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CFD analysis of coolant flow in the nuclear reactor VVER440

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Abstract

The paper introduces results of computational fluid dynamics (CFD) simulations of water flow at the reactor pressure vessel (RPV) outlet and under the RPV head. Several CFD calculations of the steady-state and dynamic processes involving forced and natural circulation of coolant are presented in the paper. In the steady-state regime, several calculations were performed for various number of the reactor coolant system (RCS) loops connected to the reactor and the results have been used to analyse the effect of the RCS configuration to the coolant flow at the reactor outlet and under the reactor vessel head. General flow patterns are described in the outlet part of the reactor and under the reactor vessel head and, also, the influence of a lower flow rate through the reactor on thermal homogeneity of coolant under the vessel head. Simultaneously, we discuss the influence of the coolant flow rate at the core outlet on the heat transfer from the under-head space. Unsteady calculation was also done for a reactor cool-down in the regime of natural circulation. The calculation conditions correspond with the data obtained from the experiments led in the frame of the cool-down process of VVER440 reactor at Mochovce nuclear power plant in 2003. In the calculations, the main attention was applied to establishing the basic trends in the cool-down of water content at the outlet part of the reactor and under the head of the reactor vessel.

Keywords: reactor coolant system, nuclear reactor

1. Introduction

Increasing requirements on nuclear power plants safety and development of new types of reactors impose requirements on accuracy and punctuality of thermo-hydraulic calculations. This leads to situations where the so far used one-dimensional simulation codes (as RELAP5, ATHLET or CATHARE) loose their ability to describe and analyse 3D thermo-hydraulic processes with sufficient accuracy. That is why CFD simulations are gradually gaining more attention.

In the frame of a project funded by the Czech ministry of industry and trade, a very complex CFD model of VVER440 reactor was created. Currently, the model consists of 12 millions computational cells [3]. A series of calculations of flow and heat transfer at the outlet part of the reactor, and mainly under the reactor vessel head, was performed for steady-state and dynamic processes.

The paper deals with computational modelling of flow conditions inside the reactor pressure vessel (RPV) at both forced and natural circulation regimes. Water flow within this reactor area has a strongly three-dimensional character. This fact makes modelling of thermohydraulic processes and subsequent model validation in one-dimensional codes like RELAP5 quite difficult. To perform a detailed flow analysis at the RPV outlet part and in the RPV head

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area, a three-dimensional CFD model of the VVER-440/V213 reactor has been jointly developed by TES and Brno University of Technology

2. Description of the reactor model

The developed 3D CFD model represents a complete pressure vessel of the reactor including the inlet and the outlet tubes. The section across this model is shown in Figure 1. Downcomer, lower and upper mixing chambers, reactor vessel, guide tubes and reactor cover were modelled in detail. The reactor cover was modelled including connecting parts of guide bushes of control rods actuators. There were six coolant system loops connected to the reactor in the type VVER-440. The six inlets were coplanar and outlets are in other parallel plane. Schematic illustration of flow paths is shown in Figure 2. Coolant is guided from inlet connections through a double wall of downcomer to the perforated bottom of the reactor, whence it rises up to the reactor vessel. The perforated bottom was modelled as a porous wall at condition that corresponded to perforation of the bottom. Stream, after passing through the perforated bottom and lower lattice (1), is separated to 312 operational fuel and 37 control bundle channels of the active core (2).

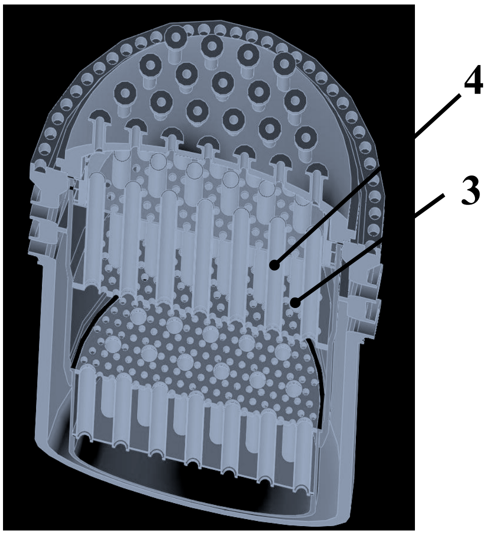

Fig. 1. Section across the reactor model.

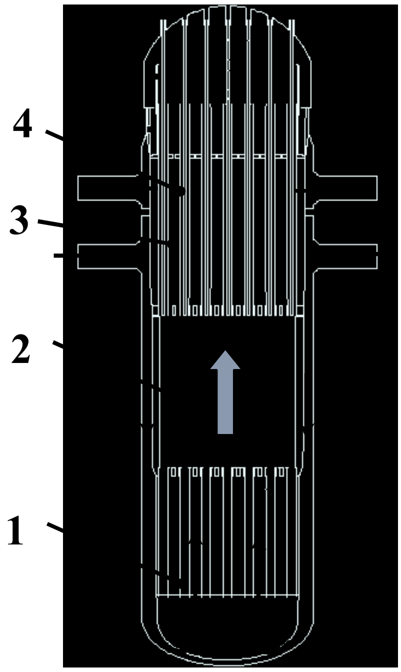

Fig. 2. Scheme of flow paths.

Heated stream leaving the operational fuel bundle channels enters the mixing chamber (3) and heated stream passes through the control bundle channels to the guide tubes (4) and through holes in the walls of the guide tubes further flows to the mixing chamber. From mixing chamber, the coolant flows through the perforated wall of the shaft to the outlet tubes.

The coolant partially flows through the holes in the perforated upper plate under the reactor vessel head and goes on partly through a bypass near the wall to the outlet tubes and partly through guide tubes of the control rods to the mixing chamber. The area under the reactor vessel head is shown in fig. 3.

A schematic illustration of flow paths under the reactor vessel head is shown in fig. 4. The bypass near the wall comprises of a slot between the cover (3) of the reactor, the wall (5) of the reactor vessel head and three square holes (1). The coolant leaves the bypass both through three square holes (2) to the outlet tubes and through the annular slot (6) located along circumference of the perforated upper plate.

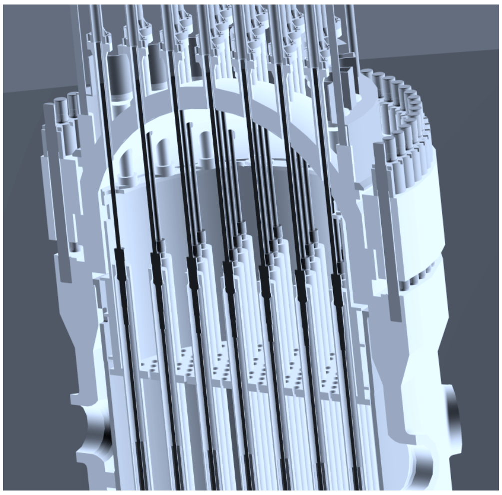

Fig. 3. The area under the reactor vessel head.

A flow field under the reactor vessel head is also influenced by heat dissipation from coolant flow inside the guide bushes of the control rod actuators, which are located above the reactor and were not modelled. Influence of the guide bushes was included into the model using additional sources for momentum and energy inside the entry parts (4) of the guide bushes. The momentum additional sources controlled mass flow rate through the guide bushes of the control rod actuators and the energy additional sources controlled heat dissipation in the model.

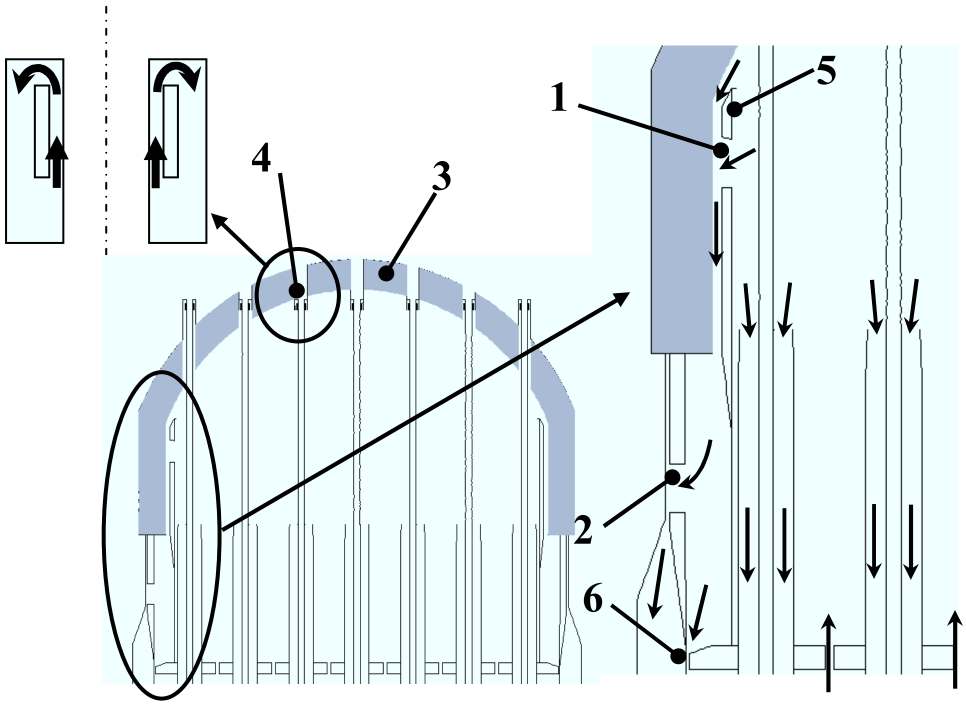

Fig. 4. Schema of flow paths under the reactor vessel head.

Hydraulic and thermal parameters were obtained with the use of a database of measured operational data of the Dukovany nuclear power plant [1]. The mass flow rate through the guide bushes of the control rod actuators is a function of temperature under the cover of the reactor and can be calculated according to the following equation:

$$\dot{m} = 2.75 \cdot 10^{-9} T^3 - 3.39 \cdot 10^{-6} T^2 + 2.08 \cdot 10^{-3} T - 0.1053 \,. \tag{1}$$

Consequently, heat dissipation is a function of the mass flow rate or velocity and it is given by the following equation, where c is specific heat and v is axial velocity:

$$\dot{Q} = c * \left(13013 \cdot v^3 - 1437 \cdot v^2 + 16.4 \cdot v - 0.087\right). \tag{2}$$

The graph, in fig. 5, shows a plot of operational data for mass flow rate and temperature of cooled coolant at the outlet of the guide bushes of the control rods actuators against temperature under the cover of the reactor. The second graph (fig. 6) shows radial power distribution of active core. Distribution of pressure drop of active core was specified via hydraulic resistances of operational fuel and control bundle channels of active core. These hydraulic resistances were determined based on the complex pre-operational measurement of hydraulic characteristics of the system. Hydraulic resistance coefficient for operational fuel and control bundles are given by following equations:

$$\xi_{OB} = 43{,}22 \,.\, Re^{-0{,}121} \,, \tag{3}$$

$$\xi_{CB} = 42{,}5 \,.\, Re^{-0{,}0886} \,. \tag{4}$$

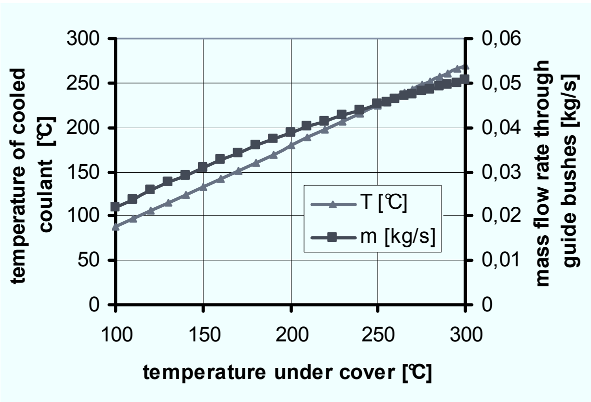

Fig. 5. Operational data for guide bushes of the control rod actuators.

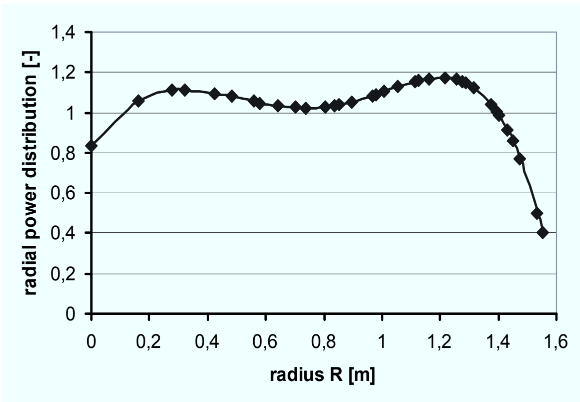

Fig. 6. Radial power distribution of active core.

3. Steady state asymmetric modes

Understanding of the flow field under the reactor vessel head is very important for an after cooling process of the reactor when there is a various number of reactor coolant system loops (CSL) connected to the reactor. This is, especially, of great importance in the case of the emergency regime, because heat dissipation from the primary circuit is not always operating with full number coolant loops in this case. The aim of these calculations was to determine the velocity profile and the flow rate at the upper perforated plate under the reactor vessel head in case of a various number of coolant loops. These parameters are the main factors affecting the cool down of the reactor cover, because deformed velocity profiles lead to an asymmetrical flow field, which has the impact on the temperature field under the reactor cover. Simulations were done for 6, 5, 4, 3, 2 and 1 connected coolant loops. Simulation conditions corresponded to a stand off condition of the reactor with the residual power of active core (AC) 9 MW. The simulation conditions are presented in tab. 1.

number of CSLs	T in [°C]	mass flow rate through the AC [kg/s]	mass flow rate per an operating CSL [kg/s]	mass flow rate per a stand-off CSL [kg/s]
6	261,4	8889,7	1482	-
5	261,4	7463,6	1614	-606
4	261,5	5877,6	1704	-465
3	261,5	4310,4	1779	-342
2	261,6	2769,0	1816	-215
1	262,0	1321,0	1859	-107

Tab. 1. Simulation conditions.

Results of the calculations are presented in a form of mass flow rate through upper perforated plate (position 5 fig. 2), control rod guide tubes in the level of the upper perforated plate, and the reactor vessel head bypass, respectively. Values of these parameters are shown in the graph in fig 7 and in tab. 2, where the comparison of these mass flow rates with total mass flow rate through the active core is also presented. The positive sign indicates the flow direction into the area under the reactor vessel head and the negative sign indicates the outward flow.

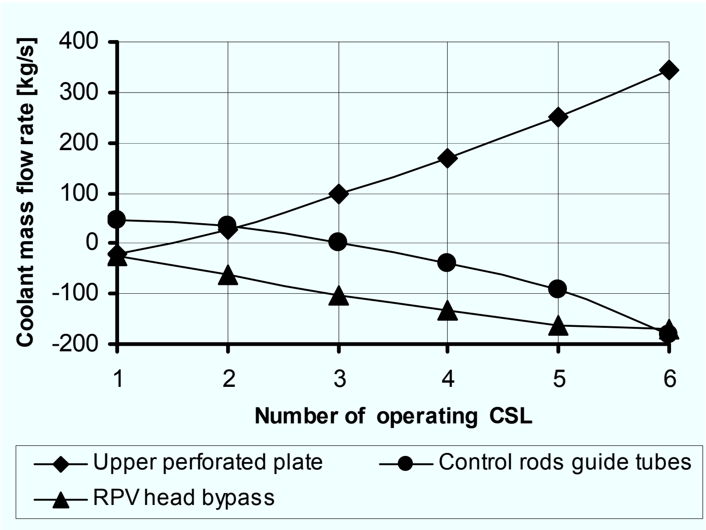

Fig. 7. RPV head coolant flow rate.

The data show that the coolant flows in through 312 holes of upper plate only, and approximately 70 % of the coolant flows back to the mixing chamber through the guide tubes. The remaining 30 % of the coolant flows outwards through the bypass directly to the area of outlet tubes. The graph in Figure 7 shows that the total flow rate to the space under the reactor cover decreases approximately linearly with decreasing number of coolant loops. Fig. 8 gives an overview of the flow fields under the upper perforated plate. There are axial velocity fields for individual variants across sections which correspond to the level of the outlet tubes shown there.

	Number of operating CSL					
	6	5	4	3	2	1
	Coolant mass flow rate [kg/s]					
Upper perforated plate	344,5	249,8	168,1	99,3	26,1	-20,7
Control rods guide tubes	-180,8	-93,6	-38,8	3	34,1	46,7
RPV head bypass	-171	-161,5	-131,5	-104,4	-60,9	-26,1
	Flow ratio (% of total active core outflow)					
Upper perforated plate	4	3,4	2,9	2,3	0,9	-1,6
Control rods guide tubes	-2,1	-1,3	-0,7	0,1	1,2	3,5
RPV head bypass	-2	-2,2	-2,2	-2,4	-2,2	-2

Tab. 2 Mass flow rate through under the reactor cover.

Fig. 9 and 10 show the axial velocity profiles across section of the upper perforated plate for a variants of 6 operating CSL and 3 operating CSL, respectively [4]. In case of 3 operating CSL can be seen markedly asymmetrical velocity profiles unlike case of 6 operating CSL. There is predominating flow upwards through 312 holes and downwards flow through guiding tubes.

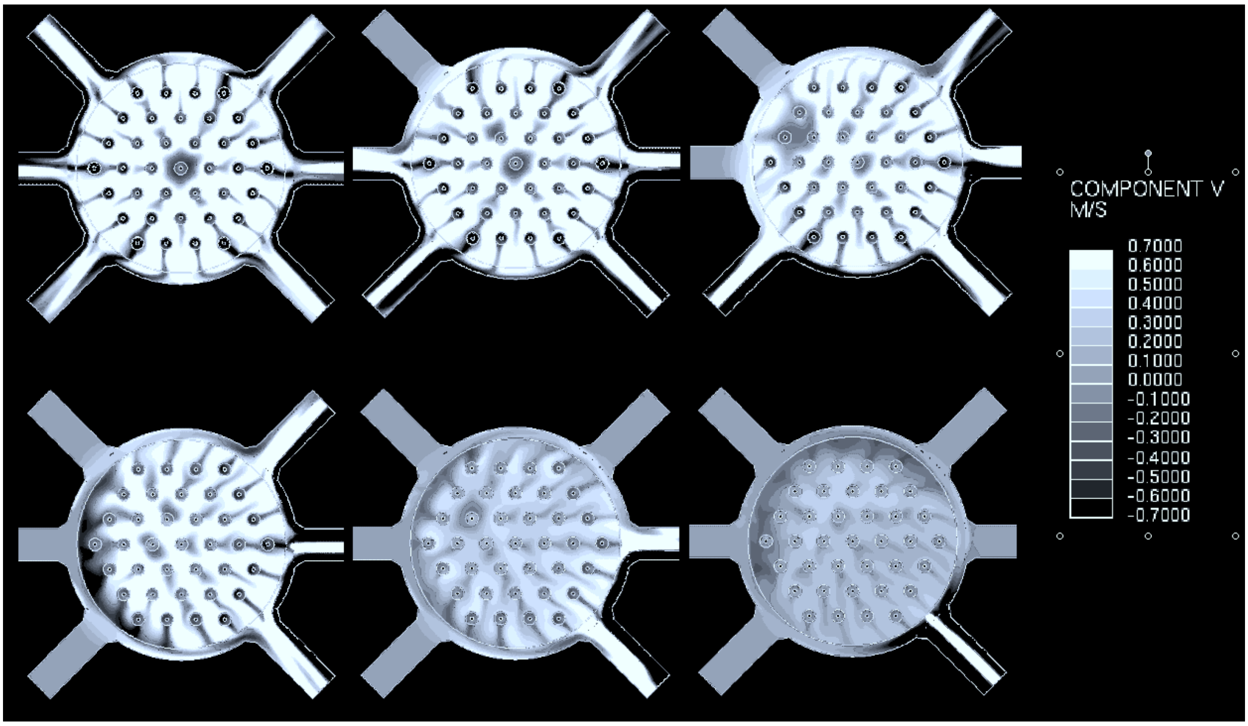

Fig. 8. Axial velocity fields at the level of the outlet tubes.

Downwards flow is remarkably larger for circumferential guide tubes. Basically, for the coolant flow through upper perforated plate, we can say that the area of higher upwards flow was moved towards stand off coolant loops and vice versa higher downwards flow was moved towards operating coolant loops.

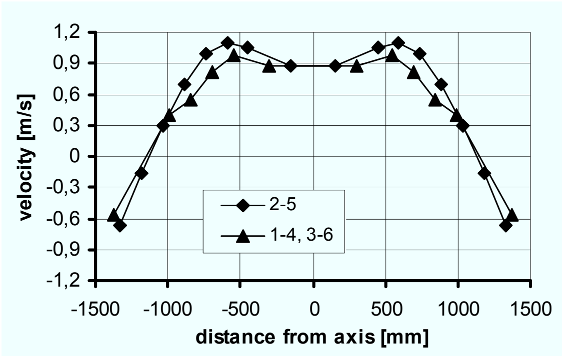

Fig. 9. Axial velocity profiles at the level of upper perforated plate for 6CSL.

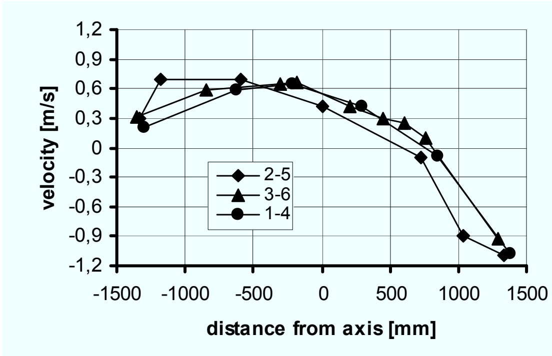

Fig. 10. Axial velocity profiles at the level of upper perforated plate for 3CSL.

4. Unsteady cool-down mode

The aim of unsteady simulations in cooldown modes was to obtain information about the limiting trends of the reactor cooldown in case of natural circulation, and to analyse critical thermo-hydraulic phenomenon under the reactor head that may cause development of a steam bubble under the cover. One of the most important factors in case of natural circulation in cooldown modes is stagnation of cover and coolant temperature. Insulating properties of cover external surface and hydraulic resistance of upper perforated plane are among the causes of temperature stagnation under the cover in comparison with coolant temperature after passing the active core. These properties reduce coolant flow above the upper plane of the mixing chamber. Coolant flow, above the upper plane, was sufficient to cover cooldown in a mode of forced circulation, but natural circulation reduced the coolant flow above the upper plane by two orders in magnitude.

There are results of simulation which correspond with operational data measured on 2nd unit of the nuclear power plant Mochovce [2] presented in the paper. Simulation parameters corresponded to a stand off condition of the reactor with residual power of the active core approximately 9 MW. Initial conditions were obtained from steady-state calculation and boundary conditions followed the operational data measured. Time temperature profiles under the reactor cover were measured by a thermal sensor of the guard system of coolant circuit. The temperatures of the coolant were also measured at inlets and outlets tubes.

The patterns of temperatures and flow rates indicate that after the onset of the controlled cool-down regime (with the trend of 15°C/hr) the flow rates under the reactor cover are significantly decreasing (nearly to zero). The flow rates under the reactor cover during a time period of 10 000 are plotted in the chart in fig. 11. The coolant flow under the cover restores when the coolant temperature above and below the perforated plate reach the same value (time 6600s).

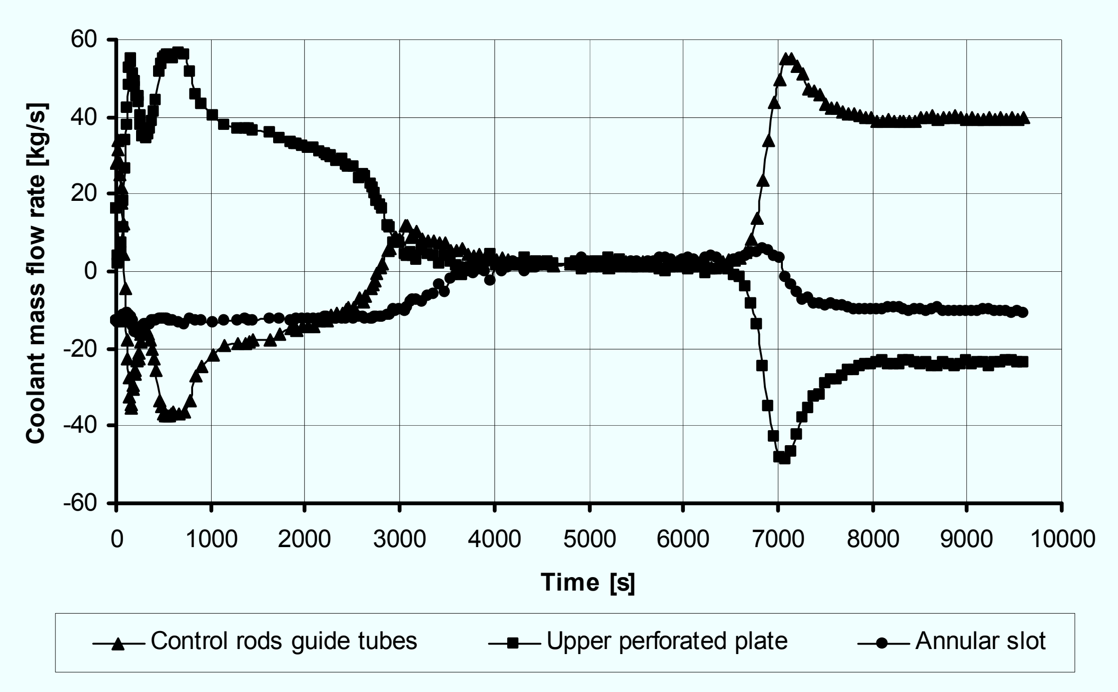

Fig. 11. Coolant flow rate under the reactor cover.

5. Conclusion

Based on set of steady state calculations of the coolant flow in asymmetrical modes, increasing degree of flow asymmetry under the reactor vessel head is clear. It corresponds to decreasing number of operating coolant system loops of the reactor. Basically, for coolant flow through the upper perforated plate, we can say that the area of higher upwards flow was moved towards stand off coolant loops and, vice versa, higher downwards flow was moved towards operating coolant loops. Total flow rate through the individual stream paths is decreasing approximately linearly together with decreasing number of operating coolant loops.

Acknowledgments

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