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Flow and heat transfer in fuel rod bundles of water-cooled reactors with modified cell-type spacer grids

V.G. Krapivtsev, P.V. Markov*, V.I. Solonin

Moscow State Technical University named after N.E. Bauman, 105005 Moscow, Russia

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Abstract

The paper considers the flow and heat transfer in coolant flows cooling the fuel rod bundles of nuclear reactors with modified cell-type spacer grids. The spacer grids were developed by JSC Mashinostroitelny Zavod, Elektrostal, and differ from standard grids in the inclination of the corrugations that contact the fuel cladding outer surface. The coolant flow inside such cells leads to tangential components of the velocity vector formed inside the flow with an orientation in accordance with the corrugation inclination direction. By arranging geometrically different or identical cells within the grid array, it is possible to generate different secondary flows in the rod bundles downstream of the grid. The paper considers spacer grids that generate two types of secondary coolant flows: around the fuel rods and between the rod rows. The investigation was based on computational fluid dynamics methods with the calculation results validated against aerodynamic test data. Mechanisms of the secondary flow formation downstream of the grids have been described, and the intensities thereof have been quantitatively estimated. Data is presented on the grid flow resistance coefficients at different Reynolds numbers both in conditions of a weakly compressed isothermal air flow and with parameters representative of the VVER-1000 reactor primary coolants. Intensification of the coolant mixing downstream of the spacer grids was analyzed by a thermal wake method for different boundary conditions. A conclusion has been made that the modified cell-type spacer grids can be used for and are efficient in flattening temperature non-uniformities in the coolant flow due to creating a directed convective transport.

Keywords: Spacer grid; Reactor core; Fuel rod; Intensification of mixing; Secondary flows; Computational fluid dynamics.

Introduction

The power of water-cooled water-moderated nuclear reactors cannot be increased without requirements to ensuring safe reactor operation under conditions of increased thermal load on the reactor core fuel rods to be complied with. High densities of heat fluxes from the fuel rod surfaces, and hydraulic inequality of the coolant circulation lines in the reactor core caused, among other factors, by the presence of local hydraulic resistances, may lead to a local overheating of the coolant, its surface boiling, and burnout, which is hazardous in terms of mechanical degradation of the fuel cladding with a subsequent cladding failure and escape of radioactive fission products into the circulation circuit [1].

The factors that trigger burnout in the cores of water-cooled water-moderated reactors, when their power is increased, can be avoided by:

- Maintaining the correspondence between the cooling conditions for individual fuel rods and the amount of heat released therein (by means of physical fuel profiling).
- Flattening the coolant velocity and temperature fields in the coolant flow, which provides for identical fuel cooling conditions in different core areas.

The latter has been implemented in fuel assemblies of foreign-made reactors using special mixers in the form of deflectors or mixing vanes introduced into the fuel spacer grid design [2,3]. Activities to design such devices for

* Corresponding author.
E-mail address: marrkov@list.ru, en7@power.bmstu.ru (P.V. Markov).
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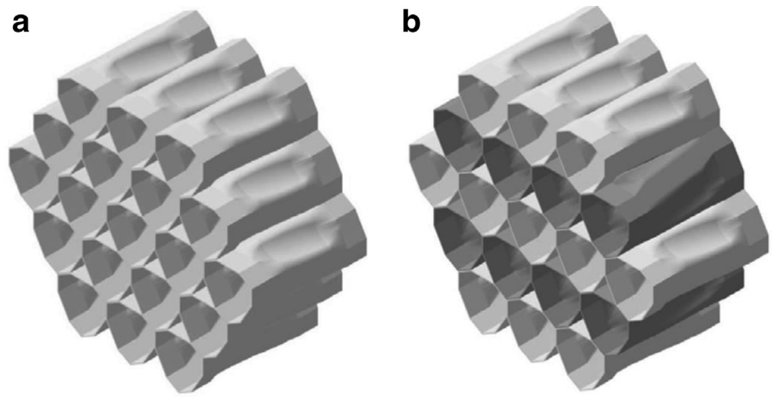

Fig. 1. Modified cell-type spacer grids designed by JSC Mashinostroitelny Zavod: (a) a spacer grid with secondary coolant flows around the fuel rods; (b) a spacer grid with secondary flows between the fuel rod rows а)=a); б)=b).

Russian reactors have led to the development of cell-type [4] and plate-type [5] mixing grids installed into the fuel rod bundles between the standard grids, with no elastic contact between the fuel cladding and the mixing grids.

Subject and method of investigation

The paper considers the possibility for intensifying the mixing in the coolant flow through installation of the modified cell-type spacer grids developed by JSC Mashinostroitelny Zavod, Elektrostal, Russia, [6,7] inside of fuel element bundles. The modified spacer grids differ from standard grids in that they have elastic corrugations on the spacer grid cells contacting the fuel cladding, which are arranged not in parallel with the fuel element axis, as in the case of standard spacer grids, but at an angle to it. The outlet cell section has a tilt of 60° relative to the inlet section, this making it possible to avoid straight through channels in the intercell grid space (Fig. 1). This technologically sound solution enables the flow mixing downstream of the grids to be intensified not only through the flow turbulence, but also thanks to the formation of velocity components in the direction perpendicular to the main coolant flow (directed convective transport).

Inside the cells, the coolant flows in parallel channels formed by the fuel cladding outer surface and the cell inner surface, and separated one from another by corrugations. Therefore, as it reaches the outlet of the modified cell-type spacer grid cell, the flow acquires tangential velocity components with an orientation in accordance with the direction of the corrugation inclination [7]. By arranging the cells with differently directed inclination angles within the spacer grid array, it is possible to generate certain secondary flows inside the fuel rod bundle downstream of the spacer grid. The length of the cells, the number of the corrugations and the corrugation inclination angle will define the coolant vortex intensity inside individual cells, and, therefore, the intensity of secondary flows [8].

Two options are considered for the modified cell-type spacer grids:

- a spacer grid formed by cells with identical corrugation inclination angles (Fig. 1a) that generates secondary coolant flows around the fuel rods (vortex-type);
- a spacer grid formed by cells arranged in alternating rows with different corrugation inclination angle directions (Fig. 1b) that generates secondary coolant flows between the rod rows.

Both grid modifications have 30 mm high cells with three corrugations on their side surface, having an inclination angle of +20° (the spacer grid with secondary coolant flows around the fuel rod) and ± 20° (the spacer grid with secondary flows between the rod rows) relative to the cell axis. Analyzed are 19-cell fragments of spacer grids without a rim (see Fig. 1) installed in a 19-rod bundle. The bundle has a length of 1 m and consists of VVER-1000 reactor fuel rod simulators with a diameter of 9.1 mm, arranged in a regular triangular package with a pitch of 12.7 mm. The fuel bundle, containing a fragment of the analyzed spacer grid, is enclosed in a hexagonal shroud with an internal flat-to-flat dimension of 57.5 mm.

The flow and heat transfer in the fuel bundles were studied based on computational fluid dynamics methods using the STAR-CCM+ software package [9]. The mathematical model used in the calculations is based on averaged continuous medium motion and energy equations closed by a nonlinear (quadratic) turbulent viscosity k-ε-model and an eddy Prandtl number model [8].

Results

Secondary vortex flows with an orientation in accordance with the corrugation inclination direction are generated around each fuel rod at the spacer grid cell outlet. The representative value of the radial velocity in these flows constitutes about 15% of the flow-average velocity value in the fuel bundle. All flows downstream of the spacer grid with no alternating cell rows are directed counterclockwise (Fig. 2a), this causing eddies, rotating oppositely (clockwise), to form inside the triangular subchannels between three adjacent rods. Besides, an annular flow emerges between the peripheral fuel rod row and the shroud, which has the same direction as the flow