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Temperature fields and heat transfer in free-packed fuel pin bundles cooled by heavy liquid metal

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Abstract

The paper considers heat transfer and temperature fields in a free-packed fuel pin bundle cooled by a heavy liquid metal with different types of spacing. Data is analyzed for three fuel assemblies with a pitch of $s/d = 1.33$: a smooth fuel pin bundle, a bundle of fuel pins spaced by a bilifar-helix wire wrapper of the "wire-to-wire" type, and a bundle with transverse spacer grids. In the free-packed smooth fuel pin bundle, there are no temperature non-uniformities around the fuel pin periphery in contrast to major general temperature non-uniformities in the bundle with wire wrapping which provides for a major decrease in the heat transfer. In the bundle with transverse spacer grids, the heat transfer only increases in the region of the grids, and, between them, is approximately equal to the heat transfer in the smooth pin bundle. Correlations are presented as recommended for the calculation of Nusselt numbers and the temperature non-uniformities around the fuel pin periphery with the above spacing options.

Keywords: Liquid-metal coolant; Model fuel assembly; Experiment; Smooth fuel pins; Spacer grids; Helical wires; Temperature field; Nusselt number; Temperature non-uniformity.

Introduction

The development of fast-neutron reactors of a new generation with a high power rating [1,2] and a high level of the fuel pin temperature in the reactor core requires reliable data on the reactor core thermal hydraulics (heat transfer, fuel pin temperatures and so on), which is one of the most important components in the justification of the reactor design and mode parameters [3].

At the present time, there is no quantitative data that characterizes the heat exchange in free-packed fuel pin bundles typical of the cores of lead-cooled fast-neutron reactors of a new generation with different types of the fuel pin spacing. If available, this data (along with drag coefficients) makes it possible to close the system of constants for by-cell thermal-hydraulic design of the lead-cooled reactor cores, allowing for the effects of the spatial geometry and power density irregularities and being an efficient tool of thermal-hydraulic analysis at the stage of the fast reactor detailed design as well as in analysis of operating modes.

Heat transfer and temperature fields in smooth fuel pin bundles

The available data on the calculation of heat-transfer coefficients for smooth fuel pins cooled by a liquid metal has been obtained based on numerous studies for fuel pin bundles in extensive variation ranges of the key parameters ($1.0 \le s/d \le 1.95$; $4 \le \mathrm{Pe} \le 3500$; $0.007 \le \mathrm{Pr} \le 0.03$; $0.02 \le \varepsilon \le 16$). This has made it possible to identify the major regularities in the heat exchange in smooth lead-cooled fuel pin bundles and to obtain versatile calculation formulas.

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The following formula has been used for generalization of Nusselt numbers ($\varepsilon \geq 0.01$; $1.0 \leq s/d \leq 2.0$; $1 \leq \mathrm{Pe} \leq 4000$) [4–6]

$$\mathrm{Nu} = \mathrm{Nu}_{lam} + f(\mathrm{e}, \mathrm{x})\mathrm{Pe}^{\varphi(\mathrm{x})}, \tag{1}$$

where Nu_{lam} is the Nusselt number for the laminar coolant flow; $x = s/d$ is the fuel pin pitch; $\varepsilon = \varepsilon_6$ is the parameter of the fuel pin thermal similarity calculated based on the fundamental harmonic of the temperature field Fourier series expansion (this is the sixth harmonic $k = 6$ for a triangular lattice); and $f(\varepsilon, x)$ and $\varphi(x)$ are empirical functions. In the Nu and Pe numbers, the hydraulic diameter of the regular lattice cell has been taken as the characteristic dimension.

The values Nu_{lam}, f and φ are calculated using formulas [4–6]

$$\mathrm{Nu}_{\mathrm{lam}} = \left[7,55x - \frac{6,3}{x^{17x(x-0,81)}}\right]\left[1 - \frac{3,6x}{x^{20}\left(1+2,5\varepsilon^{0,86}\right)+3,2}\right], \tag{2}$$

$$f = \frac{0,041}{x^2}\left(1 - \frac{1}{\frac{x^{30}-1}{6} + \sqrt{1,24\varepsilon + 1,15}}\right), \tag{3}$$

$$\varphi = 0,56 + 0,19x - 0,1/x^{80} \tag{4}$$

or taken from the respective nomograms.

The structure of formulas (1)–(4) is totally invariable only for the pitch $1.0 \leq s/d \leq 1.20$ (closely packed fuel pin bundles). For other characteristic dimensions of s/d, the formula is much simpler. Thus, for the pitch $1.2 \leq s/d \leq 1.95$, which includes the pitch of s/d =1.33, the formula for the Nusselt numbers is as follows [6,7]:

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{lam}} + \frac{0,041}{x^2}\mathrm{Pe}^{0,56+0,19x} \tag{5}$$

$$\mathrm{Nu}_{\mathrm{lam}} \cong 7,55x - 20x^{-13} \tag{6}$$

Fig. 1 presents a comparison of experimental and calculated data for the liquid metal heat exchange in free-packed smooth fuel pin bundles [5–7].

The basis for the generalization of the temperature non-uniformities is formula [4–7]

$$\Delta T = \frac{t_w^{\max} - t_w^{\min}}{\bar{q}R}\lambda_f = \frac{\Delta T_{\mathrm{lam}}}{1 + \gamma(\varepsilon)\mathrm{Pe}^{\beta(x)}} \tag{7}$$

where ΔT_{lam} is the temperature non-uniformity in the event of a laminar flow, as determined from nomogram [6,7]; and $\gamma(\varepsilon)$ and $\beta(x)$ are empirical functions.

We shall note that formula (7) has been obtained for the temperature non-uniformities around the periphery of smooth fuel pins in a closely packed bundle ($1.0 \leq x \leq 1.15$), where the mutual effects of adjoining fuel pins are significant and when the temperature non-uniformities to a great extent depend on the equivalent heat conductivity of the fuel pins (on the parameter ε). In free-packed fuel pin bundles, there are no practically temperature non-uniformities.

Heat transfer and temperature fields in wire-wrapped fuel pin bundles (helical wrapping of the "wire-to-wire" type)

Experimental FA model with wire-wrapped fuel pin simulators

The experimental FA model with wire-wrapped fuel pin simulators is designed in accordance with the thermal modeling principles developed at IPPE [6–9]. This is an assembly of 37 electrically heated fuel pin simulators (spaced by helical wrapping of the wire-to-wire type) arranged in a triangular lattice with a pitch of $s/d = 1.33$ and contained in a hexagonal tube with no peripheral displacers.

On the surfaces of the measuring (rotary) fuel pin simulators there are 12 microthermocouples embedded, at different distances from the heating start area (and uniformly across the power density region) in longitudinal grooves milled in the wall. They are installed along the simulator perimeter with a spacing of 30°. The rotation of a simulator in an angle range of 0–360° makes it possible to measure the temperature distribution over its surface. The wires are welded to the lower and the upper plugs fixed by dowels in the grids and extended on the rotary simulator, bearing closely against its surface. As the simulator rotates in the wire wrapping, each of the 12 thermocouples embedded in the simulator wall passes a portion of the perimeter beneath the wire and measures the temperature under it.

Temperature is measured on the heat-exchange surface of the measuring pin simulators and at the model assembly coolant inlet and outlet in collectors, as well as at the inlets of all model assembly cells. The model coolant is an eutectic sodium-potassium alloy having its Prandtl number numerically close to the Prandtl number of the lead used as the coolant in the BREST-OD-300 reactor (one of the thermal modeling principles [5,8,9]).

Temperature rises under wires. General temperature non-uniformity around the measuring pin simulator periphery

In the heating start area, the temperature rises under the wires for the central simulator (Fig. 2) have an interval of about 180°, and, further (axially), this interval (180°) is observed approximately, with additional maximums from adjoining wires, the numerical values of which may be great, showing themselves.

For the lateral and the corner fuel pin simulators, there is a general temperature non-uniformity (the difference between the temperature's maximum and minimum values around the simulator periphery) developing rapidly, the numerical value of which increases greatly thanks to the temperature rises under the wires, if these are in the assembly's central zone.

Dependences have been plotted and formulas have been obtained for the temperature rises under the wires and for the general temperature non-uniformities in a dimensionless form for different fuel pin simulators (Fig. 3) [10].