NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 5(1): 75–80
DOI 10.3897/nucet.5.34294

Research Article

Gas-cooled nuclear reactor core shaping using heat exchange intensifiers*

Vyacheslav S. Kuzevanov[1], Sergey K. Podgorny[1]

1 *MPEI Branch in Volzhsky, 69 Lenin str., Volzhsky, Volgograd reg., 404110, Russian Federation*

Corresponding author: *Sergey K. Podgorny* (serkonpod@gmail.com)

Academic editor: *Boris Balakin* ♦ **Received** 2 December 2018 ♦ **Accepted** 5 February 2019 ♦ **Published** 11 April 2019

Citation: Kuzevanov VS, Podgorny SK (2019) Gas-cooled nuclear reactor core shaping using heat exchange intensifiers. Nuclear Energy and Technology 5(1): 75–80. https://doi.org/10.3897/nucet.5.34294

Abstract

The need to shape reactor cores in terms of coolant flow distributions arises due to the requirements for temperature fields in the core elements (Safety guide No. NS-G-1.12. 2005, IAEA nuclear energy series No. NP-T-2.9. 2014, Specific safety requirements No. SSR-2/1 (Rev.1) 2014). However, any reactor core shaping inevitably leads to an increase in the core pressure drop and power consumption to ensure the primary coolant circulation. This naturally makes it necessary to select a shaping principle (condition) and install heat exchange intensifiers to meet the safety requirements at the lowest power consumption for the coolant pumping.

The result of shaping a nuclear reactor core with identical cooling channels can be predicted at a quality level without detailed calculations. Therefore, it is not normally difficult to select a shaping principle in this case, and detailed calculations are required only where local heat exchange intensifiers are installed.

The situation is different if a core has cooling channels of different geometries. In this case, it will be unavoidable to make a detailed calculation of the effects of shaping and heat transfer intensifiers on changes in temperature fields.

The aim of this paper is to determine changes in the maximum wall temperatures in cooling channels of high-temperature gas-cooled reactors using the combined effects of shaped coolant mass flows and heat exchange intensifiers installed into the channels. Various shaping conditions have been considered. The authors present the calculated dependences and the procedure for determining the thermal coolant parameters and maximum temperatures of heat exchange surface walls in a system of parallel cooling channels.

Variant calculations of the GT-MHR core (NRC project No. 716 2002, Vasyaev et al. 2001, Neylan et al. 1994) with cooling channels of different diameters were carried out. Distributions of coolant flows and temperatures in cooling channels under various shaping conditions were determined using local resistances and heat exchange intensifiers. Preferred options were identified that provide the lowest maximum wall temperature of the most heat-stressed channel at the lowest core pressure drop.

The calculation procedure was verified by direct comparison of the results calculated by the proposed algorithm with the CFD simulation results (ANSYS Fluent User's Guide 2016, ANSYS Fluent. Customization Manual 2016, ANSYS Fluent. Theory Guide 2016, Shaw1992, Anderson et al. 2009, Petrila and Trif 2005, Mohammadi and Pironneau 1994).

Keywords

Core shaping, heat exchange intensification, mass flow distribution, maximum channel wall temperature

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2018, n. 4, pp. 31–42

Introduction

One of the major problems in implementing gas-cooled nuclear reactors is the high core thermal intensity due to the need to achieve a high coolant gas temperature, which, respectively, results in high cooling channel wall temperatures. Because of the uneven heat generation in the core, the maximum wall temperatures in different channels may vary. At given total coolant flow and average core outlet temperature, the maximum wall temperature in the most heat-stressed channel group can be decreased if the coolant flow through the channels of this group is increased by shaping the mass flows. The other option is to install heat exchange intensifiers into the channels of this group while maintaining the coolant flow. It is obvious that, in any option of changing the core hydraulic (aerodynamic) characteristics, the total core pressure drop increases. When implementing measures to reduce the maximum wall temperature in the cooling channels, the best option would be when an acceptable wall temperature in all the channels is achieved with a minimum core pressure drop.

The influence of the coolant mass flow shaping in a gas-cooled reactor on the main gas/temperature parameters of the cooling channel walls was studied in (Podgorny and Kuzevanov 2017). The effect of installed heat exchange intensifiers on changes in the maximum channel wall temperature was analyzed in (Kuzevanov and Podgorny 2017).

The paper focuses on the effect of changes in the maximum wall temperatures from the core coolant mass flow shaping using heat exchange intensifiers. Various shaping conditions were considered with equal (1) heating or increments of enthalpies in the cooling channels, (2) coolant mass flows in the channels, and (3) maximum wall temperatures in the cooling channels.

As in (Podgorny and Kuzevanov 2017, Kuzevanov and Podgorny 2017), the GT-MHR design (NRC project No. 716 2002, Vasyaev et al. 2001, Neylan et al. 1994) is examined. In the theoretical and computational analysis, the following basic system parameters were assumed to be unchanged: the total gas coolant mass flow G_0, the average coolant temperature at the core outlet T_{av}, the reactor thermal power Q_0, and the coolant temperature at the core inlet T_0.

Main calculated dependences

The equations for calculating the coolant mass flow distribution by groups of identical cooling channels were obtained in (Podgorny and Kuzevanov 2017). In this case, channels of the same group have the same diameter and heat load, with a total of m groups of identical channels.

The relation between the total coolant pressure loss ΔP (a component of the pressure difference resulting from a temperature change can be neglected due to its insignificance), when passing from the core inlet to its outlet, and the total coolant mass flow G_0 looks like this:

$$\Delta P = 8\cdot\left(\xi_m\cdot\frac{l}{d_m}+\xi_{\text{м}.m}\right)\cdot\frac{1}{\rho_m}\cdot \left(G_0\Big/\left[\pi\cdot d_m^2\cdot\sum_{i=1}^{m}\left(n_i\cdot\prod_{j=i}^{m}k_j\right)\right]\right)^2, \quad (1)$$

where n_i is the number of identical channels in the i-group, $1 \le i \le m$; ξ_i and $\xi_{l.i}$ are the friction coefficients and local resistance coefficients reduced to the average coolant thermal parameters, respectively; l is the core height, m; d_i are the diameters of round channels, m; ρ_i is the average coolant density, kg/m^3.

The k_p coefficients for an arbitrary p-group of channels are defined by the dependence

$$k_p = \sqrt{\rho_p(\xi_{p+1}l/d_{p+1}+\xi_{\text{м}.p+1}/[\rho_{p+1}(\xi_p l/d_p+\xi_{\text{м}.p})])}\cdot (d_p/d_{p+1})^2,\quad p\neq m,\quad k_m=1, \quad (2)$$

and the friction coefficients for technically smooth round channels are determined by the Blasius dependence

$$\xi_p = 0.316 / \mathrm{Re}_p^{0.25}. \quad (3)$$

The coolant mass flow G_p in a single channel of an arbitrary group is calculated by the equation

$$G_p = G_0\prod_{j=p}^{m}k_j\Big/\left(\sum_{i=1}^{m}n_i\prod_{j=i}^{m}k_j\right). \quad (4)$$

With a known flow G_p under the conditions of constant specific isobaric heat capacity of helium c_p = const, it is easy to obtain a ratio for calculating the coolant temperature at the outlet (the «out» superscript) of a p-group channel:

$$T_p^{\text{out}} = T_0 + \nu_p Q_0 d_p\Big/\left(G_p c_p\sum_{i=1}^{m} d_i\cdot n_i\right) \quad (5)$$

where ν_p is the heat load deviation of the p-channel group from the average load.

The thermophysical properties of the coolant gas (helium) necessary for carrying out calculations – the average density $\rho_{\text{av}\,p}$ and dynamic viscosity coefficient $\mu_{\text{av}\,p}$ – are found by the ideal gas low equation and Sutherland equation, respectively:

$$\mathrm{P}_{\text{av}\,p} = [\rho_0 + (P_0 - \Delta P)/(R_{\text{He}}\cdot T_p)]/2, \quad (6)$$

$$\mathrm{M}_{\text{av}\,p} = [\mu_0 + \mu_0^*(T_p/T_0^*)^{3/2}(T_0^*+S)/(T_p+S)]/2, \quad (7)$$

where P_0 is the coolant pressure at the core inlet, Pa; ρ_0 is the coolant density at the core inlet; R_{He} is the individual gas constant for helium, J/kg·K; T_p is the outlet temperature of an arbitrary p-channel, K; μ_0^* is the control viscosity at temperature T_0^* (273 K), Pa·s; S is Sutherland constant or effective gas temperature (reference value), K; μ_0 is the viscosity at the core inlet temperature and pressure, Pa·s.

The accepted shaping condition means specifying the relationship of at least two coolant parameters. For shaping under the conditions of the same mass flows in the channels and the same coolant heating in them, the functions of the relationship between the coolant flow and its heating in any channel are trivial. For shaping under the condition of the same maximum wall temperatures in the cooling channels, the following equation for the relationship between the channel coolant flow and its maximum wall temperature Θ_{wall}^{max} was obtained in (Podgorny and Kuzevanov 2017)

$$\frac{C1_i}{\xi_i} \cdot \frac{G_0}{G_i} = a^{1/2} \cdot \left(a - C2_i \cdot \frac{G_0}{G_i} \right)^{1/2}, \tag{8}$$

$$\left.\begin{aligned} & a = \Theta_{\text{wall}}^{\max} - T_0 = \text{idem} \\ & C1_i = \chi \cdot \nu_i / b_i \cdot c_p / (\pi \cdot l) \cdot \overline{\Delta T_{\text{av}}} \Big/ \sum_{i=1}^{m} d_i \cdot n_i \\ & C2_i = \nu_i \cdot \overline{\Delta T_{\text{av}}} \cdot d_i \Big/ \left(\sum_{i=1}^{m} d_i \cdot n_i \right) \\ & b_i = c_p / [8 \cdot f \cdot (k + \varepsilon(Pr))] \end{aligned}\right\} \tag{9}$$

Relation (8) is obtained using the dependence for the heat transfer coefficient proposed by B.S. Petukhov (Petukhov and Kirillov 1958); ε(Pr) and k are the parameters of Petukhov's formula for the heat transfer coefficient. In (9), χ is the fraction of thermal power released directly in fuel elements; ΔT_{av} is the average balanced value of the coolant heating in the core, K.

It is obvious that, with the same channel coolant flow and the heat load maintained, the maximum channel wall temperature depends on whether the channel is smooth or has an extended area with specific features of the heat exchange surface (i.e., heat exchange intensifier). The dependence for a gaseous coolant, reflecting the effect of a heat exchange intensifier installed into a smooth channel on changes in the maximum wall temperature, was obtained and verified in (Kuzevanov and Podgorny 2017). It is written as

$$\Theta^*_{\text{wall}}{}^{\max} = \Theta^*_{\text{wall }0}{}^{\max} \cdot (1 + \gamma \cdot \delta T_{h.c} / \Theta^*_{\text{wall }0}{}^{\max}) / (1 + \gamma), \tag{10}$$

where

$\Theta^*_{\text{wall}}{}^{\max} = \Theta_{\text{wall}}{}^{\max} - T^{In}_{\text{int}}$, $\Theta^*_{\text{wall }0}{}^{\max} = \Theta_{\text{wall }0}{}^{\max} - T^{In}_{\text{int}}$, K; T^{In}_{int} is the coolant temperature at the inlet of the area of the installed extended heat exchange intensifier, K; $\delta T_{h.c} = T_{h.c} - T^{In}_{\text{int}}$; $T_{h.c}$ is the coolant temperature in cross section with the maximum channel wall temperature, K; the "0" subscript refers to the option of a technically smooth channel.

In Dependence (10), γ reflects the intensifier's effect:

$$\gamma = H_0/l_{\text{int}} \cdot (\Delta P/\Delta P_0 - 1), \tag{11}$$

where H_0 is the core height equal to the cooling channel length, m; l_{int} is the heat exchange intensifier length, m; ΔP_0 is the pressure difference in a technically smooth channel, Pa; ΔP is the pressure difference in a channel with a heat transfer intensifier at the same channel coolant flow, Pa.

Specific features of calculated dependences

The coolant flows are usually redistributed through the cooling channels by individual local resistances installed at the inlet to the core channels. This shaping arrangement was considered in (Podgorny and Kuzevanov 2017).

The use of heat exchange intensifiers with uniquely shaped coolant mass flows in the core at given local resistances $\xi_{\text{M}.i}$ for each identical i-group channel implies implementing the following obvious relations:

$$\xi_{\text{int},i} + \xi^*_{\text{M}.i} = \xi_{\text{l}.i}, \ \xi_{\text{int},i} \le \xi_{\text{l}.i}, \tag{12}$$

where $\xi_{\text{int},i}$ is the aerodynamic drag coefficient of a single i-group channel if a heat exchange intensifier is installed in it; $\xi^*_{\text{l}.i}$ are the modified local resistances for a single i-group channel with a heat exchange intensifier.

The uniquely shaped mass flows are determined by the condition

$$G_p = G_0 / \sum_{i=1}^{m} n_i = \text{idem}$$

or by the condition $\Delta T_p = \Delta T_{av} = \text{idem}$, when

$$G_p = G_0 \cdot \nu_p \cdot d_p / \left(\sum_{i=1}^{m} d_i \cdot n_i \right) = \text{idem}.$$

These flows do not depend on whether there are heat exchange intensifiers in the cooling channels.

For the mass flow shaping options, it is possible to calculate a decrease in the maximum wall temperatures in different cooling channel groups using Equation (10) if the aerodynamic characteristics of heat exchange intensifiers used for shaping are known. These characteristics can be represented as the γ parameter from Equation (11).

The GT-MHR core consists of fuel assemblies (FA) made of grade H-451graphite (Engle 1977, Engle and Johnson 1976) in the form of perforated prismatic hexagonal elements. The core height and each cooling channel length correspond to the height of ten fuel assemblies. It is obvious that heat exchange intensifiers should be installed in fuel assemblies with the maximum cooling channel wall temperature. For the GT-MHR core, it is the eighth assembly along the coolant flow. It is also possible to install a heat exchange intensifier of greater length in several series-connected fuel assemblies, however, as shown in (Kuzevanov and Podgorny 2017), an increase in the intensifier length over $0.1H_0$ has little effect on the maximum channel wall temperature caused by this intensifier, but leads to an increase in the pressure difference. That is why, in analyzing the heat exchange intensifier effect, when the shaping condition is formulated as $\Delta T_p° = \text{idem}$,

G_p = idem or Θ_{wallp}^{max} = idem, we consider the option of installing intensifiers in channels only along the length of assemblies with the maximum channel wall temperatures.

In contrast to the shaping conditions G_p = idem and ΔT_p = idem, the local coolant mass flow distribution under the condition that Θ_{wallp}^{max} = idem depends on whether or not there are heat exchange intensifiers in the channels. In this case, the basic calculational equation (8) for this condition of shaping the coolant mass flows will be

$$C1_i\, G_0/(\xi_{int,i}\, G_i) = a^{1/2}\cdot(a - C2_i\, G_0/G_i)^{1/2}, \quad (13)$$

where

$$\xi_{int,i} = \xi_i \cdot(1 + l_{int,i}\cdot\gamma/H_0). \quad (14)$$

Note that it does not specify the features of the heat exchange intensifier, in particular, its design. There are numerous options. We assume that the integral characteristics of the intensifier used, from which the γ parameter can be calculated, are known. We also take into account the fact that the range of γ values is limited:

$$0 < \gamma < \gamma^{max}. \quad (15)$$

The results presented in (Kuzevanov and Podgorny 2017) make it possible to estimate the maximum value $\gamma^{max} \approx 2.5$ from the condition of the technical characteristics of the intensifiers, which determine their aerodynamic characteristics. All graphs are also constructed for the values $\gamma < \gamma^{max}$, i.e., for all possible γ values. In this case, the γ limitation is due only to the minimum temperature difference between the maximum wall temperature and the coolant temperature.

Calculation results

The calculations of the GT-MHR core took into account the following design features.

The cylindrical ring-shaped core consists of perforated graphite hexagonal blocks (fuel assemblies) with cooling and fuel channels. The core thickness corresponds to the size of three rows of fuel assemblies; therefore, two peripheral (outer and inner) and central areas of the core are distinguished, each of which consists of one row of fuel assemblies located circumferentially and having their own specific heat load. The cooling channels are represented by two groups: (1) with an inner diameter of 15.88 mm and (2) with a diameter of 12.7 mm. The length of each channel is equal to the core height H_0 = 7.93 m. The core thermal power is 600 MW. The total helium mass flow is G_0 = 320 kg/s, its temperature at the core inlet T_0 = 491 °C (NRC project No. 716 2002, Vasyaev et al. 2001, Neylan et al. 1994). As in (Podgorny and Kuzevanov 2017), the cosine power shape was adopted in the core height and thickness.

With the above core specification, there will be four identical channel groups in the reactor: two groups of channels in the central area with diameters of 15.88 and 12.7 mm, respectively, and two groups of analogous channels in the peripheral area.

The analysis of the influence of heat exchange intensifiers involved in shaping the coolant mass flows on changes in the maximum channel wall temperature is made by comparison with the results obtained, when the shaping conditions were implemented by installing local resistances at the inlet of channels, and presented in (Podgorny and Kuzevanov 2017).

Table 1 shows the maximum wall temperatures in groups of identical channels at the nominal reactor power with cores that differ only in the coolant mass flow distribution through the channels.

The arrangement of shaping the coolant mass flows for any shaping condition leads to an increased core pressure drop. Table 2 shows the "price" for the result achieved under different shaping conditions, presented as the ratio $\Delta P/\Delta P_0$, where ΔP_0 is the core pressure drop without shaping, and ΔP is the core pressure drop with arranged coolant mass flow shaping.

Figures 1–3 show the calculated changes in the maximum wall temperature of different cooling channel groups, depending on the integral characteristic of heat exchange intensifiers installed in them.

Figure 1 shows the temperature changes in the reactor core under study, where the coolant mass flow is shaped under the condition that ΔT_i = idem and heat exchange intensifiers are installed in the channels of three groups with corresponding reductions in the local resistances at the inlet of these channels.

Figure 2 shows the changes in the maximum wall temperatures in different cooling channels groups when the heat exchange intensifiers partially replace the local resistances installed for shaping the coolant mass flow in the core under the condition that G_i = idem.

Figure 3 continues to show the changes in the maximum cooling channel wall temperatures when heat exchange intensifiers are used, which together with local resistances ensure that the shaping condition is met.

Table 1. Maximum cooling channel wall temperatures depending on the coolant mass flow distribution.

Core area	Channel diameter, mm	Maximum channel wall temperature, Θ_{walli}^{max}, °C			
		Without shaping	ΔT_i = idem	G_i = idem	$\Theta_{cr,i}^{max}$ = idem
Peripheral	15.88	857.108	877.037	864.811	877.671
	12.7	896.082	865.562	717.155	877.671
Central	15.88	910.185	878.504	915.623	877.671
	12.7	955.713	867.823	747.864	877.671

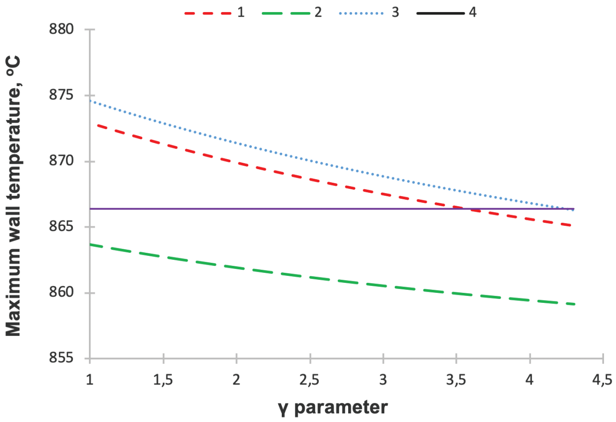

Figure 1. Dependence $\Theta_{wall}^{max} = f(\gamma)$ for identical channels of different groups with ΔT_i = idem: 1 – channels with ϕ = 15.88 mm, of the peripheral core area; 2 – channels with ϕ = 12.7 mm, of the peripheral core area; 3 – channels with ϕ = 15.88 mm, of the central core area; 4 – the maximum temperature of the channel walls with ϕ = 12.7 mm, of the central core area.

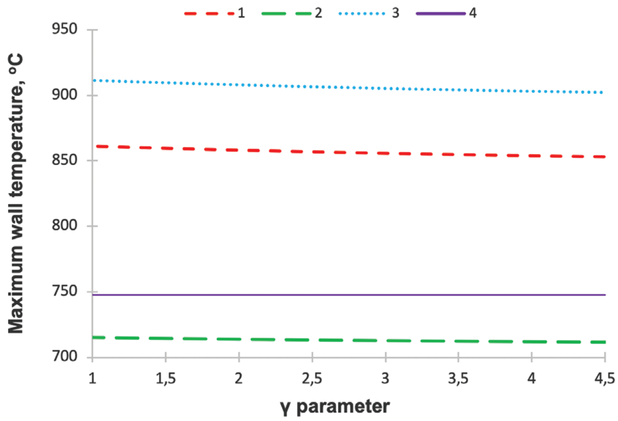

Figure 2. Dependence $\Theta_{wall}^{max} = f(\gamma)$ for identical channels of different groups with G_i = idem: 1 channels with ϕ = 15.88 mm, of the peripheral core area; 2 –channels with ϕ = 12.7 mm, of the peripheral core area; 3 –channels with ϕ = 15.88 mm, of the central core area; 4 – the maximum temperature of the channel walls with ϕ = 12.7 mm, of the central core area.

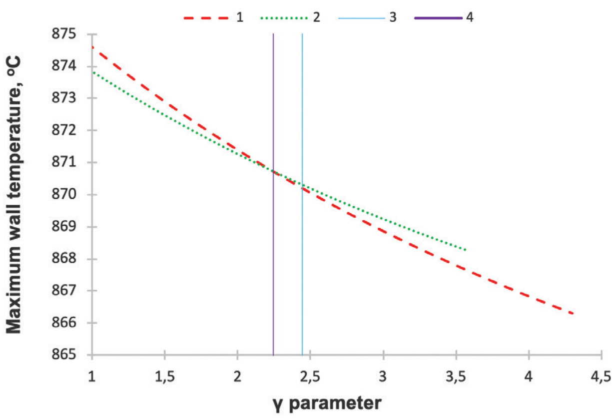

Figure 3. Dependence $\Theta_{wall}^{max} = f(\gamma)$ for the core channel with the maximum $\Theta_{wall\,i}^{max}$: 1 – the maximum wall temperature of identical channels with ϕ = 15.88 mm, of the central core area, when shaped under the condition that ΔT_i = idem; 2 – the maximum wall temperature for any channel when shaped under the condition that $\Theta_{wall\,i}^{max}$ = idem; 3, 4 – efficient shaping condition boundaries.

Table 2. The $\Delta P/\Delta P_0$ value for the mass flow shaping options.

Shaping condition	Without shaping	ΔT_i = idem	G_i = idem	$\Theta_{wall\,i}^{max}$ = idem
$\Delta P/\Delta P_0$ value	1	1.4368	2.6873	1.3562

Curves 1 and 2 in Fig. 3 show that installing a heat exchange intensifier into the core shaped under the condition that $\Theta_{wall\,i}^{max}$ = idem is more efficient than installing intensifiers into the core channels shaped under the condition that ΔT_i = idem only to Boundary 3 (or $\gamma°$= 2.247). In addition, after Boundary 4 (or γ = 2.446), the core pressure drop shaped under the condition that $\Theta_{wall\,i}^{max}$ = idem becomes greater than the core pressure drop shaped under the condition that ΔT_i = idem.

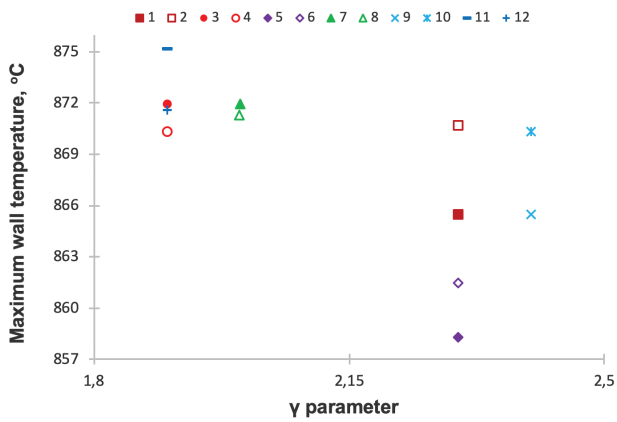

Figure 4. Comparison of $Q_{wall\,i}^{maxc}$, values obtained by direct calculation of the coolant mass flow distribution (P) and the CFD-simulation results (M): 1 – M, channels with ϕ = 15.88 mm, the central core area, shaping at ΔT_i = idem; 2 – P, channels with ϕ = 15.88 mm, the central core area, shaping at ΔT_i = idem; 3 – M, channels with ϕ = 15.88 mm, the peripheral core area, shaping at ΔT_i = idem; 4 – P, channels with ϕ = 15.88 mm, the peripheral core area, shaping at ΔT_i = idem; 5 – M, channels with ϕ = 12.7 mm, the peripheral core area, shaping at ΔT_i = idem; 6 – P, channels with ϕ = 12.7 mm, the peripheral core area, shaping at ΔT_i = idem; 7 – M, channels with ϕ = 15.88 mm, the central core area, shaping at $Q_{wall\,i}^{max}$ = idem; 8 – P, channels with ϕ = 15.88 mm, the central core area, shaping at $Q_{wall\,i}^{max}$ = idem; 9 – M, channels with ϕ = 15.88 mm, the peripheral core area, shaping at $Q_{wall\,i}^{max}$ = idem; 10 – P, channels with ϕ = 15.88 mm. the peripheral core area, shaping at $Q_{wall\,i}^{max}$ = idem; 11 – M, channels with ϕ = 12.7 mm, the peripheral core area, shaping at $Q_{wall\,i}^{max}$ = idem; 12 – P, channels with ϕ = 12.7 mm, the peripheral core area, shaping at $Q_{wall\,i}^{max}$ = idem.

Note that the coolant mass flow shaping option under the condition that $G_{i°}$=°idem is not shown in Figs 3, 4, since, as follows from Tables 1, 2 and Fig. 2, this option is inefficient (with or without intensifiers) for the core under study.

In order to verify the adequacy of the method for analyzing changes in the temperature regime of the reactor core with the combined use of local resistances and heat exchange intensifiers to ensure shaping the coolant mass flow through the core cooling channels, the calculation results were compared with the CFD simulation results (Fig. 4).

Simulations were made for single cooling channels of all the groups with given (calculated) coolant flow/heat load values. The intensifier used corresponded to the design presented in (Kuzevanov and Podgorny 2017).

Conclusion

The paper has demonstrated the capabilities of the method for calculating temperature changes in the coolant and cooling channel walls during the channel-by-channel coolant mass flow shaping using heat exchange intensifiers in the reactor core. For the investigated GT-MHR core, there are two options that can reduce the maximum cooling channel wall temperature. The first option, when there is a strict limitation on the core pressure drop, is to shape the coolant mass flows under the condition that $\Theta_{\mathrm{wall}i}^{\max}$ = idem. In this case, the use of heat exchange intensifiers slightly changes the maximum channel wall temperature and is impractical at $\gamma \geq 2.247$. The second option, when there are no principal obstacles to increasing the core pressure drop, is shaping under the condition that ΔT_i = idem with the combined use of local resistances and heat exchange intensifiers. Moreover, the second option is definitely preferable for the integral characteristic of heat exchange intensifiers (γ°>°2.247).

The calculation procedure was verified by direct comparison of the results calculated by the proposed algorithm with the results of a detailed gas flow simulation in heated channels with a specific heat exchange intensifier design.

References

- Anderson J, Dick E, Dergez G, Grundmann R, Degroote J, Vierendeels J (2009) Computational Fluid Dynamics: An introduction. Berlin, Springer-Verlag: 10–17.
- ANSYS Fluent User's Guide (2016) Canonsburg: ANSYS Inc: 238–247.
- ANSYS Fluent. Customization Manual (2016) Canonsburg: ANSYS Inc: 91–100.
- ANSYS Fluent. Theory Guide (2016) Canonsburg: ANSYS Inc: 137–177.
- Engle GB (1977) Assessment of grade H-451 graphite for replaceable fuel and reflector elements in HTGR. San Francisco: General Atomics: 29–56. https://doi.org/10.2172/5176415
- Engle GB, Johnson WR (1976) Properties of unirradiated fuel element graphites H-451 and SO818. San Francisco: General Atomics: 6–20.
- IAEA nuclear energy series No. NP-T-2.9. (2014) International safeguards in the design of nuclear reactors. Vienna. International atomic energy agency: 18–23.
- Kuzevanov VS, Podgorny SK (2017) Research of the influence of intensification of heat transfer on distribution of temperature in the active core of the gas cooled nuclear reactor of the «GT-MHR» project. Journal of Physics Conference Series, 891: 1–4. Article ID 012069.
- Mohammadi B, Pironneau O (1994) Analysis of the K-epsilon turbulence model. New Jersey.Wiley: 51–62.
- Neylan AJ, Shenoy A, Silady FA, Dunn TD (1994) GT-MHR design, performance and safety. San Diego: General Atomics: 2–8.
- NRC project No. 716 (2002) GT-MHR Conceptual Design Description Report. San Diego. General Atomics: 58–62.
- Petrila T, Trif D (2005) Basics of fluid mechanics and introduction to computational fluid dynamics. Boston.Springer: 197–239.
- Petukhov BS, Kirillov VV (1958) On the issue of heat transfer in turbulent flow of fluid in pipes. Teploehnergetika, 4: 29–31. [In Russian]
- Podgorny SK, Kuzevanov VS (2017) A method of calculation of mass flow rates and temperature of gas coolant in parallel channels of an active core of a nuclear reactor during core shaping, The Strategies of Modern Science Development. XIII International scientific–practical conference 2017. North Charleston, South Carolina, USA, 3–4 October: 27–36.
- Safety guide No. NS-G-1.12. (2005) Design of the reactor core for nuclear power plants. Vienna. International atomic energy agency: 3–8.
- Shaw CT (1992) Using Computational Fluid Dynamics. New Jersey: Prentice Hall: 100–137.
- Specific safety requirements No. SSR-2/1 (Rev.1) (2014) Safety of Nuclear Power Plants: Design. Vienna. International atomic energy agency: 4–10.
- Vasyaev A, Kodochigov N, Kuzavkov N, Kuznetsov L (2001) International Project GT-MHR – New Generation of Nuclear Reactors, The International Conference of Bulgarian Nuclear Society 2001. Varna, Bulgaria, June 17–20: 7–21.