Conference Paper

Possibility of Simulating Forced Convection in Fast Neutron Reactors Using a Light Water Test Facility

V. I. Slobodchuk, E. A. Avramova, E. M. Shchennikova, and D. A. Shal'kov

Obninsk Institute for Nuclear Power Engineering of the National Research Nuclear University MEPhI, Studgorodok 1, Obninsk, Kaluga region, 249040, Russia

Abstract

The paper evaluates the possibility of modeling the heat transfer phenomena in a liquid-metal coolant using a light water test facility. A large nuclear power reactor (like the BN-1200 project) was selected as a reactor installation to be modeled. To validate the model, the similarity theory and the "black box" method were used. The paper uses the experience of a number of researchers in this field, in particular, the accepted assumptions which do not result in serious loss in modeling accuracy. The governing criteria of similarity were estimated based on the fundamental differential equations of convective heat transfer, so were the conditions under which it is possible to model sodium coolant by using light water with adequate accuracy. The paper presents the scales of the parameters used for the model - reactor comparison. Dependence curves of certain scales with regard to others are constructed, and the possibility of achieving similarity of certain parameters in modeling was estimated. Recommendations are provided on designing a water test model of the BN reactor and on carrying out experiments using this test model.

Corresponding Author:
V. I. Slobodchuk
slobovic@mail.ru

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1. INTRODUCTION

Currently, a number of programs are underway whose purpose is to develop reactor designs which would enable closing the nuclear fuel cycle. For example, according to the Generation-4 Forum, six reactor designs have been chosen, four of which are fast neutron reactors, including those with sodium coolant. Experts believe that fast neutron reactors will play a major role in the new structure of the nuclear industry.

Engineering difficulties in developing fast neutron reactors stem from some of their inherent features. To solve all the problems which arise as a result of these features and to develop the breeder reactor technology, extensive research and development (R&D) programs are required.

Recently, the State Atomic Energy Corporation ROSATOM has made its purpose to solve the problem of closing the nuclear fuel cycle by launching a commercial BN -1200 fast neutron power unit.

A great number of research and development programs were completed from 2010 to 2014 to identify the main parameters and to validate the technological solutions for the power unit which could achieve high technical and economical characteristics and ensure safety. The results of the R&D work were summarized in the design project documentation for the BN-1200 power unit developed in 2014, and the technical project of the K-1200-16/50 turbine installation [1–3, 6].

It should be noted that many countries with fast neutron reactor programs chose sodium as a coolant. The advantages of the sodium coolant are many. These include improved neutron-physical and thermal-hydraulic characteristics, compatibility with different structural materials, relative simplicity of maintaining coolant quality during reactor operation, as well as relatively low cost. However, sodium has a serious drawback. It is very chemically active. When in contact with water, it reacts violently releasing a great amount of energy and hydrogen.

In spite of all the advantages of sodium as a coolant in power installations, its use in test facilities has certain limitations. It requires an additional system of heating and purifying sodium with cold traps, electromagnetic pumps make the technological schemes more complicated and deviations in their operation may affect the results of experiments.

Taking this fact into account, it was proposed to perform approximate modeling of thermal hydraulic processes in fast neutron reactors by using water test facilities based on the similarity theory [7, 11]. This would allow elucidating the physics of the processes occurring in the sodium circuit. The results of this research would also make it possible to simplify the process of experimental modeling, e.g. the process of cooling down the fast neutron reactors [4, 5, 7, 14-20].

The B-200 mockup is considered as a water test facility modeling the BN-1200 reactor in a 1:10 scale. Its structure reflects the circulation scheme of the coolant in the primary circuit of a fast neutron reactor both at rated power and in the cool-down mode. The layout of the equipment in the test facility is very similar to the layout of the design basis equipment of the fast neutron reactor. At present the B-200 water test facility is designed to carry out research in the field of calculation and experimental validation for performing the heat removal function by the emergency core cooling system applied for the BN-1200 reactor.

The similarity theory is applied since it helps to overcome certain difficulties related to numerical and experimental methods. One of these is obtaining disconnected and incomplete dependences whose generalization is made extremely difficult by a great number of arguments on which the target value depends. The similarity theory sets conditions for the similarity of physical phenomena, and thus makes it possible to reduce the number of variables. It provides rules for a rational combination of physical values into dimensionless complexes, the number of which is substantially less than the number of the values they consist of. These complexes can be regarded as new generalized variables.

Since all the terms of the equations are measured in the same units, all the scales of effects have identical dimensionality. Therefore, dividing all the terms of the equations by one of the scales one can obtain the equation in a dimensionless form. As a result, dimensionless complexes of physical values are derived which are called the governing criteria of similarity. The governing criteria of similarity consist of values under single-valued conditions. Therefore, they can be calculated while formulating the problem, without solving it or conducting experimental research.

To close the system of the scales obtained from characteristic values for forced convection, it is necessary to find the relations between them. The problem concerned was solved by the Japanese scientists Eguchi Y., Takeda H., Sasaki K. et al. [4, 5] by making a number of assumptions and, therefore, losing somewhat in the modeling accuracy. Taking these assumptions into account, the core and the heat exchangers were considered to be “black boxes” which have certain hydraulic resistance and a uniform volume heat source or heat sink (fig.1). From the modeling experience and expert evaluation, the authors of the method consider the accuracy of the calculation acceptable for practice and compatible with the accuracy of the calculations made by verification codes.

2. ANALYSIS OF DIFFERENTIAL EQUATIONS

Convective heat transfer equations in the Boussinesk approximation are as follows:

the continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

the momentum equation

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{x_j} = \nu \frac{\partial^2 u_i}{\partial x_j^2} + \beta \left(T - T_0\right) g\delta_{i3} - \frac{\partial P}{\partial x_i} + f\Omega \tag{2}$$

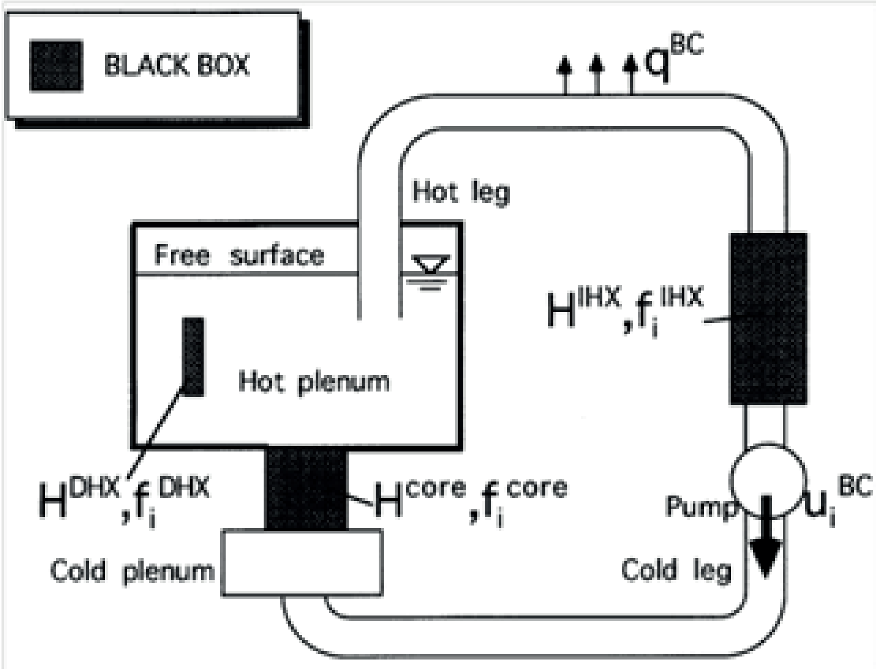

Figure 1: The reactor core and the heat exchanger as "black boxes".

the energy equation

$$\frac{\partial T}{\partial t} + u_j \frac{\partial T}{x_j} = a \frac{\partial^2 T}{\partial x_j^2} + \frac{Q}{\rho C}\Omega \qquad (3)$$

Here, u_i, u_j are coordinates, m; u_i, u_j are velocity components, m/s; t is time, s; ν is the kinematic viscosity coefficient, m^2/s; β is the coefficient of temperature volume expansion, $^{\circ}$C^{-1}; T is temperature, $^{\circ}C$; T_0 is initial temperature, $^{\circ}C$; g is gravity acceleration, м/с^2; δ_{i3} is Kronecker delta $[\delta_{i3} = 1\,(if\ i = j)\,, \delta_{i3} = 0\,(if\ i \neq j)]$; P is pressure, Pa; f is force of friction resistance in the "black box", N/kg; Ω is coefficient in equations which is equal to 1 only in the "black boxes"; $a = \frac{\lambda}{\rho}$ is the thermal diffusivity coefficient, m^2/s; λ is thermal conductivity, W/(m*K); Q is power, W; ρ is density, kg/m^3; is specific heat, J/(kg*K).

Let us consider the following dimensionless variables:

$$t^* = \frac{tU}{L}, u_i^* = \frac{u_i}{U}, u_j^* = \frac{u_j}{U}, x_i^* = \frac{x_i}{L}, x_j^* = \frac{x_j}{L}, P^* = \frac{P}{\rho U^2}, T^* = \frac{T - T_0}{\Delta T},$$

where U is characteristic velocity, m/s; L is characteristic dimension, m; ΔT is characteristic temperature difference, ,$^{\circ}C$.

Substituting these variables in (1) – (3) gives differential equations in a dimensionless form:

$$\frac{\partial u_i^*}{\partial x_i^*} = 0; \qquad (4)$$

$$\frac{\partial u_i^*}{\partial t^*} + u_j^* \frac{\partial u_i^*}{\partial x_j^*} = \left(\frac{\nu}{UL}\right) \frac{\partial^2 u_i^*}{\partial x^{*2}{}_j} + \left(\frac{\beta \Delta T g L}{U^2}\right) T^* \delta_{i3} - \frac{\partial P^*}{\partial x_i^*} + \left(\frac{fL}{U^2}\right) \Omega; \tag{5}$$

$$\frac{\partial T^*}{\partial t^*} + u_j^* \frac{\partial T^*}{\partial x_j^*} = \left(\frac{a}{UL}\right) \frac{\partial^2 T^*}{\partial x^{*2}{}_j} + \frac{Q}{\rho C U \Delta T L^2} \Omega. \tag{6}$$

The average velocity U^p in supplying pipe and heat losses Q^l can be considered as boundary conditions. The velocity is taken equal to zero at the fluid-solid boundary. Differential equations and boundary conditions give the following similarity criteria:

$$\begin{gathered} \frac{\nu}{UL} = \frac{1}{Re} = N_1; \frac{\beta \Delta T g L}{U^2} = Ri = N_2; \frac{fL}{U^2} = N_3; \frac{a}{UL} = \frac{1}{Pe} = N_4; \\ \frac{Q}{\rho C U \Delta T L^2} = N_5; \frac{Q^l L}{\rho C a \Delta T} = N_6; \frac{U^p}{U} = N_7 \end{gathered} \tag{7}$$

Here $Re = \frac{UL}{\nu}$ is the Reynolds criterion, $Pe = \frac{UL}{a}$ is the Peclet criterion, $Ri = \frac{\beta \Delta T g L}{U^2}$ is the Richardson criterion.

Criterion N_3 can be written in a more convenient form by introducing the pressure drop ΔP:

$$k_1 \rho L^3 f = k_2 L^2 \Delta P, \tag{8}$$

where $k_1 \rho L^3$ and $k_2 L^2$ are mass and cross-sectional area of the flow in the "black box";k_1, k_2 are coefficients of proportionality.

Hence, $f = k_3 \frac{\Delta P}{\rho L}$, $k_3 = \frac{k_2}{k_1}$. Coefficients $k_1 - k_3$ are common for the model and the reactor because of geometric similarity of the "black boxes". Substituting this expression for f into the N_3 criterion we obtain:

$$N_3 = k_3 \frac{\Delta P}{\rho L} \frac{L}{U^2} = k_3 \frac{\Delta P}{\rho U^2} = k_3 \frac{\xi}{2}, \tag{9}$$

where ξ is the coefficient of friction resistance.

So, the N_3 criterion is equal to the Euler criterion in the "black box", i.e.

$$N_3 = \frac{\Delta P}{\rho U^2} = Eu = \frac{\xi}{2}. \tag{10}$$

Hence, it follows from the above that in modeling it is necessary to ensure equality of the coefficient of friction resistance in the reactor and in the model. Dealing with the velocity value and the equivalent "black box" diameter, it is possible even at the stage of designing the model core to choose the optimum number of the rods, their diameter and tube diameters, the lattice pitch and more.

3. OBTAINING THE SCALE OF PARAMETERS

The similarity criteria (7) include the characteristic values of U, ΔT, L and thermal physics properties of the coolant. Due to the N_5 criterion, it is possible to determine the scales of parameters in the model if similarity is satisfied according to the N_2, N_5, N_7 criteria. As regards the N_6 criterion, it is rather difficult to satisfy similarity by using it. It is due to lack of reliable data on heat losses in the reactor under development. Thus, the main similarity criteria are:

$$Ri = \frac{\beta \Delta T g L}{U^2}, N_5 = \frac{Q}{\rho C U \Delta T L^2}, N_7 = \frac{U}{U}.$$

To obtain the scales of power, velocity and other parameters which characterize thermal hydraulic processes under forced convection mode it is necessary to make the dimensionless criteria N_2, N_5, N_7 equal for the model and for the reactor. As a result,

$$\frac{U_m}{U_r} = \frac{U_m}{U_r} \text{ – from the equality of the N}_7 \text{ criteria,} \quad (11)$$

$$\left(\frac{\beta \Delta T g L}{U^2}\right)_m = \left(\frac{\beta \Delta T g L}{U^2}\right)_r \text{ – from the equality of the } Ri \text{ criteria,} \quad (12)$$

$$\left(\frac{Q}{\rho C U \Delta T L^2}\right)_m = \left(\frac{Q}{\rho C U \Delta T L^2}\right)_r \text{ – from the equality of the N}_5 \text{ criteria.} \quad (13)$$

The indices *m* and *r* correspond to the model and the reactor, respectively. From the available expressions it is possible to obtain the following correlations:

$$\text{the scale of velocity } \frac{U_m}{U_r} = \left(\frac{\Delta T_m}{\Delta T_r}\right)^{0,5} \left(\frac{(\beta g L)_m}{(\beta g L)_r}\right)^{0,5}, \quad (14)$$

$$\text{the scale of power } \frac{Q_m}{Q_r} = \frac{\Delta T_m}{\Delta T_r} \frac{U_m}{U_r} \frac{\left(\rho C L^2\right)_m}{\left(\rho C L^2\right)_r}, \quad (15)$$

correlation between the power scale and the scales of heating up and thermal-physics properties

$$\frac{Q_m}{Q_r} = \left(\frac{\Delta T_m}{\Delta T_r}\right)^{1,5} \left(\frac{\left(\beta g \rho^2 C^2 L^5\right)_m}{\left(\beta g \rho^2 C^2 L^5\right)_r}\right)^{0,5}, \quad (16)$$

$$\text{the pressure scale } \frac{P_m}{P_r} = \frac{\Delta T_m}{\Delta T_r} \frac{(\rho \beta g L)_m}{(\rho \beta g L)_r}, \quad (17)$$

$$\text{the time scale } \frac{t_m}{t_r} = \left(\frac{\Delta T_m}{\Delta T_r}\right)^{-0,5} \left[\frac{\left(\frac{\beta g}{L}\right)_r}{\left(\frac{\beta g}{L}\right)_m}\right]^{0,5}, \quad (18)$$

$$\text{the scale of the Peclet criteria } \frac{Pe_m}{Pe_r} = \left(\frac{\Delta T_m}{\Delta T_r}\right)^{0,5} \left[\frac{\left(\frac{L\beta^3 g^3}{6}\right)_m}{\left(\frac{L\beta^3 g^3}{6}\right)_r}\right]^{\frac{1}{6}}, \quad (19)$$

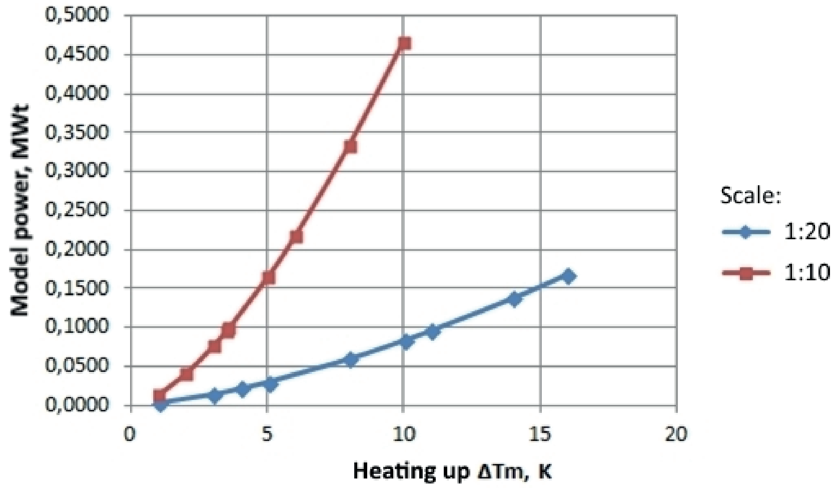

Figure 2: Dependence of the model power on the heating up.

the scale of the Reynolds criteria $\frac{Re_m}{Re_r} = \frac{Pr_r}{Pr_m}\left(\frac{\Delta T_m}{\Delta T_r}\right)^{0,5}\left[\frac{\left(\frac{L\beta^3 g^3}{6}\right)_m}{\left(\frac{L\beta^3 g^3}{6}\right)_r}\right]^{\frac{1}{6}}$, (20)

where Pr is the Prandtl criterion.

4. NUMERICAL ESTIMATIONS

The derived scales of power, velocity and other parameters which characterize thermal hydraulic processes under forced convection mode can be used to derive the corresponding parameters in the reactor from the data obtained by using the model, and vice versa. The inverse procedure in the current work is necessary to study the possibility of using the B-200 test facility to model the processes in the BN-1200 reactor.

Since the relationship between heating up in the model and in the reactor is an argument in all the expressions for scales, by constructing the corresponding curves it is possible to determine the range of parameter changes and their approximate values and to establish the conditions under which modeling at the B-200 test facility is possible.

The estimation is performed using the properties of water and sodium [9, 10, 13] at average temperatures at the B-200 test facility and the BN-1200 reactor, at 50% N_{nom} (1400MW (th)), as well as for the 1:10 geometric scale (B-200 test facility) and for the 1:20 scale (for comparison). The available scale expressions (11) - (20) can be used to construct the following dependence curves (presented below).

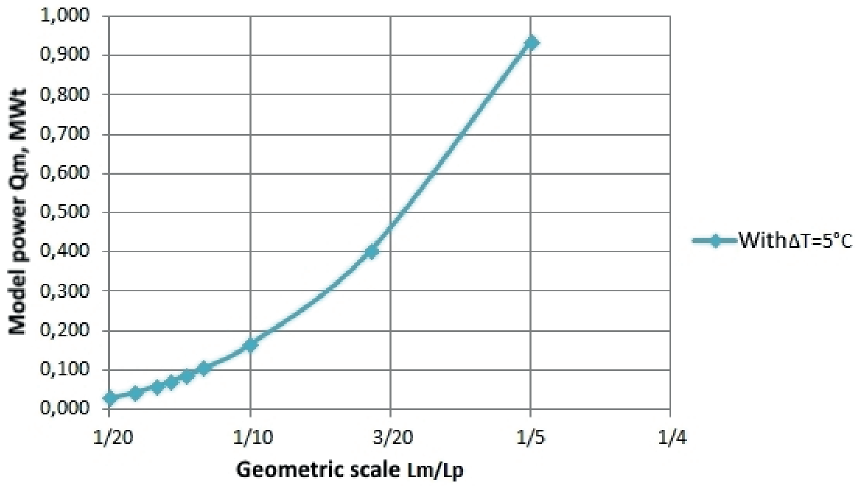

Figure 3: Dependence of the model power on the geometric scale.

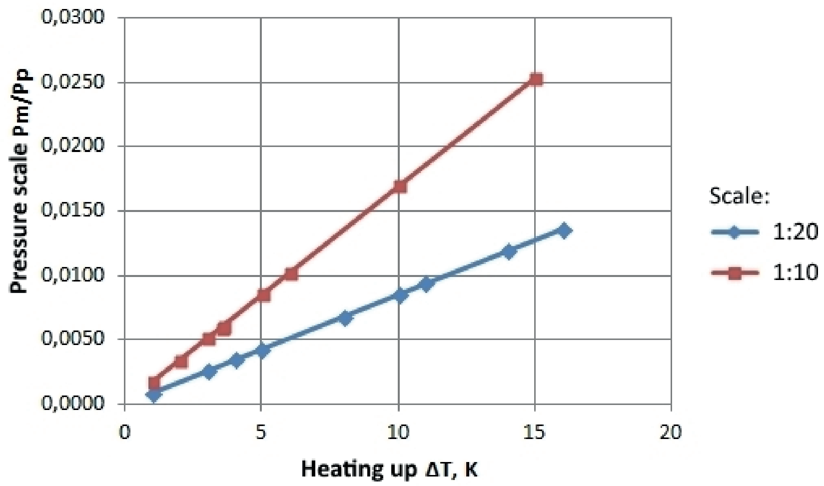

Figure 4: Dependence of the pressure scale on heating up in the model.

It can be seen in fig.2 that reliable modeling at the installation having the 1:10 scale is possible with heating up exceeding 3-5 °C. It is necessary to provide the installation power more than 80 kW. For the model which is smaller in scale, this power will amount to about 15 kW, which is more convenient from the theoretical point of view but is difficult to accomplish technically. From the curves in fig.3 it is clear that it is theoretically expedient to make small scale models to reduce the power and increase the heating up to acceptable values.

According to the curves in fig. 4-6 it is very difficult to achieve similarity by using the pressure and Peclet criteria, and it is practically impossible to achieve similarity by using the Reynolds criterion.

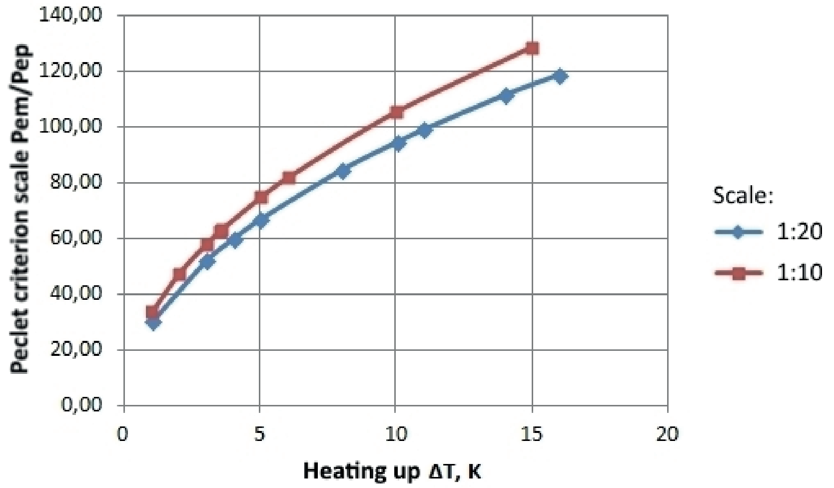

Figure 5: Dependence of the Peclet criterion scale on heating up in the model.

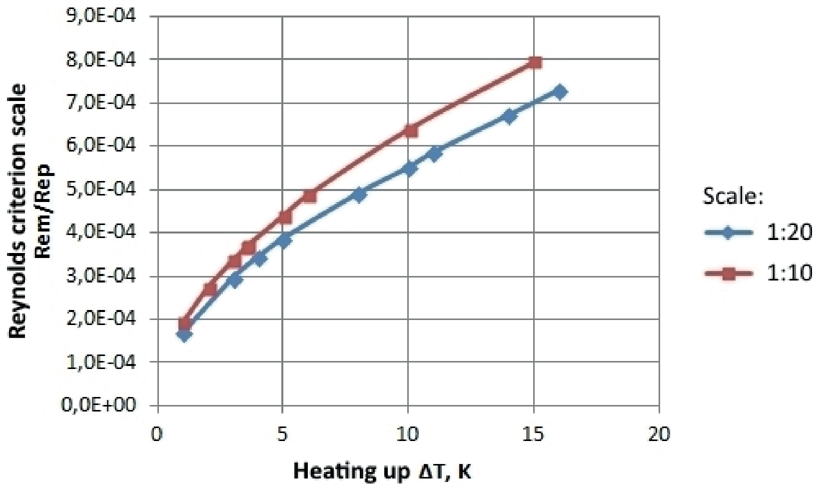

Figure 6: Dependence of the Reynolds criterion scale on heating up in the model.

5. RECOMMENDATION FOR EXPERIMENTS AT THE B-200 INSTALLATION

The results of numerical estimations make it possible to formulate the conditions necessary to create a BN-1200 water test model and to draw up some recommendations for the experiment using the B-200 test facility with due account of its characteristics.

The general conditions for the BN-1200 water test model are as follows:

1. The minimum geometric scale which is technically feasible;
2. the power level resulting in appreciable heating up;
3. choosing the above parameters so that the Peclet criterion is as small as possible;

4. choosing the model core parameters so that the coefficient of friction resistance in the model and that in the reactor coincide.

Recommendations for conducting experiments at the B-200 installation

1. to correct the friction resistance values, to measure them;
2. to set the turbulent flow mode;
3. to increase the power of the heaters step by step, with time delays at each step to stabilize the temperature in the primary circuit (to estimate the dependence of heat losses on the temperature level);
4. to set the heating up level of ≈3.6 °C, regulating the flow rate and changing the power of the heaters and flow rate of the primary circuit, with the integral power of all the imitators amounting to 100 kW;
5. to measure the temperature and velocity distribution.

The above recommendations can make possible approximate modeling of thermal hydraulic processes in the BN-1200 reactor using the B-200 test facility.

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