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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 $\mathrm{Re_H}$ and Euler numbers $\mathrm{Eu_H}$. 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:

  $\zeta_H = \zeta_M\,(\mathrm{Eu_H} = 2\zeta_H = \mathrm{Eu_M} = 2\zeta_M)$;
- 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 $Q_H = 0.460\,\mathrm{m^3/s}$ ($G_H = 464.54$ kg/s);
- $\mathrm{Re_H} = 92{,}860$ - Reynolds number calculated for pressure pipe fitting diameter $D400 = 400\cdot10^{-3}$ m;
- Inlet temperature $T_{in} = 50\,°\mathrm{C}$;
- Outlet temperature $T_{out} = 70\,°\mathrm{C}$;
- Working pressure (superpressure) $P = 0.235$ MPa;
- Mass of reactor vessel with coolant ≈ 30 t;
- OFC diameter $D_H = 80\cdot10^{-3}$ 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:

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