameter. Pressure gauges were located directly in the dispensing (1) and collecting (5) manifolds at the inlet (p1) and the fluid outlet (p2) from the area occupied by pebbles.

Simulation of internal heat generation in pebbles is provided through high-frequency induction heating by means of an inductor (7), which is connected to the IHS20-60 induction heating unit. 15 cable thermocouples, installed in 4 sections along the height of the filling were placed to measure the temperature in the pebble volume. (T1-T15).

Pebbles in test sections were produced as 2.0 mm diameter spheres made of AISI 420 steel. The porosity of the pebbles $\varepsilon = 0.385$.

Experimental data

Temperature field without coolant flow. The use of induction heating to simulate the volumetric internal heating in a pebble bed is a non- standard method. Therefore, experiments on heating a pebble bed without the flow of coolant were carried out. The test section in these experiments was filled with water. The thermocouple readings were recorded during the experiments. The induction heating power was 1 kW. Temperature distribution along the height and radius of the test section is shown in Fig.3.

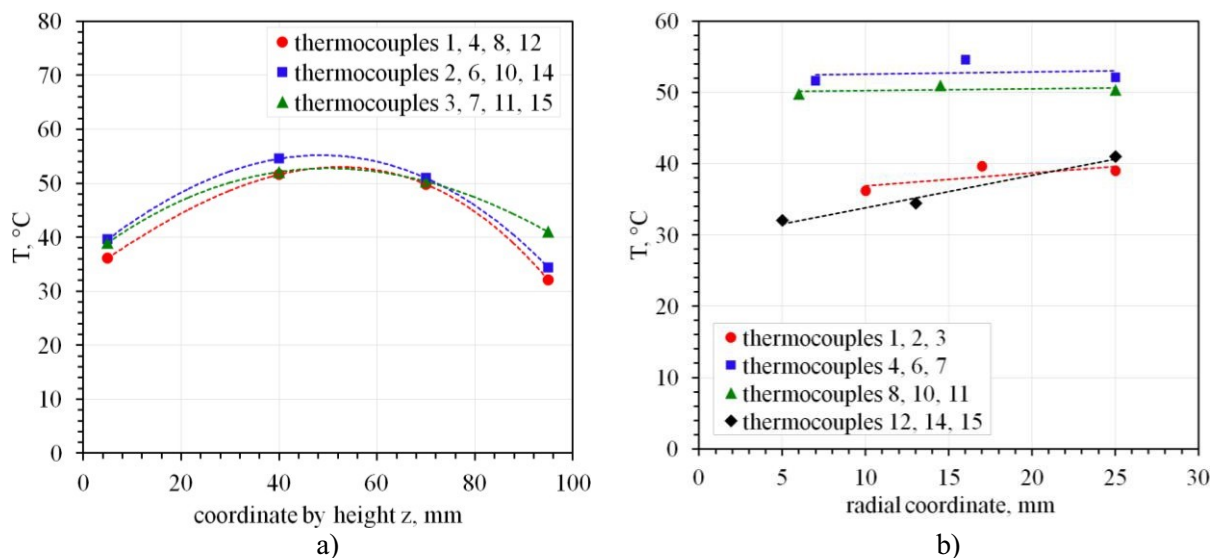


Figure 3. Temperature distribution along the height a) and radius b) of the test section

As a result of the experiments, the volume density of heat release at each point was determined by the formula:

$$q_v = \left[\varepsilon \rho_f c_{pf} + (1 - \varepsilon) \rho_s c_{ps} \right] \frac{dT}{dt}$$

where $-q_v$ is the volumetric heat release density, W/m^3 , c_{pf} is the specific heat of the liquid at constant pressure, c_{ps} is the specific heat of the balls at constant pressure. The temperature at each point increases linearly with time, so the derivative dT/dt can be replaced by the temperature increment ΔT over the time τ . The distribution of the volumetric density of heat release normalized to the maximum value with respect to the dimensionless axial coordinate is shown in Fig. 4. Heat release along the height of the pebble bed has a strong heterogeneity.

When comparing the distributions of heat release along the axis in a dimensionless form with the data presented in the literature [3–5], a satisfactory agreement is observed, both qualitative and quantitative, in the central part of the backfill. At the edges of the pebble bed, the values obtained are understated. The difference between the profiles is probably due to the different geometry of the inductors.

The experimental data obtained in this paper are well described by a harmonic function:

$$q_v = q_{\max} \cos\left(2,5 \frac{z - z_c}{H}\right),$$

where z is the coordinate of the height of the backfill, z_c is the coordinate of the center of the fill in the height

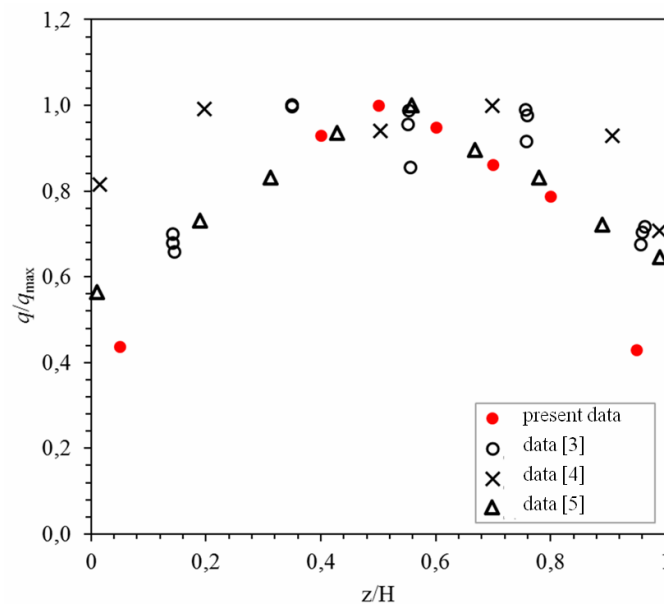


Figure 4. Dependence of the dimensionless density of volumetric heat release on a dimensionless coordinate by height

Temperature field with radial coolant flow. The heat transfer and temperature distribution in the test section were studied for a range of coolant flow rates from 0.1 to 0.6 kg/s and volumetric heat release in the pebbles from 4.3 to $9.3 \cdot 10^7 \text{ W/m}^3$. The distribution of temperatures recorded along the height and the radius of the pebbles are shown in Fig. 5 a), b). The results are presented for coolant flow rate 0.12 kg/s and volumetric heat release in pebbles $9.3 \cdot 10^7 \text{ W/m}^3$. On the distribution of temperature along the height of pebbles, a maximum in the central part of the pebbles and a decrease in temperature to the ends were observed. Such a decrease in temperature is due to the peculiarities of induction heating and is due to the uneven heat release along the height. Uniform heat release is observed only in the central part of the pebbles, in the region where the thermocouples 4-7 and 8-11 are located. The graph of temperature

distribution along the radius of the pebbles is as expected with a linear increase in temperature from the inner to the outer cover, which indicates uniform heating of the coolant.

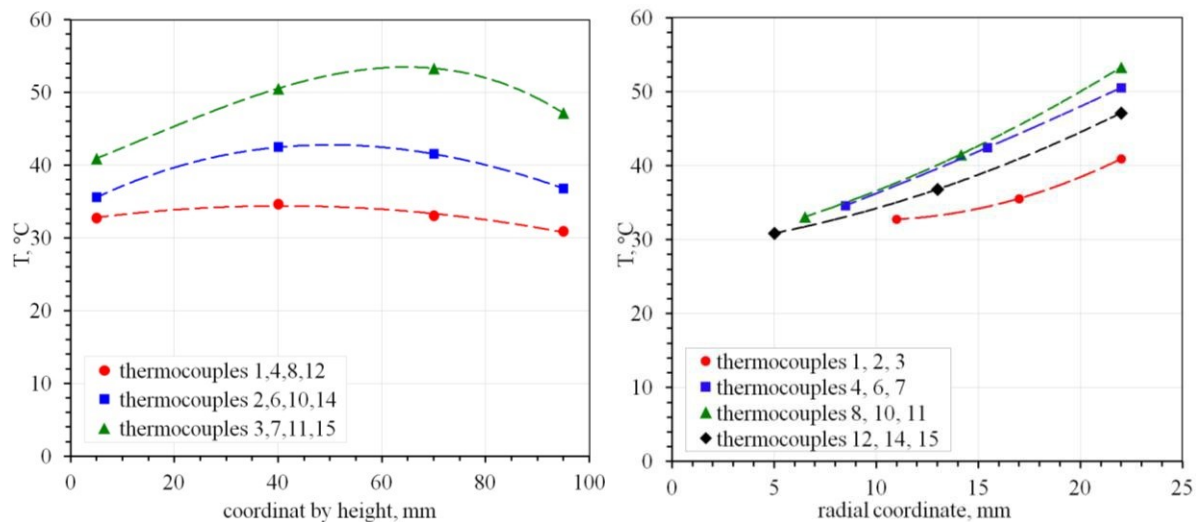


Figure 5. Distribution of temperature over height a) and radius b) of the TS. Coolant flow rate 0.12 kg/s, volumetric heat release in the pebbles $9.3 \cdot 10^7$ W/m³.

Conclusion

In this paper, a profile of volume heat release was obtained in a pebble bed heated by induction heating. It is shown that induction heating can be used to simulate the internal heat release in a pebble bed. Temperature distributions are obtained at the radial flow of the coolant through a pebble bed in conditions of internal heat release.

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