A simulation study of processes for mixing non-isothermal flows under dynamic effects

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The processes for mixing of non-isothermal streams essentially define the parameters of the heat-carrier on an input in a core in modes with incomplete structure of the working equipment and, as a consequence, - a heat engineering condition of a core. Besides, the task of researching the temperature pulsations accompanying practically all modes of currents for non-isothermal streams is extremely relevant, as these pulsations lead to additional thermocyclic loadings on elements of the equipment and in many cases define its resource. The paper describes the research of mixing processes for non-isothermal water coolant flows in hydraulic model of ship nuclear power plant. In several experiments, attention was paid to the mixing processes when feeding non-isothermal flows through the circulation loops located opposite of each other. To simulate the effect of external dynamic force in the form of periodic effect on the spatial orientation of the model, the ship was tested on a stand "Swinging platform". These vibrations affected the mixing processes occurring within the model. The main impact they had on the transition time, temperature gradient, vertical component of the velocity projection. In the future, these parameters will be clarified and the influence of other factors on the mixing of non-isothermal flows in the ship's nuclear power plant will be studied in more detail.

Key words: *non-isothermal stream, the ship's nuclear power plant, core simulator, the mixing.*

1. Introduction

Reaction of the reactor core to perturbation of reactivity, which occurs due to a decrease in concentration of liquid absorber (boric acid) or temperature of coolant in one of loops of the first circuit essentially depends on degree of mixing with other unperturbed loops [1].

The work of nuclear power plant in transitional modes requirements on reliability of heat removal from reactor core and its safety should be fulfilled. The main transitional modes of operation of reactors of pressurized water reactor (PWR) type are operation at sudden decrease of the heat-carrier flow due to shutdown of the circulation pump of the 1st circuit and operation of nuclear power plant at resetting of electric load or shutdown of turbine-generator [2].

Mixing processes are investigated by several scientific groups, including abroad. The result of their work were experimental installations: ROCOM (Germany), Vattenfall (USA), Fortum PTS (Finland), OKB "HYDROPRESS" (Russia).

Thus, at the HYDROPRESS stand the experiments were carried out on a four-loop model of the VVER-1000 reactor on a 1:5 scale [3].

It should be noted that most of the phenomena occurring in the systems under consideration can be studied with a sufficient degree of representativeness on small-scale models, from which a significant amount of information can be obtained [4].

All models involved mixing processes only in stationary modes on PWR-type reactor plants.

During operation the ship's reactor plant is subject to external dynamic forces of a different nature [5]. The ship is practically constantly under the influence of external dynamic forces influencing its spatial orientation both in normal operation and especially in emergency situations. In this paper, the effect of the periodic rocking phenomenon will be investigated.

The main impact of rocking in nuclear power plant is on the reactor and steam generator, as well as heat exchangers of mixing type, where non-isothermal mixing of flows takes place, which can negatively affect the operating modes of nuclear power plant. Also modern tendencies of nuclear power plant safety lead to the development of autonomous methods of chilling, natural circulation (NC) [6]. Due to the complexity of this process, which depends on many factors, the swinging also has a negative impact on it.

2. Materials and methods

Several small-scale models of the ship's nuclear power plant hydraulic path were used to study the processes of nonisothermal flows mixing. In [7-9] the mixing processes taking place in the single-network mixing model were described. It consists of one of four circulation loops. The nuclear power plant KLT-40 [10] (a shipboard nuclear power plant installed on a floating nuclear power plant ("Akademik Lomonosov"), as well as the icebreakers "Taimyr" and "Vaigach" and the light carrier ("Sevmorput") were taken as a prototype chosen for the modeling.

The circulation loop in this work is understood as a hydraulic path (from the entrance to the model (inlet nozzle)), a standpipe, a ring gap, a pressure collector, an imitator of the active zone (made in the form of hydraulic resistance - hole sheet (scale 1:5)) and an outlet nozzle.

The study of temperature distribution fields in characteristic areas of mixing was used as a main method of investigation. This is achieved by building a layer-by-layer picture of temperature distribution, which is done by changing the vertical coordinate of sensors located on the flow mixing path.

This work has identified the key factors that affect these processes. The influence of external dynamic force on the mixing of non-isothermal flows was also assessed.

However, this model required more detailed improvement and approaching to the real hydraulic path of the ship's nuclear power plant. Mixing issues, occurring during operation / disconnection of circulation loops, are also particularly interesting research topics.

To solve these problems, a four-loop stand was proposed to study the processes for mixing non-isothermal flows. The main technical characteristics of the stand are presented in table 1.

Table 1. Main parameters of the experimental stand

Parameter	Amount
Simulated reactor plant	KLT-40 - 1:5
Number of simulated circulation loops	4
The number of measuring probes in the simulator	19-38
The number of probes for monitoring the preparation of injections of media	6
Flow sensors	4
Number of level sensors	3
Reinforcement elements	15
Injection temperature	10-90°C

The general view of the stand is shown in fig. 1, and the fuel assembly simulator is shown in fig. 2.

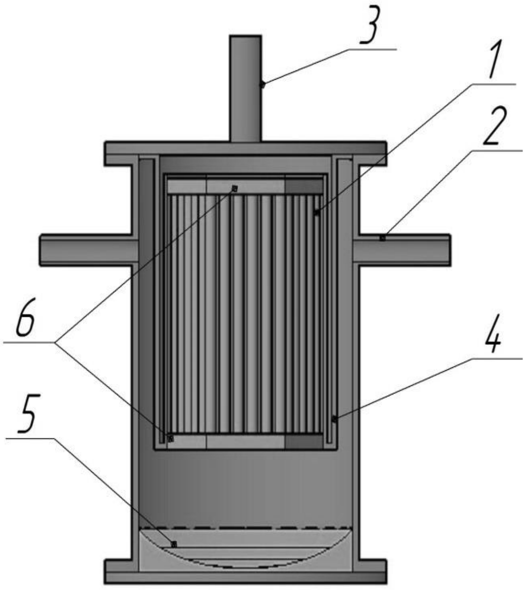

Fig. 1. General view of the research stand: 1 – fuel assembly simulator; 2 - pipe of the coolant inlet; 3 - pipe of the coolant outlet; 4 - shells; 5 - elliptical insert; 6 - remote grates)

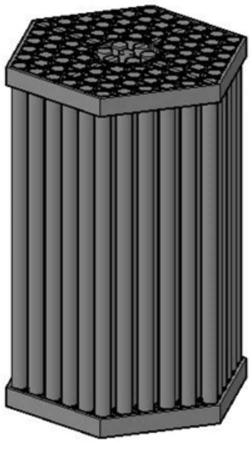

Fig. 2. Fuel assembly simulator

Similarity of processes in a natural reactor and in a model is observed under condition of geometrical, dynamic and thermal similarity. Similarity of heat transfer (as basic process in work) is observed under condition of equality of numbers Pekle (Pe) in model and in natural object:

$$Pe = \frac{v \cdot l}{a} = Re \cdot Pr, \quad (1)$$

where v - flow velocity; l - characteristic size; a - temperature diffusivity coefficient; Re - Reynolds number; Pr - Prandtl number.

The Pe_{mod} number for our model is calculated:

$$Pe_{mod} = Re_{mod} \cdot Pr_{43} \approx 22 \cdot 10^3 \cdot 4.07 \approx 8.95 \cdot 10^4, \quad (2)$$

where the number Pr is taken for the average temperature in steady-state mode (43^{0}C).

Pe number for average coolant parameters in the core of KLT-40 reactor:

$$Pe_{reac} = Re_{reac} \cdot Pr_{298} \approx 10^5 \cdot 0.87 \approx 8.7 \cdot 10^4, \quad (3)$$

where number Re in the reactor is on average (1-5)·10^5-10^7, number Pr is taken for average parameters of the coolant (p=12.7 MPa; $t_{average}$=298^{0}C).

Accordingly, it is possible to draw a conclusion that the adopted model is applicable to the analysis of processes, as $Pe_{mod} \approx Pe_{reac}$.

A new core simulator has also been developed to provide a more detailed approximation of the simulated reactor plant. It is an equivalent cassette of KLT-40 main mass.

An equivalent cassette is a set of elements (simulator tubes) (shown in the fig.3 and fig.4) of the main body of the fuel assembly mounted on the lower (support) and upper remote control grilles. Some of the rods (control rods) are placed behind the model cover through the grommets. Temperature parameters are controlled through these rods. Temperature sensors are located directly inside these channels (thin-walled channels are a sleeve). In addition, the cover is equipped with additional cable glands (in the course of this experiment are silenced) through which it is possible to install additional channels for measurement (temperature and pressure drop).

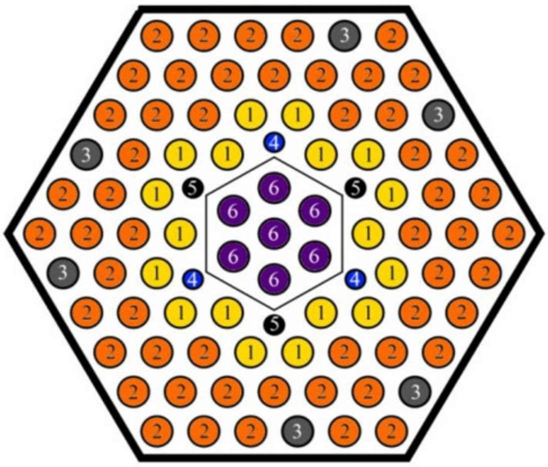

Fig. 3. Internal elements of the fuel assembly control unit 1 - "light" fuel element (18), 2 - "heavy" fuel element (54), 3 - burnable absorber 1 type (6), 4 - burnable absorber 2 type (3), 5 - zirconium displacer (3), 6 - compensating rods (6)

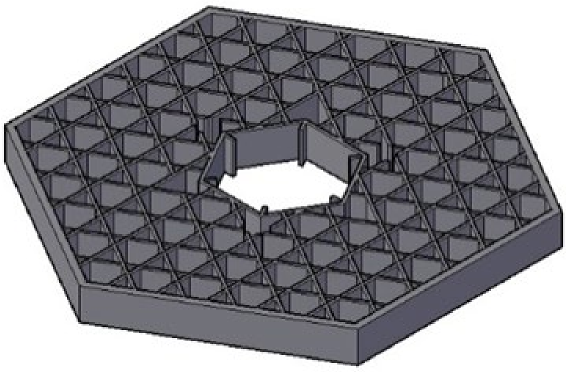

Fig. 4. General view of the remote gratings

To model the impact of external dynamic force in the form of periodic impact on the spatial orientation of the model a "Swinging platform" stand was proposed (fig.5). It consists of a frame rigidly fixed to the power plate. The Oscillating platform is connected to the frame through the shaft and bearings. The electric motor through the crank mechanism transmits a rotational force on a rod which in turn drives the investigated model on a platform. Due to the change of the crank radius as well as the frequency of rotation of the electric motor (frequency converter), it is possible to change the amplitude and period of the rocking model.

Fig. 5. General view of the "Swinging platform" stand

The model can vibrate in a given plane, like a mathematical pendulum, by law:

$$\phi = \phi_{\max} \cdot \sin(\frac{2\pi\tau}{T}), \qquad (4)$$

where φ – corner, φ_{max} – oscillation amplitude, [Rad]; T – the oscillation period, [s]; τ – the current time, [s].

In this work, the media were supplied to the model from two spigots (1 and 3) located opposite each other.

In the dynamic mode, the flow was fed simultaneously with the harmonic oscillations of the model with an amplitude of 15^0 degrees and a period of 4 seconds.

3. Results

The diagrams (top view) of temperature distribution through control channels are shown below (figs. 6. and 7.). Temperature sensors are located at the bottom at the input to the model-simulator core (except for sensors of channels 18 and 78, where sensors are also located at the output of the simulator). The central hexagonal channel for compensation rods is plugged.

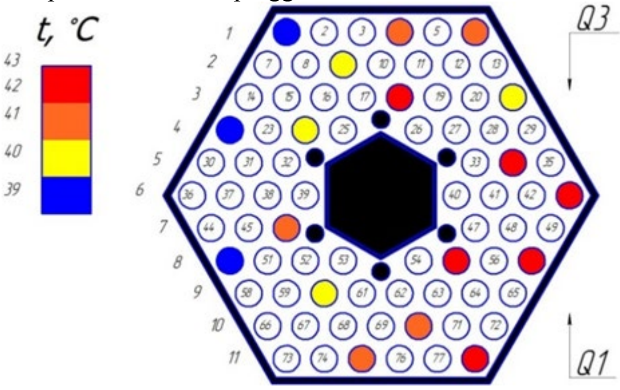

Fig. 6. Input temperature distribution of to the simulator active zone in a stationary mode

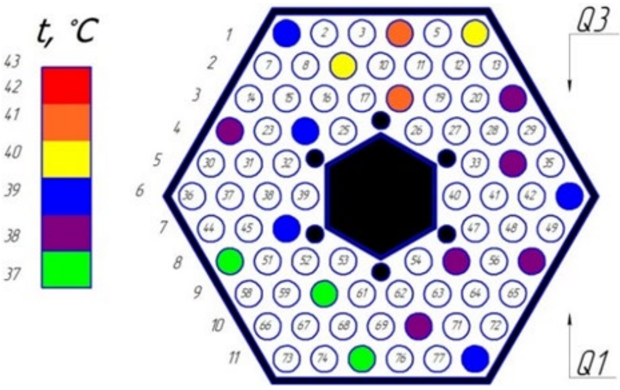

Fig. 7. Distribution of temperature at the input to the simulator active zone in dynamic mode

The data obtained in the course of the work have been processed and the key points are given in Table 2.

Table 2. Border conditions

Parameter	Fixed position	Swinging
Volume flow (Q1)/temperature (t1)	10 *l/min* / 60^0C	10 *l/min* / 60^0C
Volume flow (Q3)/temperature (t3)	10 *l/min* / 20^0C	10 *l/min* / 20^0C
Re1/Re3 (on input to the model)	22367/10574	22367/10574
Swing amplitude	-	15^0
Swing period	-	4 sec.
Time of transition	≈225 sec.	≈174 sec.

Vertical projection of velocity Δz/Δτ (on channel 78), where Δz=f(Δt)	≈14 cm/s	≈3.5 cm/s
Vertical projection of velocity Δz/Δτ (on channel 18), where Δz=f(Δt)	≈17.5 cm/s	≈3 cm/s
Maximum temperature gradient in steady-state mode	4 ^{0}C	3.82 ^{0}C

4. Discussion

Having analyzed the results obtained, the following conclusions can be drawn:

4.1. In stationary operation (without jogging), the hot flow is counterclockwise, cold flow is in a clockwise direction. The maximum temperature is concentrated in the right side sectors (near the wall) for both cold and hot flow.

During the work analysis [11] where authors used a technique of research of mixing of streams by conductometric method, at similar modes of work in the field of natural circulation of the heat-carrier at giving in circulation loops of solutions with different salt content the following laws correlating with our results have been revealed:

4.2. On the periphery there are two segments with "zero" trace concentration, where there was no mixing.

4.3. According to the location of these segments and the place of formation of the front kernel with an increased concentration of the tracer ("heavy" salt solution - if we interpret it by the method described above - cold flow Q3), we can see that there was a clockwise twist of the flow.

4.4. In dynamic mode, the flow curl is disturbed. This is probably due to the fact that the dynamic force acting in the direction parallel to the spigots moves the hot vortex to the opposite wall. The cold vortex also shifts, but the degree of its displacement is greater. This is due to the fact that the centrifugal force has a greater influence on the cold vortex (due to its higher density and viscosity) than on the hot vortex.

This confirms the mathematical model described by us in [9], where the centrifugal force was set when exposed to an elementary mole as a ratio:

$$\partial F_c = \rho R \left(\frac{\partial \phi}{\partial \tau}\right)^2 \partial v, \quad (5)$$

where, ∂v - volume change, [m^3]; ρ- density, [kg/m^3]; g - free fall acceleration, [m/s^2]; R - radius, [m]; ∂φ - angle element, [rad]; ∂τ- elementary time increment, [s].

From this dependence it follows that the degree of influence on the external dynamic force flow is directly proportional to the density of the coolant.

4.5. The transition time of the rocking action is reduced

4.6. The vertical projection of speed of a stream calculated indirectly on change of temperature, makes for a stationary mode on the average ≈15-16 cm/s that is comparable to speed of natural circulation of the heat-carrier (10-20 cm/s). In dynamic mode, the vertical component is much smaller (about 3 cm/s). It means that the stream influencing external force receives acceleration along a rolling plane, that is the horizontal projection of a vector of speed of a stream increases.

4.7. The maximum temperature gradient when exposed to external dynamic force decreases slightly.

5. Conclusion

Research of processes for mixing non-isothermal water coolant flows in a hydraulic model of ship nuclear power plant KLT-40 has been carried out. In the experiments, attention was paid to the mixing processes when feeding the non-isothermal flows through the circulation loops located opposite each other. The results correlated with the results of other leading scientific groups dealing with this problem and used other methods that have been obtained.

To investigate the effect of external dynamic forces, this model was tested under the effect of periodic oscillations. These oscillations influenced the mixing processes occurring within the model. The main impact they had was on the time of transition, temperature gradient, vertical component of the velocity projection. In the future, these parameters will be clarified and the influence of other factors on the mixing of non-isothermal flows in the ship's nuclear power plant will be investigated in more detail.

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