Heat Transfer and Temperature Non-Uniformities in Pin Bundles with Heavy Liquid Metal Coolant at Various Spacing Ways

J.A.Kuzina[1], A.P.Sorokin[1]

[1]JSC «SSC RF – IPPE», Obninsk, Russia

E-mail contact of main author: ukyzina@ippe.ru

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, s/d = 1.28: 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 perimeter 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.

Key Words: Model fuel assembly, smooth fuel pins, spacer grids, helical wires

1. Introduction

The development of fast-neutron reactors of a new generation with a high power rating 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.

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 hydrodynamical resistance 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.

2. 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.

The following formula has been used for generalization of Nusselt numbers ($\varepsilon \ge 0.01$; $1.0 \le s/d \le 2.0$; $1 \le \mathrm{Pe} \le 4000$) [1-3]:

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

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).

$$\varepsilon_6 = \frac{\lambda_{cl}}{\lambda_c} \cdot \frac{x_1 m_1 (m_2 - x_2) + x_2 (1 - x_2 m_2)}{x_1 m_1 (m_2 + x_2) + x_2 (1 + x_2 m_2)}, \quad (2)$$

where $x_1 = \left(\frac{r_{fuel}}{R}\right)^{12}$; $x_2 = \left(\frac{r_{inner}}{R}\right)^{12}$; $m_1 = \frac{\lambda_g - \lambda_{fuel}}{\lambda_g + \lambda_{fuel}}$; $m_2 = \frac{\lambda_{cl} - \lambda_g}{\lambda_{cl} + \lambda_g}$, λ_{fuel}, λ_g, λ_{cl}, λ_c – heat conductivity of a fuel, a gas gap, a cladding and a coolant, respectively; r_{fuel} – radius of a fuel pellet, r_{inner} – inner radius of a fuel cladding, R – external radius of fuel element. $f(\varepsilon, x)$ 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 [1-3]

$$\mathrm{Nu}_{lam} = \left[7.55x - \frac{6.3}{x^{17x(x-0.81)}}\right]\left[1 - \frac{3.6x}{x^{20}\left(1 + 2.5\varepsilon^{0.86}\right) + 3.2}\right], \quad (3)$$

$$f = \frac{0.041}{x^2}\left(1 - \frac{1}{\frac{x^{30} - 1}{6} + \sqrt{1.24\varepsilon + 1.15}}\right), \quad (4)$$

$$\varphi = 0.56 + 0.19x - \frac{0.1}{x^{80}}. \quad (5)$$

or taken from the respective nomograms.

For other characteristic dimensions of s/d, the formula is much simpler. For free-packed fuel pin bundles (the pitch $1.2 \le s/d \le 1.95$), which includes the pitch of s/d =1.33 and s/d =1.28, the formula for the Nusselt numbers is as follows [3, 4]:

$$\mathrm{Nu} = \mathrm{Nu}_{lam} + \frac{0.041}{x^2}\mathrm{Pe}^{0.56+0.19x}, \quad (6)$$

$$\mathrm{Nu}_{lam} \cong 7.55x - 20x^{-13}. \quad (7)$$

Fig. 1 presents a comparison of experimental and calculated data for the liquid metal heat exchange in free-packed smooth fuel pin bundles [2-4].

The basis for the generalization of the temperature non-uniformities is formula [2-4]:

$$\Delta T = \frac{t_w^{\max} - t_w^{\min}}{\overline{q}R}\lambda_f = \frac{\Delta T_{lam}}{1 + \gamma(\varepsilon)\mathrm{Pe}^{\beta(x)}}, \quad (8)$$

where ΔT_{lam} is the temperature non-uniformity in the event of a laminar flow, as determined from nomogram [3, 4]; 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 perimeter 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.

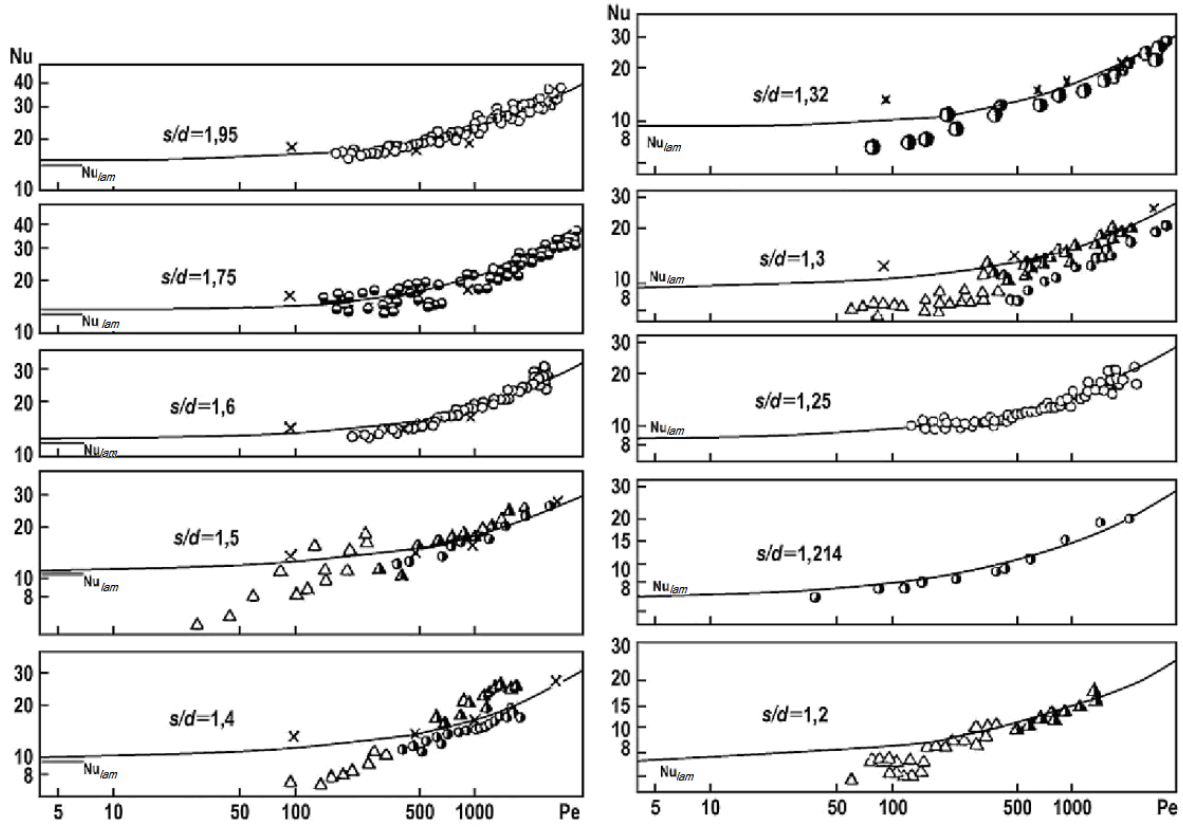

FIG. 1. A comparison of calculated (lines) and experimental (symbols) data on the liquid metal heat exchange in free-packed smooth regular pin bundles ($1.2 \leq s/d \leq 1.95$) (solid line – calculation based on formula (5)).

3. Heat Transfer and Temperature Fields in Wire-Wrapped Fuel Pin Bundles (Helical Wrapping of the «Wire-to-Wire» Type)

3.1 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 [3-6]. 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 to 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 lead-cooled reactor (one of the thermal modeling principles [2, 5, 6].

3.2. Temperature Rises under Wires. General Temperature Non-uniformity around the Measuring Pin Simulator Perimeter

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 (the peak appears at approximately at 160° because of possible small displacement of the wire around the simulator), with additional maximums from adjoining wires, the numerical values of which may be great, showing themselves.

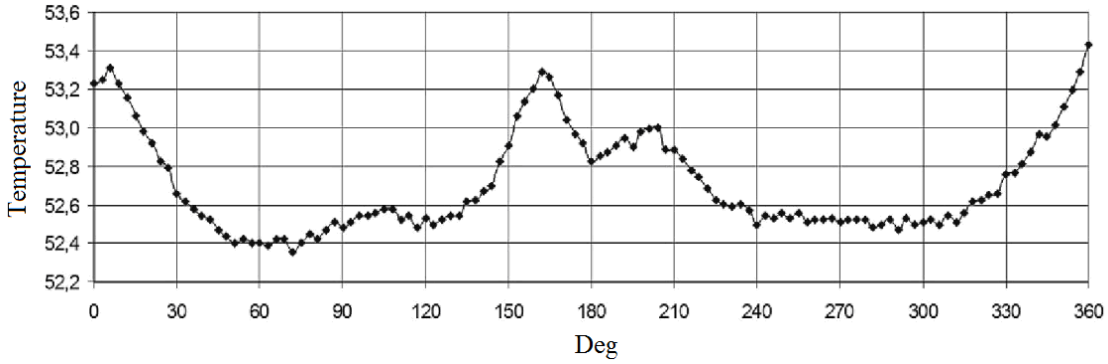

FIG. 2. A temperature field of the model assembly's central pin simulator in the heating start area for one of the experimental modes.

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 perimeter) 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.

3.3. Heat Transfer

A variation in the "wall-liquid" temperature difference along the heating region (an example is presented in Fig. 3) is characterized by rather low dispersion of experimental data. The dispersion of average temperature at the central cells outlet is low also.

Experimental data on the heat transfer for the central pin simulator is presented in Fig. 4. By comparing the experimental data for the central simulator against the formula for smooth fuel pins (1), we get [7]

$$\mathrm{Nu}_c = \mathrm{Nu} \cdot f(\mathrm{Pe}), \tag{9}$$

where Nu is the Nusselt number dependence for smooth fuel pins as may be calculated using formula (5); and $f(\mathrm{Pe})$ is the correction to the Nusselt number for the fuel pin wires.

It can be seen that the heat transfer in experiments on the assembly with s/d = 1.33 with bilifar-helix wire wrapping of the "wire-to-wire" type is much lower than for smooth fuel pins. Of importance here is the following peculiarity of wired systems cooled by liquid metals: the heat transfer decreases due to the temperature non-uniformities under the wires since the turbulization effect of wires on the liquid metal turns out to be insignificant as compared to the temperature rises under the wires. As Pe increases, the effects of the temperature rises under the wires on heat transfer decrease (the role of turbulence is growing), so the drop in the heat transfer coefficients for the wired fuel pins becomes smaller as compared to smooth channels. If, with Pe ≈ 1000, the drop is about 40%, then with Pe ≈ 2300, the heat transfer for wired and smooth fuel pins is equalized, that is, with the given Pe number, the turbulence of the liquid-metal flow and the temperature rises under the spacing wires seem to compensate each other.

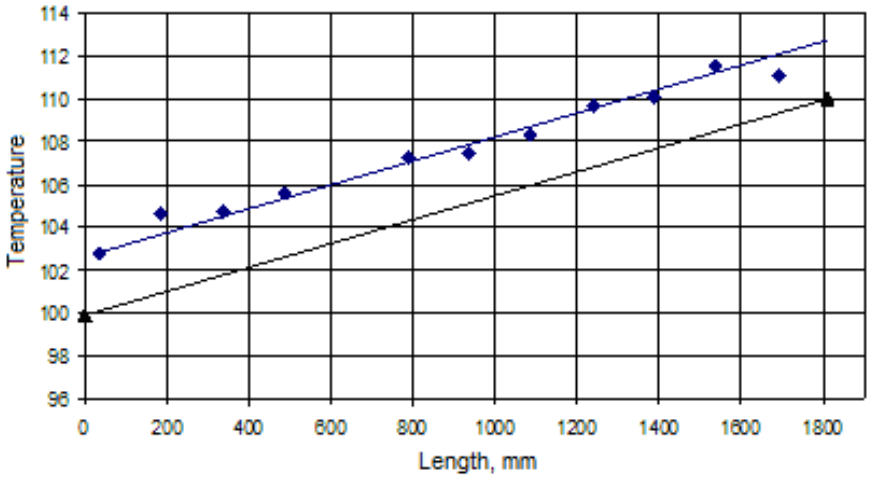

FIG. 3. A variation in the "wall-liquid" temperature difference along the heating region of the wired central fuel pin simulator of the fuel assembly for one of the experimental modes: —▲— – coolant temperature, —♦— – wall temperature of the measuring fuel pin simulator.

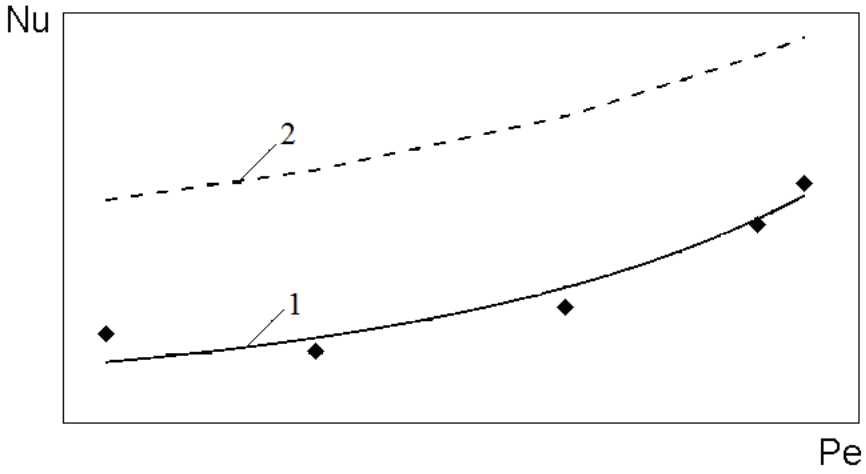

FIG. 4. Schematic dependence of the Nusselt numbers on the Peclet numbers for the central fuel pin simulator in the model assemblies: ♦ – experimental data; 1 – approximation by relation (8) for a wired fuel pin simulator; 2 – Nusselt number dependence for smooth fuel pin bundles with s/d = 1.33 (5).

4. Heat Transfer and Temperature Fields in Fuel Pin Bundles Spaced by Transfer Grids

4.1. Model FA with spacer grids

Experiments to study the temperature field and heat transfer in fuel pins with spacer grids were conducted on model 37-pin assemblies (s/d = 1.33 and s/d = 1.28) described in the previous section, with transverse grids (four grids along the heating region) used instead of wires for spacing [8, 9]. The thermocouples in the central measuring pin simulator are most often embedded in the region of grid 3, which makes it possible to study the effects thereof on the heat transfer.

Fig. 5 presents the cross-section of the model assembly with the spacer grid design.

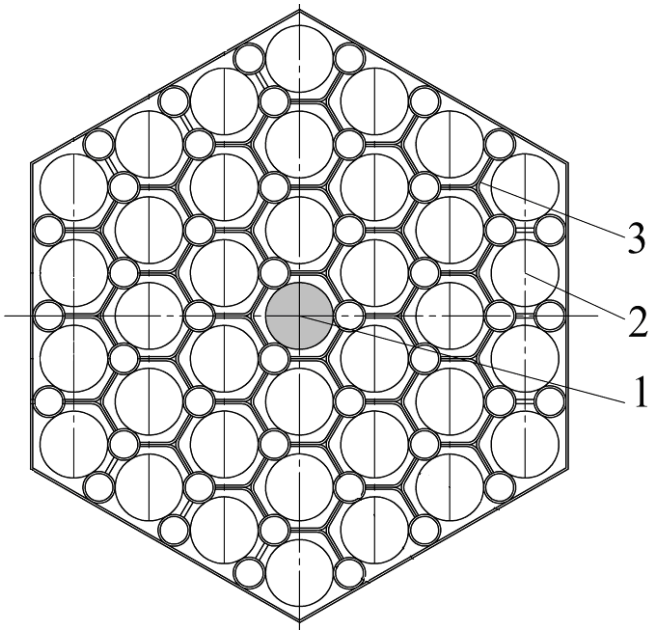

FIG. 5. Cross-section of the model assembly in the spacer grid region: 1 – the measuring (rotary) fuel pin simulator; 2 – one of the non- measuring fuel pin simulator; 3 – the spacer grid.

4.2. Results of Experiments in the Model FA with Spacer Grids

Experimental data was processed for the smooth length of the fuel pin simulators and the spacer grid region.

Fig. 6 shows an example of the measuring pin simulator's temperature field based on readings of the thermocouples installed between the spacer grids. There have been many experiments at different temperature levels. This figure is for one of the experimental mode.

In the studied range of Peclet numbers, the obtained dependence for the Nusselt numbers in the smooth part of the fuel pin simulators with s/d = 1.33 and s/d = 1.28 spaced by transverse grids, is described by the formula [8, 9]

$$\begin{aligned} \mathrm{Nu}_{smooth} &= A + B \cdot \mathrm{Pe}^{C}, \\ 200 &\le \mathrm{Pe} \le 1150, \end{aligned} \tag{10}$$

which fits the general type of the Nu(Pe) dependences in the fuel pin bundles (1) cooled by liquid metals.

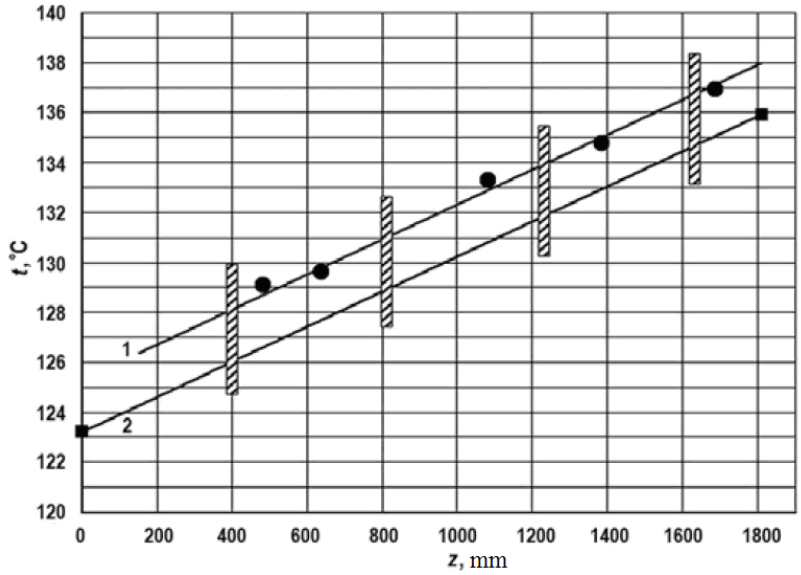

FIG. 6. A variation in the "wall-liquid" temperature difference along the heating region of the grid-spaced central pin simulator based on readings of the thermocouples between the grids, for one of the experimental modes: 1 – wall temperature with no correction for the thermocouple embedding; 2 – liquid temperature

Fig. 7 demonstrates a characteristic temperature field of the measuring pin simulator based on readings of the thermocouples near the third grid.

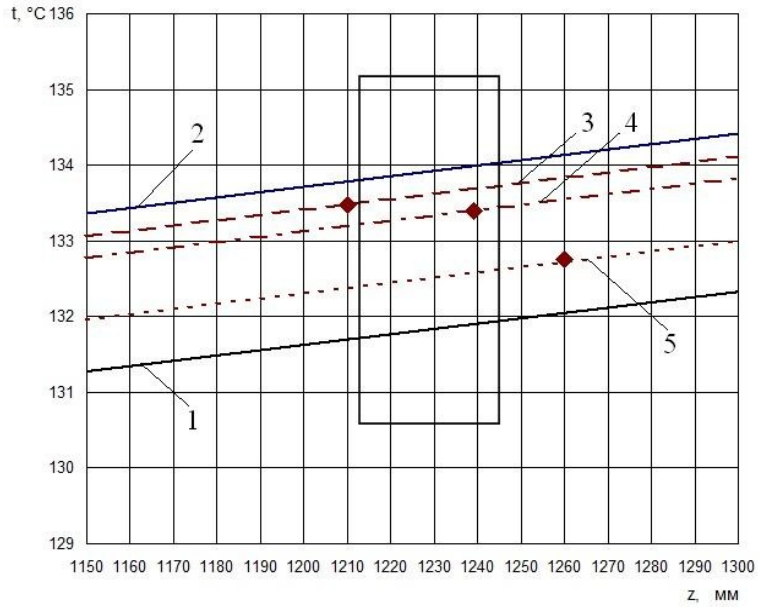

FIG. 7. Temperature fields of coolant and pin simulator surface near the third grid for one of the experimental modes: 1 – coolant temperature; 2 – temperature of pin simulator surface based on readings of the thermocouples between the grids (smooth length); 3-5 – temperature of pin simulator surface based on readings of the thermocouples (upstream, downstream and inside of the grid).

Experiments have shown that spacer grids lead to a local burst in the heat transfer which turns out to be higher than for smooth lengths of the fuel pin simulators (between the grids). The heat transfer increases as the coolant moves in the grid. If the "wall-liquid" temperature difference at the grid bottom (line 3) is close to the temperature difference for the smooth regions of the simulators, then it decreases inside the grid (line 4) and becomes especially small near the grid top (line 5) due to the grid's turbulizing effect on the coolant flow. It is here that the greatest increase in the heat transfer is observed.

The formulae for calculation of local heat transfer coefficients for different regions of the spacer grids (upstream, downstream and inside of the grid) are received.

4.3. A comparison of the Heat Transfer and Temperature Fields in the Fuel Pin Bundles Spaced by Wire Wrapping of the "Wire-to-Wire" Type and in Fuel Pins Spaced by Transverse Grids (*s/d* = 1.33)

Fig. 8 presents a comparison of the heat transfer in smooth fuel pin bundles and in fuel pins with different types of spacing ("wire-to-wire" wrapping and spacer grids).

It may be presumed that the effects of spacer grids on fuel pins are not great in the investigated range of Peclet numbers (the distance between the grids is comparatively short and their thickness is small), as the result of which the obtained Nu numbers practically coincided with the Nu numbers for the smooth fuel pin bundles with a pitch of $s/d = 1.33$ (the dashed line in Fig. 0). The difference in the heat transfer for the smooth fuel pin bundles and the heat transfer in the smooth length of the fuel pin simulators spaced by transverse grids was ~ ±20% for high and low Pe numbers respectively.

Therefore, calculations for the smooth regions of the fuel pins spaced by transverse grids may be based on the formula for smooth fuel pins (5) or on a newly obtained formula of type (9).

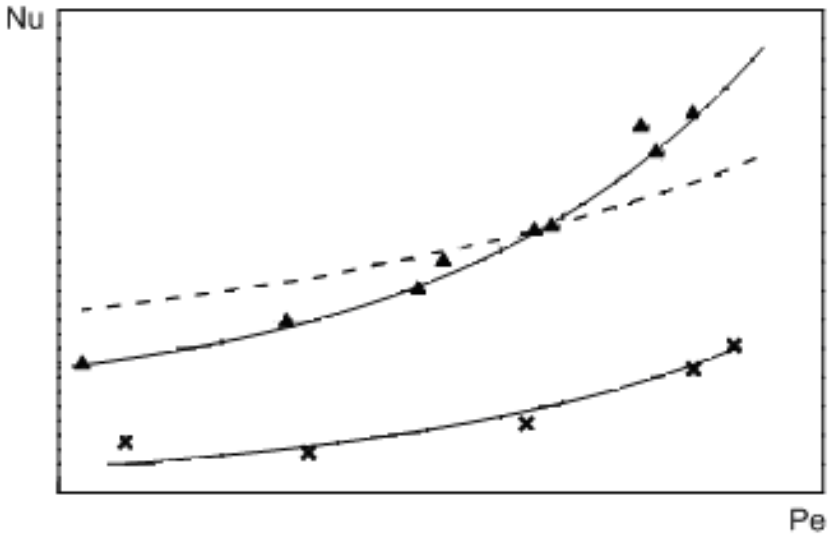

FIG. 8. Schematic dependence of Nusselt numbers on Peclet numbers for the central fuel pin simulator in the model assemblies with s/d = 1.33: —▲— – experimental points for the Nusselt numbers for the smooth length of the pin simulators spaced by transverse grids, with an approximation curve described by formula (9); - - - - - – – dependence for the Nusselt numbers for the smooth fuel pin bundles with s/d = 1.33 calculated based on formula (5); —×— – dependence for the Nusselt numbers for the fuel pin simulators with bifilar-helix wire wrapping of the "wire-to-wire" type [7]

The data on the Nusselt numbers (a pitch of s/d = 1.33) with bilifar-helix wire wrapping of fuel pins (see Fig. 8) lie much lower. This is explained by great azimuthal temperature non-uniformities as compared to the considered cases.

As has been noted, there are no temperature non-uniformities around the fuel pin perimeter in free-packed smooth fuel pin bundles cooled by liquid metal, which leads to a high heat transfer.

In a bundle with spacer grids, the azimuthal temperature non-uniformities are much smaller (nearly twice as small with large Peclet numbers) than in the case of the fuel pin spacing by wire wrapping of the "wire-to-wire" type.

At the low Peclet numbers, the azimuthal temperature non-uniformities for wired pin simulator and for pins spaced by the grids are approximately equal (Fig. 9). However at the high Peclet numbers the difference of the azimuthal temperature non-uniformities for these types of spacing is considerable.

Therefore, all other conditions being equal, fuel pin spacing by transverse grids appears to be the preferred option, in terms of temperature field and heat transfer characteristics, for free-packed fuel pin bundles with a liquid metal coolant as compared to bifilar-helix wrapping of the "wire-to-wire" type.

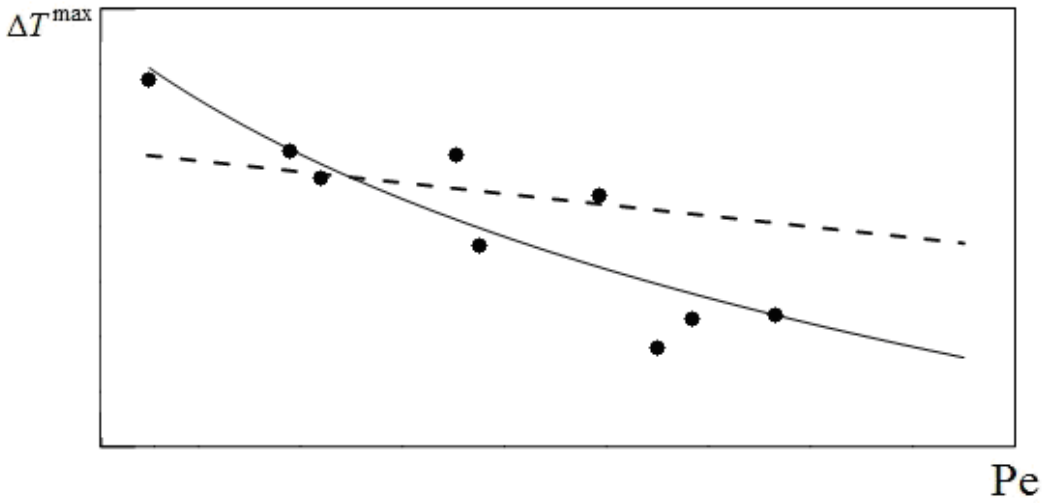

FIG. 9. Schematic dependence of dimensionless general temperature non-uniformities on the Peclet numbers: —●— – experimental data and approximating curve based on readings of the thermocouple inside the spacer grid;- - - - - – major general temperature non-uniformities for the central pin simulator at spacing by wire wrapping of the "wire-to-wire" type spacing [7]/

5. Conclusions

An analysis indicates to the reliable correlations obtained before for the calculation of heat exchange in channels and in smooth fuel pin bundles in idealized conditions of a "pure" coolant. Newly obtained data on the heat exchange in free-packed fuel pin bundles, normally used in lead-cooled fast reactors, indicates to a worsened heat transfer when helical wrapping is used for spacing and to an increased azimuthal non-uniformity of the fuel pin temperature as compared to smooth fuel pins and with transverse grids used as spacers.

6. References

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