DEVELOPMENT OF A 3D MODEL OF TUBE BUNDLE OF VVER REACTOR STEAM GENERATOR

V.F. Strizhov, M.A. Bykov, A.Ye. Kiselev A.V. Shishov,
A.A. Krutikov, D.A. Posysaev, D.A. Mustafina

IBRAE RAN, Moscow, Russia

Abstract

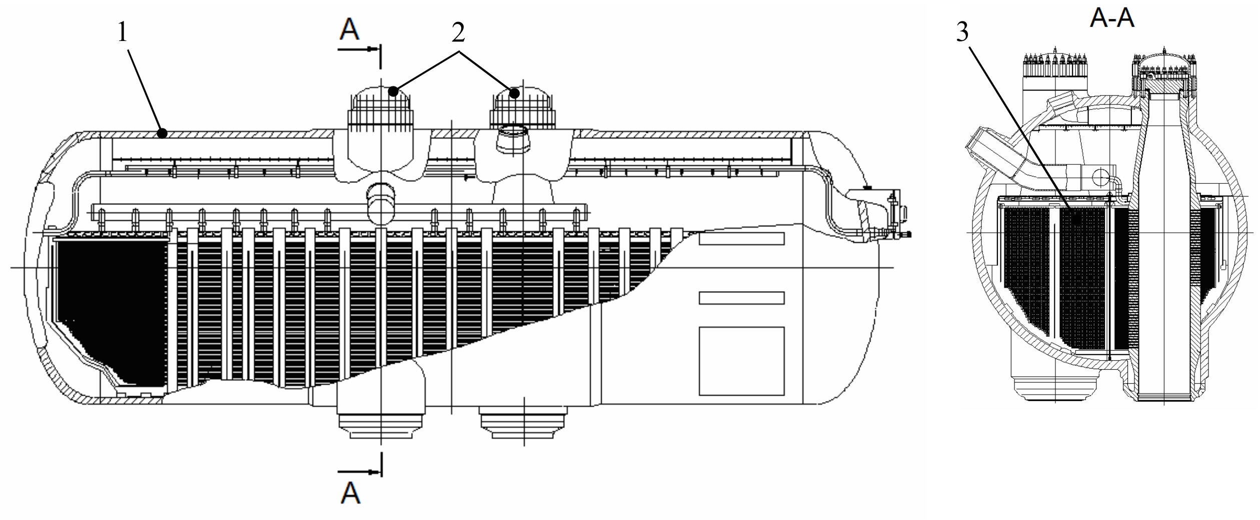
A three-dimensional model was developed for studying the hydrodynamics flow of the primary side of the steam generator circuit for simulation of design-basis and beyond design-basis accidents of NPP with VVER reactors. The model describes the hot and cold steam generator collectors, and all the interconnecting heat exchanging tubes. In order to reduce the dimension of the calculation grid, and to allow for numerical solution of the problem, it was proposed to simulate the flow inside the tube bundles utilizing the porous body model. A number of calculations of pressure and coolant velocity fields inside the heat exchanging tubes was carried out using ANSYS CFX and STAR-CD codes in order to confirm the applicability of the porous body model. The results were compared with the analytical values of pressure losses for a number of typical heat-exchanging tube dimensions.

The comparison demonstrated the adequacy of applying the porous body model for the study of hydrodynamics of the steam generator tube bundle. The resultant dimension of the calculation grid was about 3.5 million control volumes. STAR-CD was applied in a series of calculations aimed at measuring the pressure fields and coolant velocities in the flow part of the primary side of the steam generator. A distribution of coolant flow along the heat exchanging tubes characteristic for π-shaped collector system was obtained as a result of the analysis.

1. STRUCTURE DESCRIPTION

The steam generator is a single-body horizontal heat exchanging apparatus with immersed heat exchanging surface (figure 1). It includes a vessel, two elliptic bottoms and a number of nozzles of various purposes. Inside the generator there are two collectors with bundles of heat exchanging tubes, an immersed perforated sheet, a device for feedwater supplying and distributing, as well as the top perforated sheet.

The collector of the steam generator primary circuit is a thick-walled cylinder with variable diameter and thickness. The cylindrical part of the collector has a perforated section for mounting the ends of heat exchanging tubes. The bores on the outer surface of the collector are located in a staggered order. The heat exchanging surface includes approximately 11 000 tubes with an internal diameter of 13 mm. The heat exchanging tubes have U-shaped coils and are collected in heat exchanging bundles. The tubes are spaced inside the bundle in a corridor order. The tubes are separated from one another with wavelike strips and flat laths. The design of tube mounting takes into account their thermal expansion.

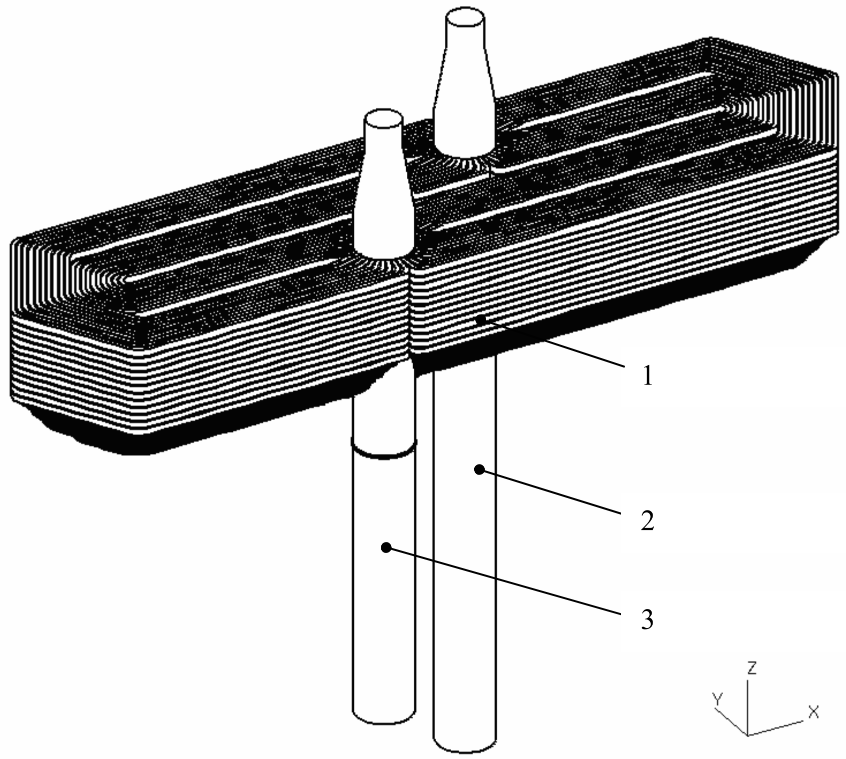


1 – vessel, 2 – collectors of the first circuit,
3 – heat exchanging tubes bundle

Fig. 1. Diagram of steam generator

2. CALCULATION METHODOLOGY

The calculation area shown in Fig. 2 covers inlet (hot) and outlet (cold) collectors as well as heat exchanging tubes connecting thereof to study hydrodynamics of steam generator primary circuit flow-through. Coolant flow stabilization at inlet collector requires modeling of 4-meter pipeline cylinder part. In much the same way 6-meter pipeline cylinder part was modeled at outlet collector.



1 – heat exchanging tube bundle; 2 – outlet collector; 3 – inlet collector.

Fig. 2. Calculation area

Numerical solution of 3D problem by using CFD codes requires the calculation grid exceeding 1 billion of control volumes. Now this makes the problem irresolvable. But it is possible to replace three-dimensional modeling of liquid flow in the tubes with hydraulically equivalent one-dimensional ratios considering such peculiarities as explicitly demonstrated one-direction flow in heat exchanging tubes and dominant affect of friction in the structure of hydraulic losses.

Therefore the calculation area consisting of inlet collector, heat exchanging tube bundle and outlet collector can be replaced by simplified calculation model – 3D collectors and one-dimension tube bundle rather than use standard calculation model (3D collectors and 3D tube bundle). This simplified calculation model can be applied as follows: option 1 – each heat exchanging tube is replaced by equivalent one-dimension bond and option 2 – several near-by located tubes are assembled in a single tube bundle. This option is based on the assumption of negligible change of hydraulic resistance of the tubes located close to each other.

Thus it is proposed to calculate collector pressure drop (Δp) at each tube or tube bundle to model hydrodynamics of heat exchanging tube bundle by using

$$\Delta p = \xi \frac{\rho U^2}{2}, \tag{1}$$

where ρ - coolant density, kg/m^3; U - coolant average weight velocity, m/s; ξ - coefficient of hydraulic resistance as

$$\xi = \frac{L}{d} \frac{0.3164}{\mathrm{Re}^{0.25}}. \tag{2}$$

Here d – heat exchanging tube diameter, m; L - heat exchanging tube length, m; Re – Reynolds number.

Porous body model built in STAR-CD can be used to apply the proposed simplified model in STAR-CD and perform modeling of one-dimensional coolant flow along the tubes or tube bundles instead of making 3D calculation of each heat exchanging tube. This will allow reducing calculation grid dimension by three orders.

Equality of hydraulic losses (if the flow rate is similar) is the condition of equivalency of the calculation by using porous body model and 3D calculation of each heat exchanging tube:

$$\Delta p = \xi \frac{\rho U^2}{2} = \frac{\mu \Phi L}{k}, \tag{3}$$

where μ - dynamic viscosity, kg/(m·s); k - porous block permeability, m^2; Φ - velocity of coolant filtration in porous block, m/s.

Coolant filtration velocity in porous block correlates with average weight velocity as

$$\Phi = \varphi U. \tag{4}$$

where φ - porosity which is the ratio of coolant volume in porous body block to the volume of entire porous block..

The above dependences provide the possibility to explicitly obtain permeability value for each porous block.

A set of calculations of pressure fields and coolant turbulent flow velocity in heat exchanging tubes was performed by using ANSYS CFX and STAR-CD to justify the applicability of one-dimensional model of porous body for the description of hydrodynamics in heat exchanging tubes. Additionally the comparison with analytical values (1) of pressure losses was conducted for separate distinctive dimension-types of heat exchanging tubes.

All 3D calculations were performed by using two codes at similar calculation grids of 60,000 – 300,000 control volumes by using deference schemes of the second order. The calculations are performed for four optional designs of heat exchanging tubes (Fig. 3). Fig. 4 shows the calculation grid in heat exchanging tube cross-section.

Analytical values of hydraulic losses Δp (1) are identified for each design of heat exchanging tube taking into account the losses due to friction and local resistance under average coolant velocity of 4.5 m/s. Numerical three-dimensional and one-dimensional calculations were performed for the same pressure drops. Comparison data shown in Table 1 demonstrate that deviation of calculated values of average weight velocity does not exceed -5.0 % for both single tube and tube bundle. The results of the studies allow making conclusion on the adequacy of one-dimensional procedure for calculation of hydrodynamics in heat exchanging tubes by using porous body model.

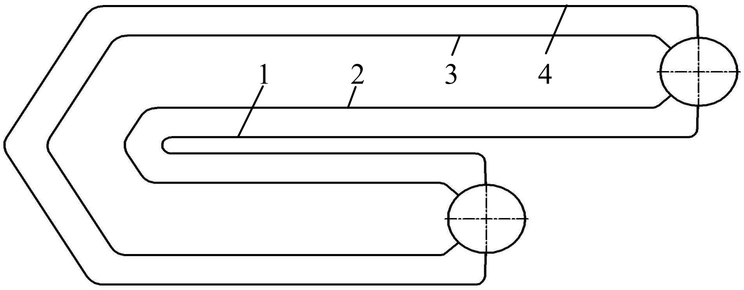


Fig. 3. Four design options of heat exchanging tubes

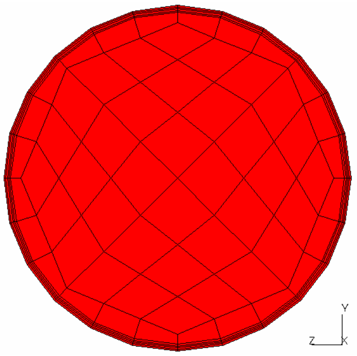


Fig. 4. Calculation grid in heat exchanging tube cross-section

Table 1. The results of numerical modeling of heat exchanging tubes hydrodynamics

Option	ΔP, Pa	Three-dimensional calculation				One-dimensional calculation			
		CFX		STAR-CD		STAR-CD, φ = 1		STAR-CD, φ = 0,25	
		U, m/s	Deviation, %	U, m/s	Deviation, %	U, m/s	Deviation, %	U, m/s	Deviation, %
1	$1.785\cdot10^5$	4.350	3.33	4.289	4.69	4.536	0.80	4.532	0.71
2	$1.781\cdot10^5$	4.465	0.78	4.307	4.29	4.526	0.58	4.528	0.62
3	$2.314\cdot10^5$	4.475	0.56	4.304	4.36	4.521	0.47	4.524	0.53
4	$2.705\cdot10^5$	4.440	1.33	4.302	4.40	4.523	0.51	4.524	0.53

Two configurations of collector systems (horizontal and vertical (Fig. 5)), which inlet and outlet tubes of large diameter were connected by 9 tubes of smaller diameter, were studied to justify the compliance of simplified calculation methodology (3D-1D-3D) with standard one (3D) for collector effects modeling. Hydrodynamic modeling for these configurations of collector systems was performed using both simplified and full-scale 3D modeling methodology. Numerical calculation was conducted at the grids of 770,000 – 2,400,000 control volumes for horizontal collector system and at the grids of 320,000 – 3,500,000 control volumes for vertical collector system in case of full-scale 3D calculation methodology and at the grids of 200,000 control volumes in case of simplified calculation methodology (3D-1D-3D).

Fragments of the grids which illustrate the peculiarities of tube connection with collectors are shown in Figs. 6 and 7 for horizontal and vertical collector systems respectively. Deference schemes of the second order as well as semi-empirical turbulence models of κ-ω type were applied and used for digitization. The calculations were performed under average weight velocity value. The calculations were performed when average weight velocity value was equal to 0.1 m/s. The results of numerical calculations of horizontal collector system and the results obtained according to [1] are shown in Table 2.

The comparison demonstrated that the error did not exceed 6.5 % for connecting tube length of 0.6 meters and dropped up to 0.5 % when the length was increased up to 6 meters. Similar results were obtained for vertical collector: maximum errors dropped from 6 % to 1 % when the length of connecting tubes was increased from 1 to 10 meters. The analysis of the studies performed allows making conclusion that it is possible to apply simplified methodology to calculate hydrodynamics in collector systems consisting of inlet and outlet collectors linked by connecting tubes.

Table 2. The results of modeling of horizontal collector system hydrodynamics

Tube bundle length, m	Pressure losses Δp, Pa	Analytical value Δp, Па	3D calculation	Deviation, %	3D-1D-3D calculation	Deviation, %
0.6	General	1939	2025	4.45	1832	5.52
	at tube bundle	1136	1174	3.34	1208	6.30
6	General	11799	11821	0.18	11754	0.37
	at tube bundle	11360	11384	0.21	11304	0.49

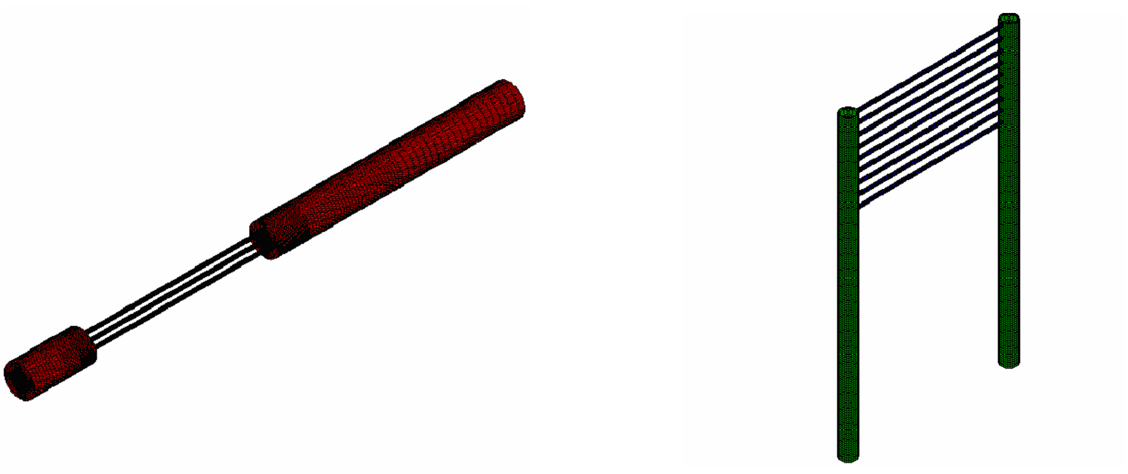

a) б)

Fig.5. Collector systems: a) horizontal б) vertical

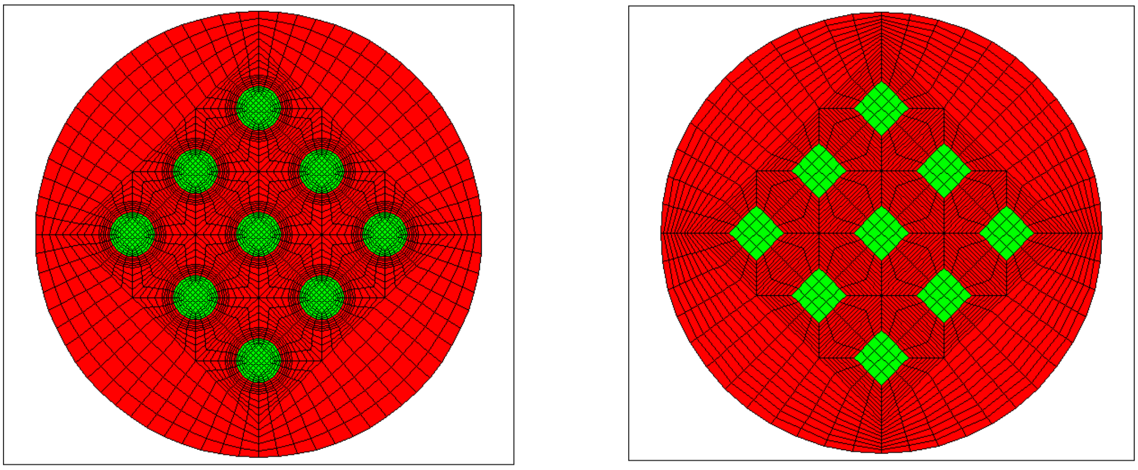
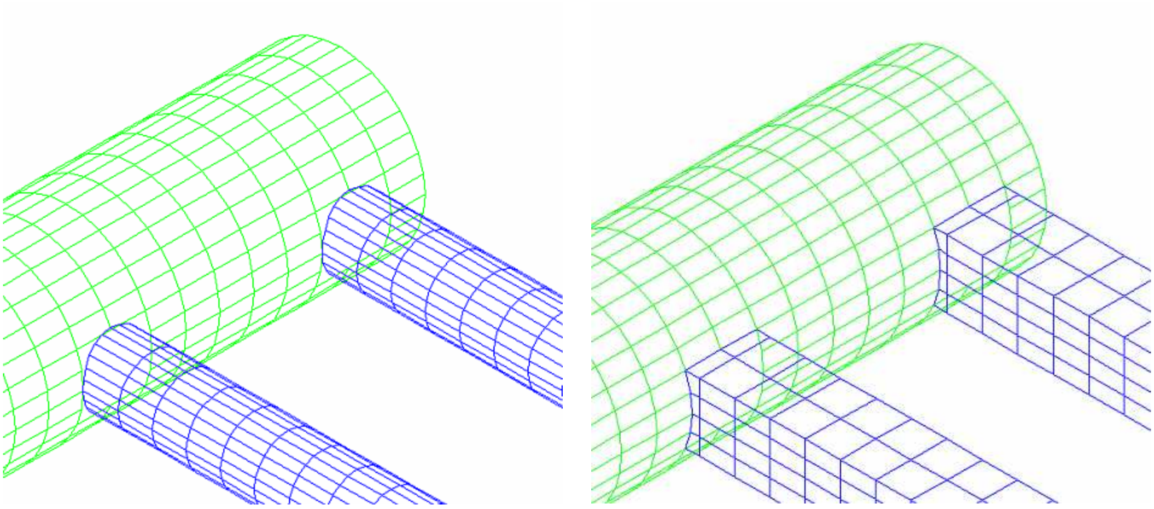

a) б)

Fig.6. Cross-section of horizontal collector system grid:
a) tubes; б) porous bodies.



а) б)

Fig.7. Fragment of vertical collector system grid: а) tubes; б) porous bodies.

3. THREE-DIMENSIONAL MODEL

Two three-dimensional models were developed for studying the hydrodynamics of the flow in the primary part of the steam generator in process of simulating design-basis and beyond design-basis accidents of NPP with VVER reactors. The models describe the hot and cold steam generator collectors, and all the interconnecting heat exchanging tubes. The first model includes 738 blocks of heat exchanging tubes, when every block is considered as a one-dimensional porous structure. Each block includes of 4 to 18 heat exchanging tubes. The number of control volumes in the block cross-section perpendicular its axis corresponds to the number of heat exchanging tubes in each block. The resultant dimension of the calculation grid for the first model is 2.5 million control volumes. The second model described each heat exchanging tube as an individual porous body. The dimension of the calculation grid was 3.5 million control volumes.

Figure 8 shows the position of heat exchanging bundle cross-section used for calculations of relative static pressure and coolant velocity fields. Figure 9 shows the calculation grid of the first model in the tube bundle cross-section. The porosity parameter is $\varphi = 0.33$. Figure 10 shows the calculation grid of the second model for the same tube bundle cross-section. The porosity parameter is $\varphi = 1$.

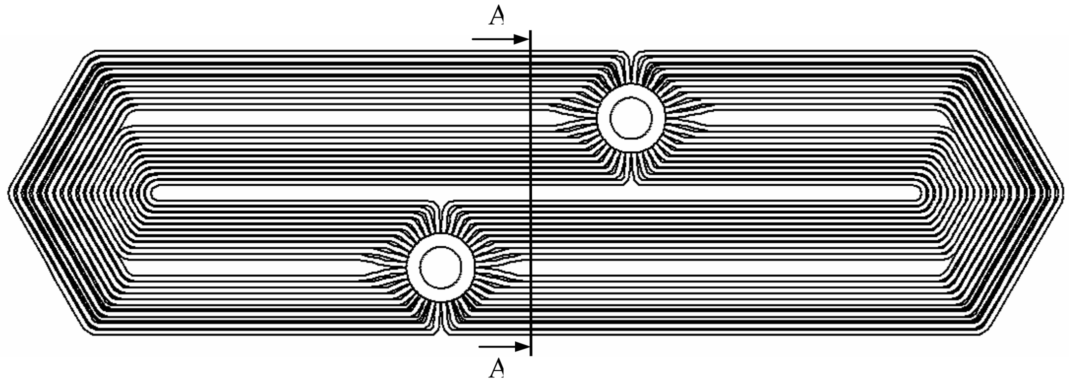


Fig. 8. Position of heat exchanging tubes bundle cross-section

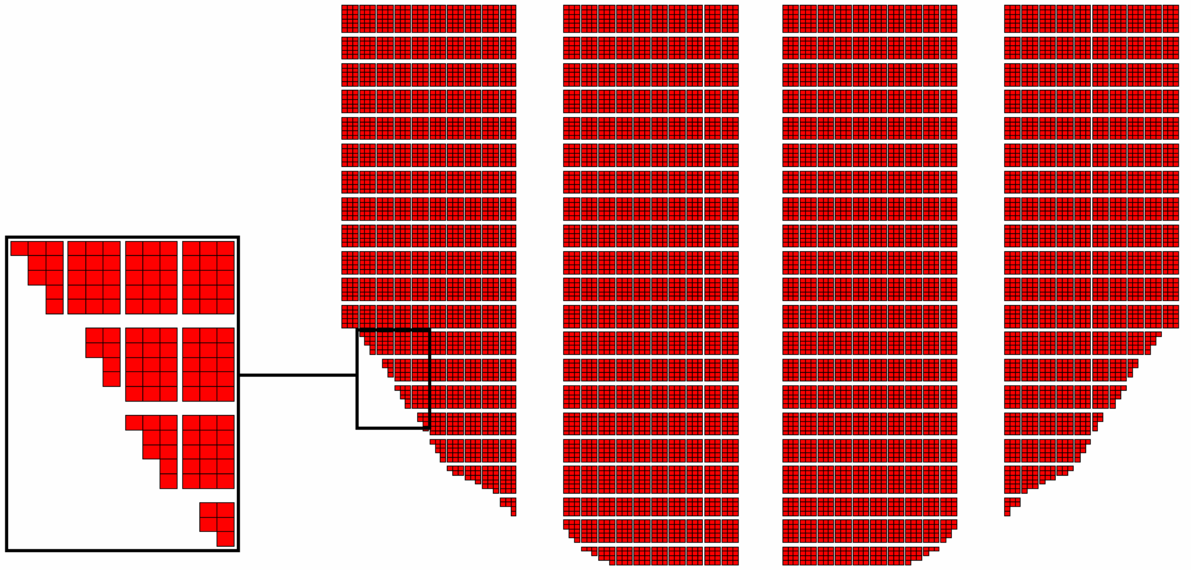


Fig. 9. Calculation grid in the tube bundle cross-section
(heat exchanging surface is represented by blocks of heat exchanging tubes)

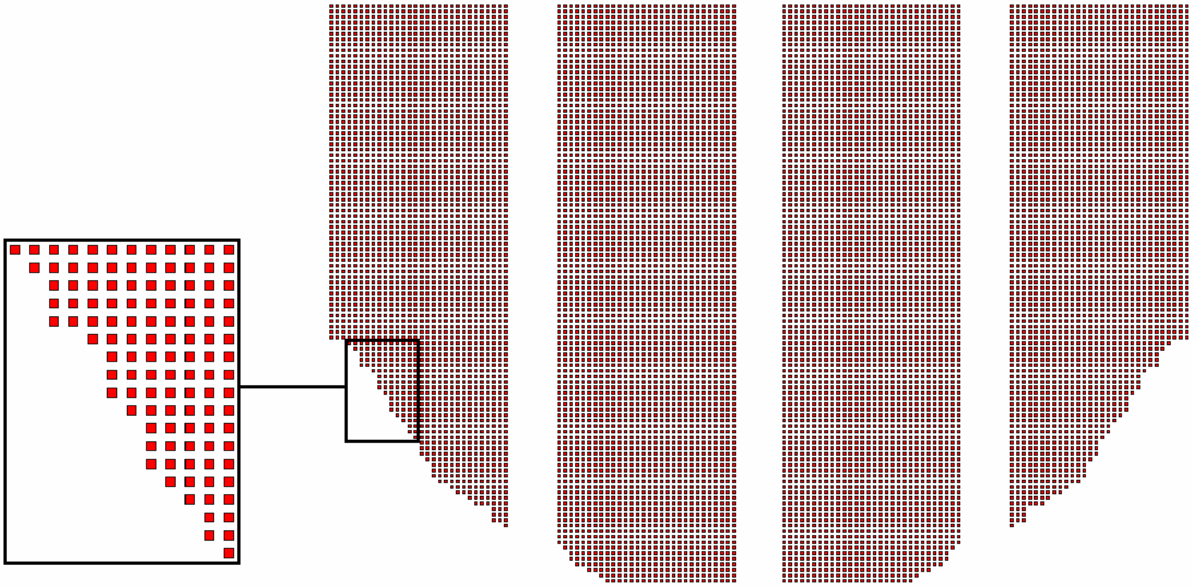


Fig. 10. Calculation grid in the tube bundle cross-section
(heat exchanging surface is represented by each tube individually)

4. CALCULATION RESULTS

The developed three-dimensional models were used to determine pressure fields and coolant velocities of the flow in the primary side of steam generator. Two variants of calculations were carried out for the first model. UD type first order digitization was used in the first case and MARS type second order digitization was used in the second case. UD-type first order digitization was used for calculations with the second model. The coolant flow is 21500 m^3/h at the temperature of 315 °C.

Figures 11 – 16 show the pressure and coolant velocity fields in the transverse A-A section of the tube bundle shown in figure 8. Calculation results shown in figures 11 – 14 were obtained using the first model, and those shown in figures 15 and 16 were obtained using the second model.

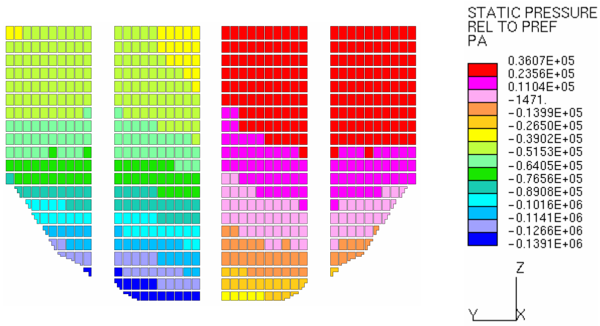


Fig. 11. Relative static coolant pressure field inside the tube bundle
(UD-type digitization circuit)

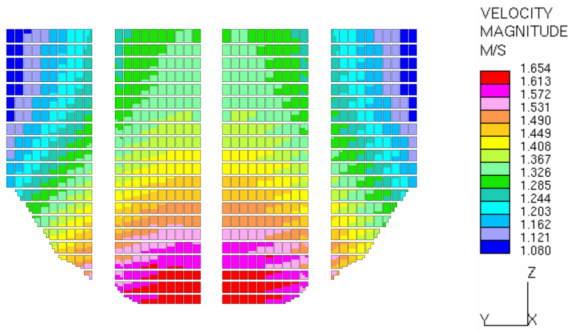


Fig. 12. Coolant velocity field inside the tube bundle
(UD-type digitization circuit)

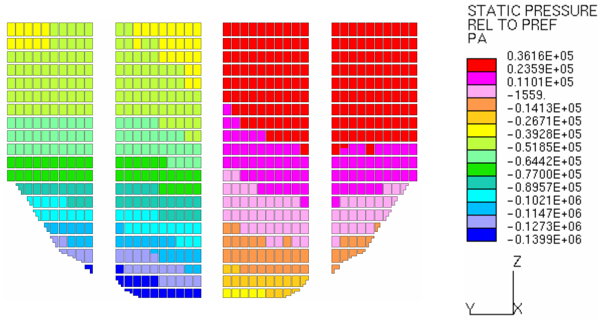


Fig. 13. Relative static coolant pressure field inside the tube bundle
(MARS-type digitization circuit)

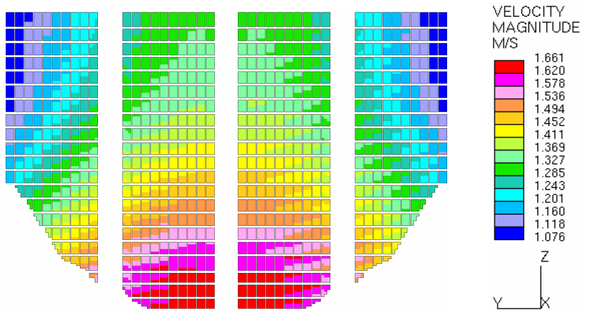


Fig. 14. Coolant velocity field inside the tube bundle
(MARS-type digitization circuit)

Static pressure drop between inlet of the hot collector and outlet of the cold collector was approximately 0.14 MPa. Maximum coolant velocity is found in the tubes located near the inlet of the perforated part of the hot collector. True coolant velocity in the heat exchanging tube can be found by dividing the filtering rate given in figures 12 and 14 by the porosity of $\varphi = 0.33$. The maximum coolant flow velocity inside the heat exchanging tubes is equal to 5.03 m/s, while the minimum is 3.26 m/s. Minimum coolant flow velocity is found at the tubes with the highest hydraulic resistance. In the current case these are the longest tubes.

Figures 15 and 16 show the distribution of the relative static pressure and the coolant filtering rate inside the heat exchanging tubes for UD-type first order digitization. Figure 13 gives the true coolant velocity, as the porosity in this model is equal to 1. The maximum coolant flow velocity inside the heat exchanging tubes is equal to 4.80 m/s, while the minimum is 3.32 m/s. The ratio of these velocities is 1.45, corresponding to the maximum ratio of the flow rates of the heat exchanging tubes.

The difference between the maximum coolant flow velocities for two models is to be found less than 5 %.

The future stages of work assumes implementation the models developed for aerosol deposition in the tube bundle. For this purpose, some of the heat exchanging tubes, previously replaced by the porous body model, will be simulated by a three-dimensional grid. The analysis will include two models for interaction of the gaseous flow with the droplets of the liquid phase and the walls of the pipes.

Fig. 15. Relative static coolant pressure field inside the tube bundle
(UD-type digitization circuit)

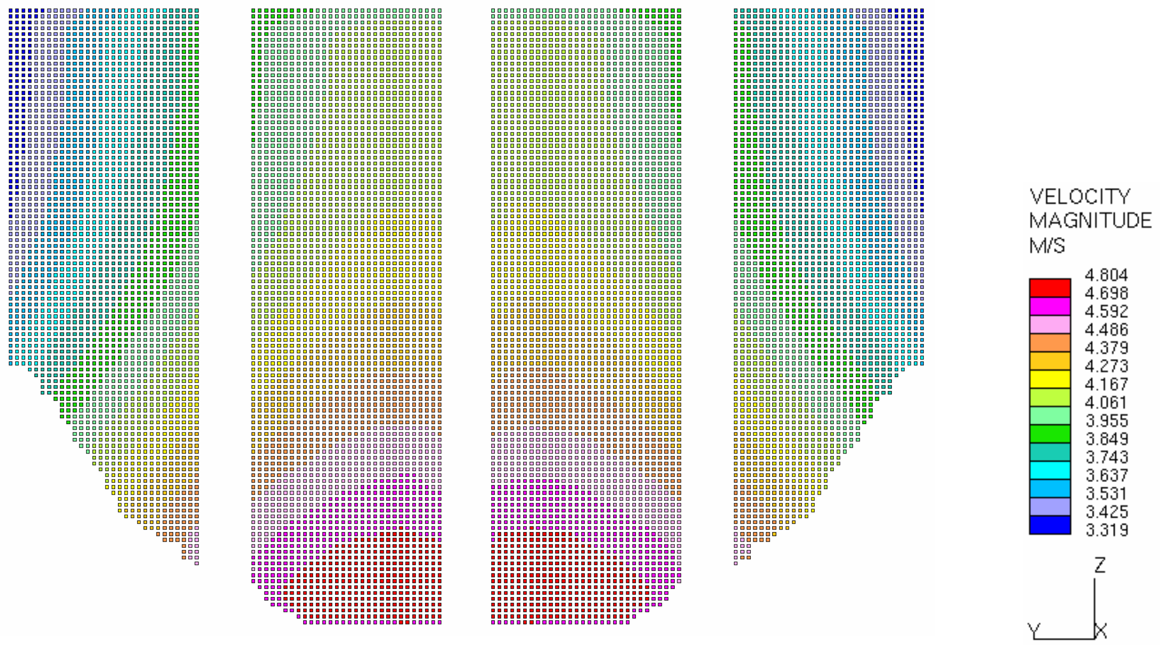


Fig. 16. Coolant velocity field inside the tube bundle
(UD-type digitization circuit)

Conclusions:

1. A full-scale three dimensional model simulating hot and cold collector, as well as blocks of heat exchanging tubes with a size of 2.5 million control volumes was developed in order to study the hydrodynamic flow in the primary side of steam generator. The heat exchanging tubes were replaced by a model of a single-dimension porous body applied for 738 tube blocks.

2. A three-dimensional model of the flow in the primary side of steam generator consisting of approximately 11 000 heat exchanging tubes, simulated individually by the model of single dimension porous body, was developed. The dimension of the calculation grid was 3.5 million control volumes.

3. Numerical experiments allowed to obtain pressure fields and coolant velocities through the heat exchanging pipes for normal flow rates through SG. The maximum coolant flow velocity inside the heat exchanging tubes is equal to 5.03 m/s, while the minimum is 3.26 m/s.

4. The developed three dimensional model and the analysis method can be used for justification of design solutions and analysis of both design-basis and beyond design-basis NPP accidents with VVER reactors.

REFERENCES

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