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Experimental substantiation of selection of fuel channel imitator for hydrodynamic model of nuclear reactor

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Abstract

Description is given of the methodology for experimental substantiation of hydrodynamic characteristics of imitators of fuel channels in the model of reactor unit with two-loop configuration. It is known from the experience of development of reactor units of different types that it is practically not feasible to select the channel to serve as the imitator with simple geometry for which the dependence of pressure drop due to hydraulic losses would be the same as the dependence for full-scale operating fuel channel containing fuel assemblies. Therefore, only approximate modeling of hydraulic losses in operational fuel channels with fuel assemblies and imitating channels within the limited range of Reynolds numbers can be discussed as well as inclusion of all coolant flow regimes within the reactor vessel predicted by design calculations.

Selection of final geometry of imitating channels was made based on the following several basic assumptions of approximate modeling of flow path in the full-scale fuel channel with fuel assembly under nominal operational mode of the nuclear reactor using the channel with simplified geometry: (1) range of variation of coolant flow rates in the operational fuel channel with fuel assembly in nominal operational mode of the reactor is known from physical and from preliminary thermal physics calculation studies; (2) equality of Euler numbers for nominal coolant flow regimes in the reactor and for coolant flow in imitating channels. Experiments were conducted with three types of imitators and the most suitable among them was chosen as the result. The finally selected design of imitating channel included a pipe with high-quality of manufacturing, two diaphragms and a nozzle with configured using the method suggested by Vitoshinsky.

Keywords: Reactor unit; Hydraulic resistance; Operational fuel channel; Imitating channel; Thermal hydraulic model of nuclear reactor; Reactor core; Fuel assembly; Modeling scale; Geometry distortion of the model; Euler numbers; Reynolds numbers.

Introduction

Development of new reactor facility is usually preceded by experimental studies conducted on model facilities. Geometry characteristics and circulation parameters of the model are found from the condition of satisfaction of respective criteria of model similarity with the full scale device. Only in this case experimental results obtained using the model can be translated on or recalculated for the real full scale facility. Under the selected scale of the model facility satisfaction of even two similarity criteria may result in mutually contradicting requirements imposed on the parameters of circulation in the model. Therefore, those criteria are accepted from numerous similarity criteria which are in correspondence with the main forces (or processes) acting in the full scale facility.

Ensuring strict geometry similarity often leads to the impossibility to achieve under laboratory conditions the required parameters of circulation in the model. The need arises to develop the model with certain geometrical distortions as compared to the full scale modeled device.

In the present study the authors faced specifically such circumstances. Modeled reactor facility (RF) is characterized with comparatively low coolant heating within the reactor

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core volume and with not high working pressure (≈0.3 MPa). Installation in the imitation channels (IC) reproducing full scale operational fuel channels (OFC) of geometrically similar imitators of fuel elements with satisfied Reynolds criterion results in very high pressure drops in the IC and, correspondingly, leads to the necessity to use pumps with unrealistically high and not achievable pressure head.

In accordance with the main objectives of experimental study using hydraulic model of the reactor (namely, the establishment of non-uniformity of flow rates in the OFC) reduced resistance coefficient for the IC must be equal to the reduced resistance factor of the reactor OFC (to satisfy Euler criterion).

Initially full scale reactor OFC with fuel assembly was manufactured, circulation experiments were performed using this OFC and dependence of the total resistance coefficiesnt versus Reynolds number was obtained. Achieving such resistance factor in the IC was accomplished using the effect of interplaying local resistances [1]. The effect is manifested as the difference between the real aggregate resistance coefficient and the sum of tabulated values of local resistances taking into account the distance (location) between the local resistances. Two identical washers with resistance coefficients equal to approximately one half of the resistance factor for the full scale OFC were used as the local resistances in the IC. Aggregate resistance coefficient for Reynolds numbers corresponding to the full scale OFC was determined in the experiment depending on the distance between the washers. Beside the resistances of the washers the aggregate resistance coefficient also includes resistance produced by the nozzle and friction resistance.

The determined distance between the washers was adhered to in the manufacturing all ICs of the reactor OFC. Control circulation run was performed with the manufactured ICs to check similarity of their resistance.

As refers to Reynolds number modeling was implemented approximately, which, however, did not affect the exact satisfaction in the hydraulic model of Euler criterion, since circulation experiments in the full scale OFC with fuel assembly demonstrated that starting from certain values of Reynolds numbers the reduced resistance factor remains practically unchanged. The latter consideration served as the basis for circulation experiments in the ICs with lesser Reynolds numbers as compared with full scale ones.

In order to substantiate the geometry of the experimental model hydraulic pressure drops on separate sections of flow channel of the full scale reactor OFC were experimentally determined and hydraulic testing of prototype ICs was performed beside the determination of aggregate resistance factor for the full scale reactor OFC.

Substantiating experimental studies were implemented using the “Circulation loop” (CL) and “Parallel channels” (PC) thermal hydraulics test facilities of the Department of Thermal Physics of the Obninsk Institute for Nuclear Power Engineering, National Research Nuclear University “MEPhI” and were finalized by the development of dedicated thermal hydraulics test facility with MIR reactor model and by hydraulic testing of this facility. Detailed description of the test facility and its main characteristics are provided in [2–4].

Modeling conditions and selection of scale of hydraulic model

The determining similarity criteria for reactor with forced circulation are Reynolds numbers Re_H and Euler numbers Eu_H. Here and below indices “H” and “m” refer to the full scale and model facilities, respectively.

The main modeling conditions are the following:

- Geometrical similarity of elements of flow channels of the hydrodynamic model (HDM) and the reactor with exception of ICs of the model and the OFC with reactor fuel assembly;
- Equality between hydraulic resistance factors in the elements of in-vessel loop of the model and in the flow channel of the HDM and the respective hydraulic resistivity factors in the elements of in-vessel loop of the model and in the flow channel of the reactor as a whole as follows:

  $\zeta_H = \zeta_M\,(Eu_H = 2\zeta_H = Eu_M = 2\zeta_M)$;
- Similarity of initial and boundary conditions expressed in the geometrical similarity of inlet and outlet manifolds (arrangement of bends);
- Replacement of the incomplete geometrical similarity between the OFC with fuel assembly and the IC by the equality of their hydraulic resistance factors along the lengths of flow channels;
- Determining linear dimension of the HDM is the diameter of the inlet pipe fitting D_M;
- Determining linear dimension of the OFC with fuel assembly is the hydraulic diameter of the OFC D_H.

Input data for modeling are presented below:

- Water flow rate through the reactor $Q_H = 0.460\,m^3/s$ ($G_H = 464.54\,kg/s$);
- $Re_H = 92{,}860$ - Reynolds number calculated for pressure pipe fitting diameter $D400 = 400 \cdot 10^{-3}\,m$;
- Inlet temperature $T_{in} = 50\,°C$;
- Outlet temperature $T_{out} = 70\,°C$;
- Working pressure (superpressure) $P = 0.235\,MPa$;
- Mass of reactor vessel with coolant ≈ 30 t;
- OFC diameter $D_H = 80 \cdot 10^{-3}\,m$;
- HDM mass with water, not more than 800 kg (from the restriction on the mass for installation of the HDM at the INPE NENU “MEPhI”).

Selection of HDM scale is, possibly, one of the most complex modeling problems. Calculation of the modeling scaling factor was implemented as described below. Pressure drop ΔP_H in the flow channel of the in-vessel structure of the RF was calculated as follows:

$$\Delta P_H = \zeta_H \cdot (\rho_H \cdot V_H^2)/2, \quad (1)$$

where ρ_H is the density [kg/m^3]; V_H is the average velocity [m/s]; ΔP is the pressure drop [Pa]; ζ_H is the local resistance factor. Evaluation of pressure drop in the flow channel of the in-vessel structure of the HDM was performed in a similar way:

$$\Delta P_M = \zeta_M \cdot (\rho_M \cdot V_M^2)/2. \quad (2)$$

Ratio of capacities of pumps required for circulating fluid in the RF and in the HDM is equal to:

$$N_H/N_M = (\rho_H \cdot V_H^3 \cdot D_H^2)/(\rho_M \cdot V_M^3 \cdot D_M^2). \quad (3)$$

If the conditions $\rho_H = \rho_M$ and $V_H = V_M$ are satisfied in the experiments, than

$$N_H/N_M = D_H^2/D_M^2 = M^2, \quad (4)$$

where M is the geometrical similarity scale.

Taking into account the equality of densities and velocities we obtain from the ratios of (1) and (2) the following:

$$\Delta P_H/\Delta P_M = (\rho_H \cdot V_H{}^2)/(\rho_M \cdot V_M{}^2) = 1. \quad (5)$$

It is clear from the above ratio that equality of pressure drops in the loops of the model and in the full scale reactor is achieved for any geometrical scale of the HDM.

Ratio of volume flow rates of water through each of the circulation loops in nominal operation mode of the reactor and those for the HDM is equal to:

$$Q_H/Q_M = (V_H \cdot D_H{}^2)/(V_M \cdot D_M{}^2) = M^2. \quad (6)$$

It is assumed hereinafter that the loop of the water-circulation test facility will consist of pipelines with internal pipe diameter equal to 100 mm ($F_M = 7.85\ 10^{-3}$ m^2) because it is not justifiable to apply water circulation velocities in the pipelines in excess of 2 m/s in order to escape the need to undertake special measures for preventing vibrations of pipelines. Flow rate through one loop of the HDM will be equal to:

$$Q_M = F_M \cdot V_M = 2.0 \cdot 7.85 \cdot 10^{-3} = 0.0157\text{m}^3/\text{s} = 56.5\text{m}^3/\text{h}.$$

Approximate value of the HDM geometrical scale is determined from (6):

$$M = (Q_H/Q_M)^{1/2} = (0.2298/0.0157)^{1/2} = 3.83. \quad (7)$$

It was assumed based on (7) that M = 1:4 will be the acceptable geometrical scale for the HDM. With such scaling internal diameter of the IC will be equal to D_M = 20 mm. Reynolds number for water flow in the IC is equal to Re_M = 23215, which satisfies the modeling conditions. We assume below that Re_M = 23,215–23,200.

Calculation substantiation of design of the HDM IC

It is known from the experience of development of models of different types of RF [5] that it is practically not possible to choose ICs with simple geometry for which the dependence of hydraulic pressure losses would be the same as the respective dependence for the full scale OFC with fuel assemblies. In this case fluid flow velocity averaged over the channel cross section in geometrically similar cross sections of the IC and the OFC is understood as the average flow velocity. Therefore only approximate modeling of hydraulic pressure losses in the OFC with fuel assembly and in the IC within limited range of Reynolds numbers taking into account all coolant flow regimes in the reactor vessel can be discussed here.

It was understood without doubt that high-quality pipe must be used as the basis for IC manufacturing. It was necessary to arrange inside the pipe a throttling device with pressure drop values corresponding to pressure drops in the OFC with fuel assembly. The simplest design of the throttling device is a washer with diameter of central bore calculated and tested in experiments. It is also necessary to install inside the pipe the flow restrictor for local increase of dynamic overpressure needed for enhancing accuracy of flow rate measurements in separate ICs of the HDM. The device must satisfy the following two conditions: to have low hydraulic resistance to water flow and to shape uniform velocity field at the outlet from the device. Nozzle with profile configured according to Vitoshinsky [6] satisfies these requirements.

Selection of the final IC geometry was made based on the following several postulates of approximate modeling of flow channel of fill scale OFC with channel having simplified geometry: (1) Range of variation of coolant flow rates in the OFC with fuel assembly is known from physical and preliminary thermal physics calculation studies; (2) Hydraulic pressure losses along the length of the OFC with fuel assembly with coolant circulation in nominal reactor operation mode are known; (3) Internal diameters of IC pipes (D_M = 0.02 m) and OFC pipes (D_H = 0.08) are the determining linear dimensions for the IC and the OFC; 4) Equality of Euler numbers $Eu_H = 2\zeta_H = Eu_M$ with nominal coolant flow regime in the reactor to Reynolds number Re_H and to Re_M number for water flow in the IC.

Simplicity of IC design for ensuring ease of manufacturing in the conditions of mass production (151 items of IC in the HDM) and the need to have IC design allowing achieving the required profiles of flow rates without installation of additional elements are the additional conditions imposed on the IS design.

Results of studies of hydraulic resistance of flow channel of the OC with fuel assembly are presented in Fig. 1 in the form of graphic dependence $\zeta_H = f(Re_H)$ [7]. In accordance with initial data the nominal reactor operation regime corresponded to Re_H = 92860 which, in turn, corresponds to $\zeta_H \approx 142.7$. It was taken in consideration in the HDM design that the highest accuracy of investigations is ensured under the condition of equality of velocities and temperatures in the HDM and in the real full scale reactor. In such case the hydraulic resistance factor for the whole flow channel within the reactor vessel will be constant within comparatively wide range of Reynolds numbers including the value of Reynolds number for the nominal reactor operation regime.

Design calculations made using hydraulic codes demonstrated that flow rates (as well as Reynolds numbers) in the RF for all OFCs with fuel assemblies and for all possible reactor operation regimes can deviate by ±30% from the values

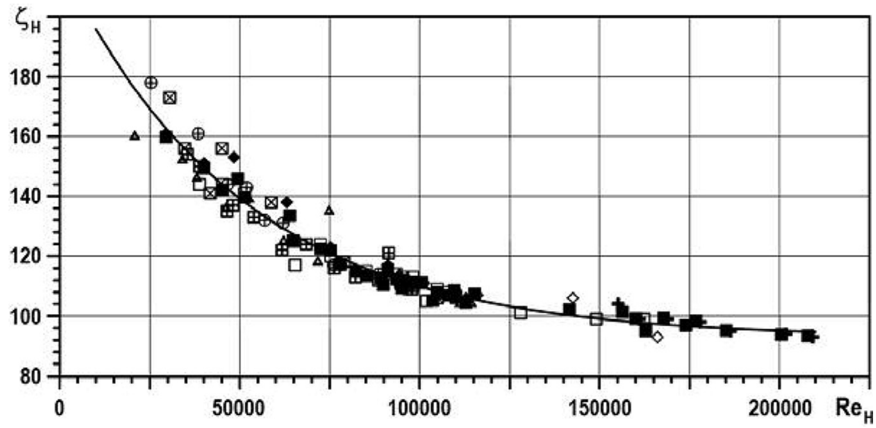


Fig. 1. Dependence of resistance factors for the full scale fuel assembly on the Reynolds number obtained in mass measurements from 16.12.2003 to 06.04.2004 within the range from 20 to 60 °C: $\zeta_{H} = 92.77+125.89\cdot\exp(-Re_{H}/50138.89)$ [7].

Table 1
Basic geometric charactiristics of all IC.

IC type	Channel diameter, mm	Number of washers	Washer bore diameter, mm	Flow restricting device	Washer length, mm	Edge shape
IC-1	25.0 × 2.5	1	8.2–10.0	No	25.0	Sharp
IC-2	25.0 × 2.5 24.0 × 2.50	2	6.9–10.2	No	2.5–10.0	Sharp
IC-3	25.0 × 2.5	2	6.9–7.8	Yes	2.0–10.0	Sharp

Table 2
The geometri of the IC-1.

Single washer				
Item No.	d, mm	L_w, mm	Material	Channel Ø
1	9.0	26.0	Brass	25 × 2.5
2	9.2	26.0	Brass	25 × 2.5

averaged for the reactor core. Thus, the examined range of Reynolds numbers for OFC with fuel assemblies must amount to $Re_H = 63{,}700–120{,}000$, and that for IC to $Re_M = 15900 – 29700$. Within this range the hydraulic resistance factor of model of OFC with fuel assembly varies within the range of $\zeta \approx 104.3–128.1$ (see Fig. 1). Therefore, it is necessary to ensure for the IC within the indicated range fulfillment of the following condition:

$$z_M(15,900 \leq Re_M \leq 29,700) \\ = z_H(63,700 \leq Re_H \leq 120,000).$$

IC design was not known originally. That is why three prototypes characteristics of which are presented in Table 1 were examined in the substantiation of the IC design.

The first prototype (IC-1) is the fuel channel with one washer having increased thickness and length $L_w = 26.0$ mm and different diameters of the central bore: Ø 8.2–10.0 mm (only two washer options are presented in Table 2).

Different options of configuration with two washers having thicknesses equal to 2.5–10.0 mm and central bore diameter equal to 6.9–10.2 mm (Table 3) were examined as the second prototype IC (IC-2).

Washers with offset central bore were tested beside that (Table 3).

Imitator of working fuel channel of the third type (IC-3) included the following elements: fuel channel corresponding to the OFC to scale $M = 1{:}4$; two washers with central bore diameter equal to 6.9, 7.0, 7.2, 7.5 and 7.8 mm and contoured nozzle with length equal to Lw (see Table 3). General appearance of the IC-3 is shown in Fig. 2b.

General appearance of the working section of the "PC" test facility with IC-1 incorporated in its configuration is shown in Fig. 2a.

For prototypes of the second type distance between the washers S varied within the interval of 0–110 mm ("in the light").

It was found out in the calculations that design of IC-1 in the form of combination of fuel channel and single washer does not allow creating the model of OFC with fuel assembly acceptable from the viewpoint of technological feasibility. In connection with this subsequent calculation substantiation of the IC-1 design was not performed.

Calculation substantiation for IC-2 and IC-3 is similar with the only difference being that in case of IC-3 geometry characteristics and nozzle resistance were taken under consideration, i.e. the system consisting of the OFC, two washers with thicknesses equal to $L_w = 8$ mm each and nozzle with length equal to $L_p = 34$ mm was examined. The calculation substantiation consisted of the following.

Calculation of friction resistance coefficient for round channel was performed using Blasius formula and was found to be equal to $\lambda_0 = 0.0257$ (calculation was performed taking average value Re = 23,200). Reduced hydraulic resistance coefficient for the IC was estimated using the following formula:

$$\zeta_f = \lambda_0(LIC–2 \cdot L_w–L_p)/D_{LC},$$

Table 3
The geometri of the IC-2 and IC-3.

Two washers

Item No.	d, mm	L_w, mm	Material	Channel Ø	S, mm
1	6.9	8.0	Brass	25.0 × 2.5	40
2	7.0	8.0	Brass	25.0 × 2.5	20, 40, 50
3	7.0	10.0	Brass	25.0 × 2.5	40
4	7.2	8,0	Brass	25.0 × 2.5	80, 100
5	7.5	8.0	Brass	25.0 × 2.5	35, 40, 60, 80, 110
6	7.8	8.0	Brass	25.0 × 2.5	0, 30, 35, 60, 75, 80
7	8.2	4.2	Brass	24.0 × 2.0	40
8	8.25	4,2	Stainless steel	24.0 × 2.0	40
9	8.5	4.0	Stainless steel	25.0 × 2.5	40
10	8.95	4.2	Stainless steel	24.0 × 2.0	40
11	8.9	4.0	Stainless steel	25.0 × 2.5	40
12	9.0	4,2	Stainless steel	24.0 × 2.0	40
13	9.5	2.5	Aluminum	25.0 × 2.5	40
14	9.5	2.0	Stainless steel	25.0 × 2.5	40
15	10.0	4,0	Stainless steel	25.0 × 2.5	35
16	10.0	4.2	Stainless steel	24.0 × 2.0	40
17	10.0	8.0	Stainless steel	25.0 × 2.5	40
18	10.1	6.0	Brass	25.0 × 2.5	40, 60, 80
19	10.2	4,2	Stainless steel	24.0 × 2.0	40

Two washers+nozzle

Item No.	d, mm	L_w, mm	Material	Channel Ø	S, mm
1	7.0	10.0	Brass	25.0 × 2.5	20, 30, 40, 50, 60
2	7.2	8.0	Brass	25.0 × 2.5	40, 60, 80
3	7.5	8.0	Brass	25.0 × 2.5	35, 40, 60, 80, 100
4	8.0	8,0	Brass	25.0 × 2.5	30, 35, 40, 60, 80

Two washers with offset central bore

Item No.	d, mm	L_w, mm	Material	Channel Ø	S, mm	Angle, °
1	7.0	10.0	Brass	25.0 × 2.5	20, 30, 40, 50, 60	0
2	7.2	8.0	Brass	25.0 × 2.5	40, 60, 80	180

and was equal to $z_f = 1.26$. Hydraulic resistance coefficient for two washers $2{\cdot}\zeta_w$ is equal to the value of hydraulic resistance coefficient for the OFC with fuel assembly ζ_{H} established in the experiments less the hydraulic resistance coefficient for the nozzle ζ_{p} and the reduced resistance coefficient ζ_f as follows:

$$2\cdot\zeta_w = \zeta_{\text{H}}–\zeta_f–\zeta_p = 142.7–1.26-1.7 = 139.74 = 2\cdot 69.87.$$

It was assumed that the calculation which is presented here and was performed in accordance with [1] gives uncertainty equal to $\pm 15\%$.

In this case washer must be selected based on the values of hydraulic resistance coefficients as follows: $69.87{\cdot}0.85 = 59.39 – 80.35 = 69.87{\cdot}1.15$. Thus, the range of variation of hydraulic resistance coefficient of the IC with two washers will amount to $\zeta_{\text{IC}} \approx 120 – 161$.

Reference data [1] were used in the calculation of central bore diameter of the washer. Diaphragm with thickened edges was examined; pipe sections before the washer $F1$ and after the washer $F2$ are identical: $F1 = F2 = 3.14{\cdot}10^{-4}$ m^2. Hydraulic resistance coefficient for the washer was calculated according to the following formula:

$$\zeta_w = (\zeta_{0w} + \lambda_0\cdot L_w/D_w)\cdot(F_{IC}/F_{0w})^2,$$

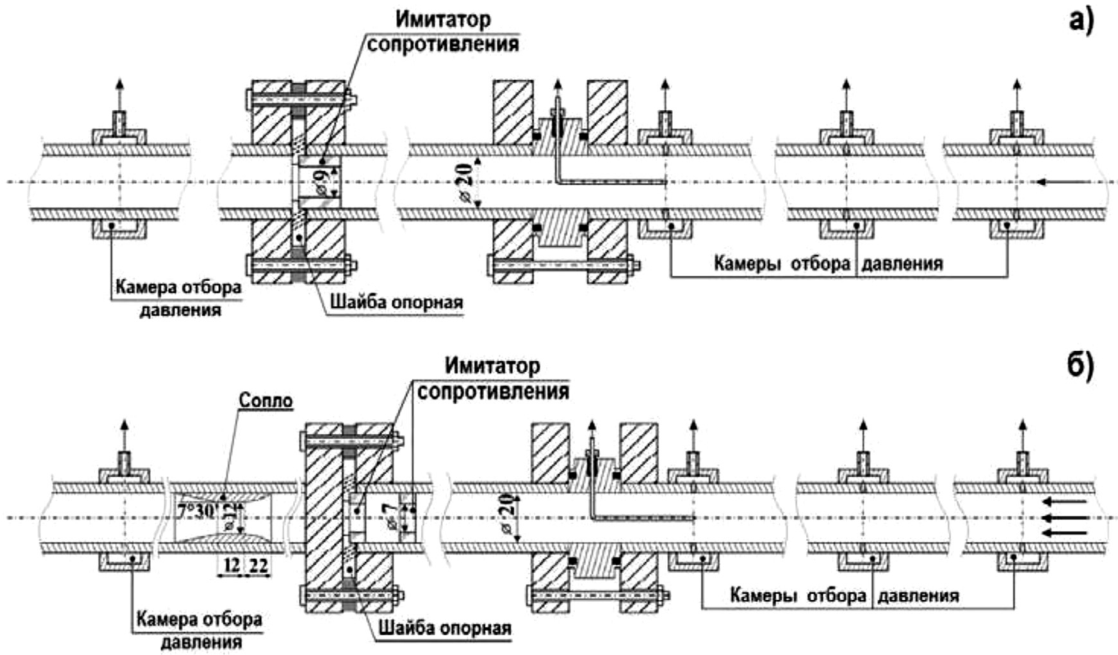
where F_{IC} is the area of the IC cross section; ζ_{0w} is the hydraulic resistance coefficient of the washer without taking into account friction along its length; D_w is the diameter of the bore in the diaphragm; F_{0w} is the area of the cross section with diameter D_w. The value of hydraulic pressure losses inside the washer was ignored because of its smallness.

For simplification of calculations tabulated data on $z_{0w} = f\,(F_{0w}\ /\ F1)$ from reference book [1] were approximated by the following calculation dependence:

$$\zeta_{0w} = f\,(D_w) = 2351-688.8D_w + 69.2D_w{}^2–2.35Dw^3,$$

from which it follows that with $D_w = 7.9$ mm $\zeta_{0w} = 63.4$; with $Dw = 7.7$ mm $\zeta_{0w} = 71.3$; and with $D_w = 7.5$ mm $\zeta_{0w} = 80.5$. Thus, optimal diameter of the washer central bore is within the range of $D_w = 7.5–7.8$ mm. The following analytical formula for calculation of hydraulic resistance coefficient for single washer is provided in reference book [1]:

$$\zeta_{0w} = (1–F_{0w}/F_1)/2 + (1–F_{0w}/F_1)^2 + \tau\cdot(1–F_{0w}/F_1)^{3/2},$$



Имитатор сопротивления	Imitator of resistance
Камера отбора давления	Pressure takeoff chamber
Шайба опорная	Support washer
Сопло	Nozzle
Камеры отбора давления	Pressure takeoff chambers

Fig. 2. Layout of incorporation of IC-2 (a) and IC-3 (b) imitators in the experimental facility in the course of circulation experiments.

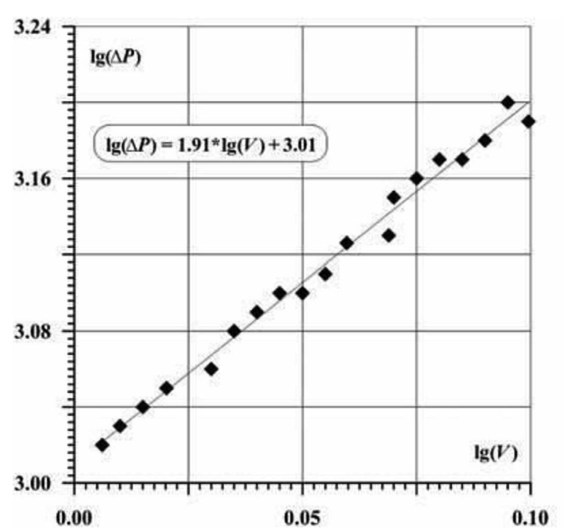
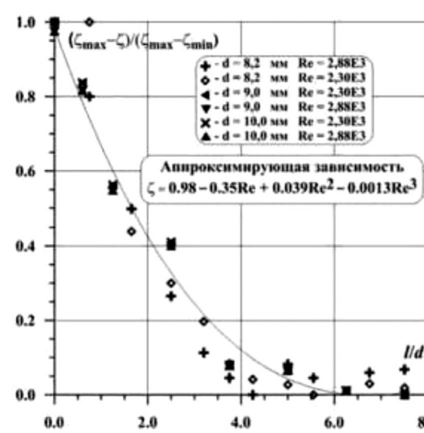


Fig. 3. Experimental dependence lg(DP) = f(lg(V_{cp})).

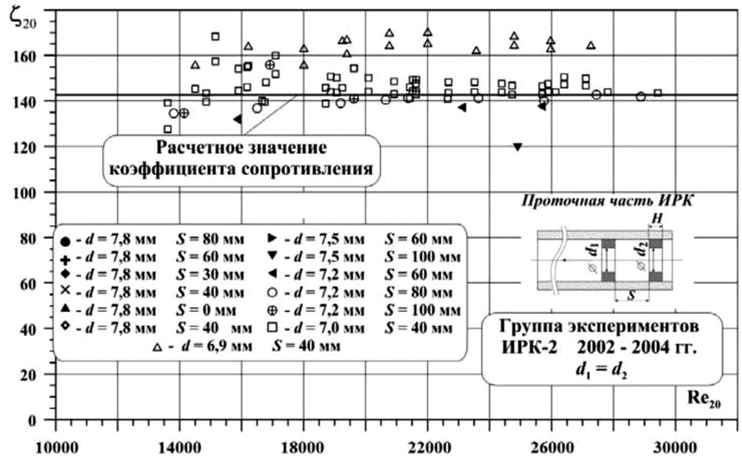


Аппроксимирующая зависимость	Approximation curve

Fig. 4. Dependence of resistance coefficient for IC-2 on Reynolds number and nozzle profile.

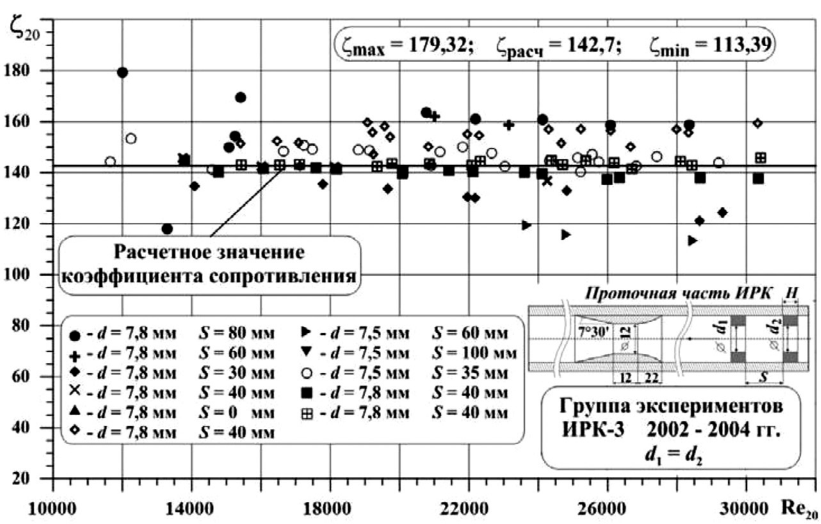
where coefficient τ takes into account the washer thickness. Calculation of hydraulic resistance coefficients using this formula for two central bore diameters $D_w = 7.5$ and 7.8 mm produced the values equal to $\zeta_{0w} = 67.8$ and 57.2, respectively.

Results of calculations performed using the analytical formula demonstrated that when two washers with central bore diameter equal to 7.5 mm are used maximum hydraulic resistance coefficient for the IC will amount to $\zeta_{IC} = 2 \cdot 67.8 + 1.3 + 1.7 = 138.6$. This value is somewhat smaller (approximately by 3%) than the value obtained in the experiments with OFC with fuel assembly. Therefore, this size of washers is suitable (within the limits of uncertainty of experiments) for application in IC.



Расчетное значение коэффициента сопротивления	Calculated value of resistant coefficient
Проточная часть ИРК	Flow channel of the working channel imitator (IRK)
Группа экспериментов ИРК-2 2002 – 2004 гг.	Group of experiments on IRK-2 in 2002 - 2004

Fig. 5. Dependence of resistance coefficient for IC-2 on the Reynolds number.



Расчетное значение коэффициента сопротивления	Calculated value of resistant coefficient
Проточная часть ИРК	Flow channel of the working channel imitator (IRK)
Группа экспериментов ИРК-2 2002 – 2004 гг.	Group of experiments on IRK-3 in 2002 - 2004

Fig. 6. Dependence of resistance coefficient for IC-3 on the Reynolds number.

Selection of distance between the washers was made by iterations by successively increasing the distance between the washers. It was necessary to find as the result of iterations the distance between the washers when hydraulic resistance coefficient for the IC has the value $\zeta_{IC} \approx 142.7$.

Experimental iterative method consisted of calculation of each subsequent value of the distance between the washers using the following formula:

$$S^{i+1} = S^i[69.9\,/\,(\zeta_{IRC}{}^i - 72.8)]^2.$$

In the first approximation the distance between the washers was set to be different but, however, it was not less than $S^1 =$ 20 mm ("in the light"). It was obtained from the calculations that optimal distance between the washers with Ø7.5 mm is equal to 35.0 mm, and that between the washers with Ø7.8 mm is equal to 80.0 mm.

Experimental substantiation of the IC design

Experiments for establishing the resistance coefficient for the IC for modeling resistance of the OFC with fuel assembly were carried out on the "Parallel channels" experimental facility at the Department of Thermal Physics of the Institute for Nuclear Power Engineering, National Research Nuclear University "MEPhI", described in details in [2].

Since it was not possible to draw any final conclusion about the dimensions of central bore of the washers and the distance between the washers based on the estimation calculations, experiments were performed with several options of ICs where washers with central bore diameters equal to 7.0, 7.2, 7.5 and 7.8 mm and with varying distance between the washers were used.

Layout of incorporation of the IC-2 and IC-3 in the configuration of the experimental facility is presented in Fig. 2b. Nozzle entrance section of the IC-3 had the profile configured using Vitoshinsky's formula [6] as follows:

$$r = R_0/(1-(1-(R_0/R_1)^2)\cdot(1-3(x/a)^2)/(1+(x/a)^2))1/^2,$$

where r, R_0 and R_1 are the current, exit (in the working section) and entrance radii of convergent nozzle; x is the longitudinal coordinate along the convergent nozzle axis. Value a having linear dimension is determined based on the convergent nozzle length L and is taken to be equal to

$$a = \sqrt{3}L.$$

Length L was chosen to be equal to $4R_0$. With $x = 0$, $r = R_1$; with $x = L$, $r = R_0$. In our case $R_1 = 10\cdot10^{-3}$ m and $R_0 = 6\cdot10^{-3}$ m. Cylindrical section of the nozzle had the length equal to 8.0 mm. For preventing flow breakdown from the wall the exit section of the restricting device had tapered shape with angle on top equal to 15°. Results of experimental determination of hydraulic smoothness of the channel are presented in Fig. 3, and results of circulation runs of IC-1 are shown in Fig. 4. It was discovered in the course of experimenting with IC-1 that its design does not satisfy the preconditions for approximate modeling and was excluded from further examination.

Based on the analysis of circulation runs of IC-2 and IC-3 diameter of central bore of the washers was taken to be equal to $D_w = 7.8$ mm with distance between the washers equal to 40 mm; the value of resistance coefficient $z_{IC} = 142$ corresponds to this geometry. Configuration of IC-3 was selected as the base design.

All ICs (151 pieces) of the hydraulic model were manufactured with installation of two washers with the geometry and distances between the washers established as the result of the present studies.

Conclusion

Selection of geometry of the IC imitating the hydraulic model of reactor with resistance coefficient equal to resistance of operating fuel channel with fuel assembly of the real full scale reactor was substantiated by experimental method.

The substantiated design of the IC allowed performing measurements of flow rates in the ICs in a convenient and straightforward manner using the "frame" probe developed at the Department of Thermal Physics of the INPE NENU "MEPhI" by introducing the probe in the central part of the nozzle structure [8].

The developed methodology allows reaching the required values of resistance coefficients in the ICs of fuel assemblies in the development of hydraulic models of reactor cores with other fuel assembly configurations.

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References

[1] I.E. Idelchik, Spravochnik po gidravlicheskim soprotivleniyam (Reference Book on Hydraulic Resistances), Mashinostroenie Publication, Moscow, 1975, p. 559. in Russian.
[2] E.F. Avdeev, I.A. Chusov, A.Ya. Ustyuzhanin, V.V. Maksimovskiy, D.S. Lazikyan, V.A. Levchenko, S.V. Borodastov, I.N. Leonov, V.A. Belugin, Yu. D. Levchenko, Yu. S. Yur'ev, Yadernaya Energetika 4 (2004) 70–83 in Russian.
[3] E.F. Avdeev, I.A. Chusov, V.A. Levchenko, Yu. D. Levchenko, Yu. S. Yur'ev, Yadernaya Energetika 4 (2005) 77–85 in Russian.
[4] E.F. Avdeev, I.A. Chusov, V.I. Belozerov, Proceedings of the VI International Conference "NPP Safety and Training of Personnel", Book of abstracts, Obninsk, October 4-8, 1999, p. 43.
[5] M.S. Fomichev, Eksperimentalnaya gidrodinamika YaEU (Experimental Hydrodynamics of Nuclear Power Installations), Energoatomizdat, Moscow, 1989, p. 246.
[6] G.N. Abramovich, Turbulentnoe smeshenie gazovyh struy. (Turbulent Mixing of Gas Jets), Nauka Publishers, Moscow, 1974, p. 272.
[7] E.F. Avdeev, I.A. Chusov, V.A. Levchenko, Yadernaya energetika 3 (2005) 69–80 str.
[8] G.N. Abramovich, Prikladnaya gazovaya dinamika. (Applied Gas Dynamics), 1, M.: Nauka, 1987, p. 537.