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Study of the three-dimensional flow characteristics inside the WWER-440 fuel assembly

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Abstract: Lumped parameter codes such as RELAP and TRACE are the thermal hydraulic codes that are usually used for nuclear safety analysis of various nuclear plants such as the Armenian Nuclear Power Plant. These codes calculate the pressure drop inside reactor fuel assemblies based on head loss coefficient data that is input. The coefficient data is usually obtained empirically using experiments which involve geometries that may not be entirely applicable to the WWER-440 fuel assembly geometry. Computational fluid dynamics codes such as ANSYS CFX may be used to remedy this situation by providing head loss coefficient data specifically tailored for the specific fuel assembly in use. Thus, a computational fluid dynamics model of flow through the fuel assembly of a WWER-440 nuclear reactor was created using ANSYS-CFX and analyzed to obtain the specific head loss coefficients that could then be applied back to RELAP and TRACE 1D codes to analyze the pressure drop in the core. The boundary data for the CFD model was obtained from the corresponding model solved in RELAP with the aforementioned coefficient data. The results of the analysis showed that during nominal state of ANPP fuel assembly lattices cause significant pressure losses. Calculation results for two lattices in different locations showed that pressure drops in lattices were equal. However, the lower lattice creates a comparably small pressure drop due to a larger flow area. The local resistance coefficients for the upper lattices were 0.332 and 0.335. The lower lattice has a local resistance coefficient of 0.372. During natural circulation, however, the results showed the pressure changes to be mostly linear along the fuel assembly with a small deviation occurring at lattices. Linearity of pressure changes across fuel assembly are mainly due to the small velocity which leads to small wall shear stress.

Keywords: ANSYS CFX, Computational Fluid Dynamics, WWER-440, Fuel Assembly Modeling, Nuclear Safety, Thermal Hydraulics.

1 Introduction

One of the important components of reactor vessel internal is fuel assembly which has complicated geometry leading to uncertainties during process of head losses calculation with standard methodology. Also lumped parameter models do not consider non-uniformity of flow in fuel assembly which directly affects the heat transfer from fuel rods. In the current paper it was decided to develop model of WWER-440 core fuel assembly and investigate flow characteristics inside fuel assembly during accident conditions. Results of assessment will be used to assess the pressure losses in different parts of fuel assembly.

The present paper has been prepared with the purpose to document the results of the analysis. Particularly, the following topics were addressed in the current activity:

- Analysis of coolant flow characteristics in fuel assembly,
- evaluation the pressure head loss coefficient,
- Improvement of ANPP RELAP5 system TH code model,

Calculations were performed for normal operation condition of ANPP and for condition with natural circulation.

2 Fuel assembly model

Fuel assembly is structured to group fuel rods, in which heat from nuclear fission is generated. Depending on the reactor type fuel assembly design and number of fuel rods can differ. The fuel assembly in WWER-440 type reactors contains 126 fuel rods and one hollow central tube (Figure 1: WWER-440 fuel).

Geometrical model of fuel assembly was developed using ANSYS-CFX. Design-Modeler. The detailed model was created, which consists of the following bodies:

- Cylindrical bottom part,
- Fuel assembly shell,
- Fuel rods, central rod,
- Grids,
- Top part.

The geometrical model of fuel assembly is presented in **Hata! Başvuru kaynağı bulunamadı.**.

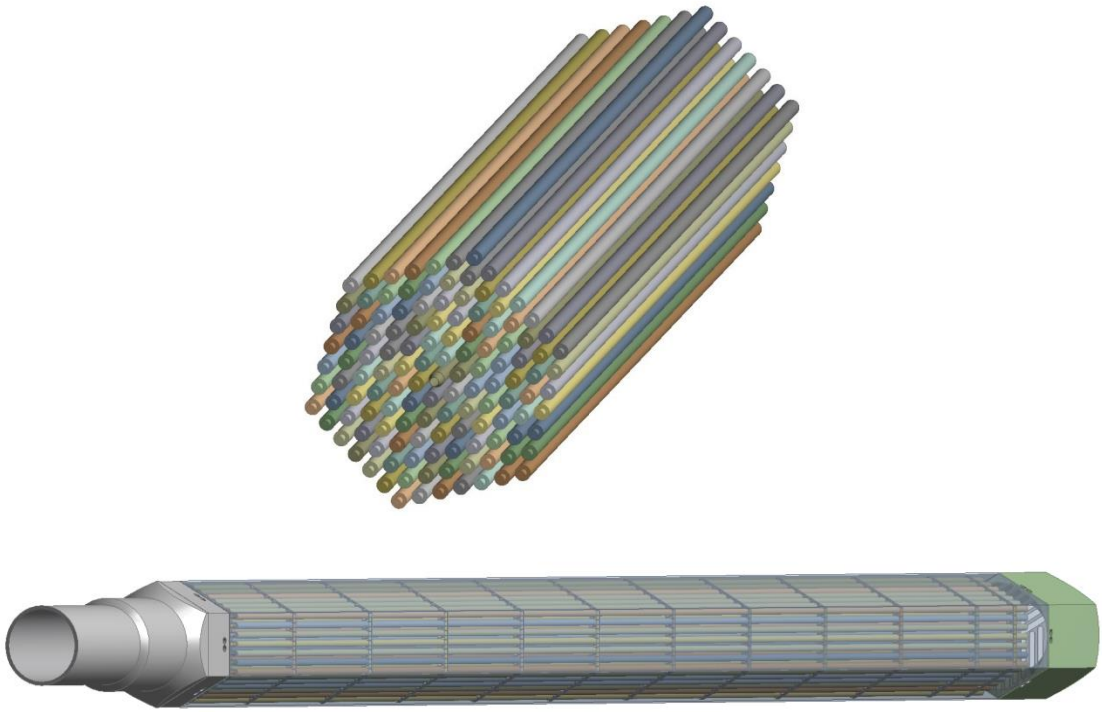


Figure 1: WWER-440 fuel assembly

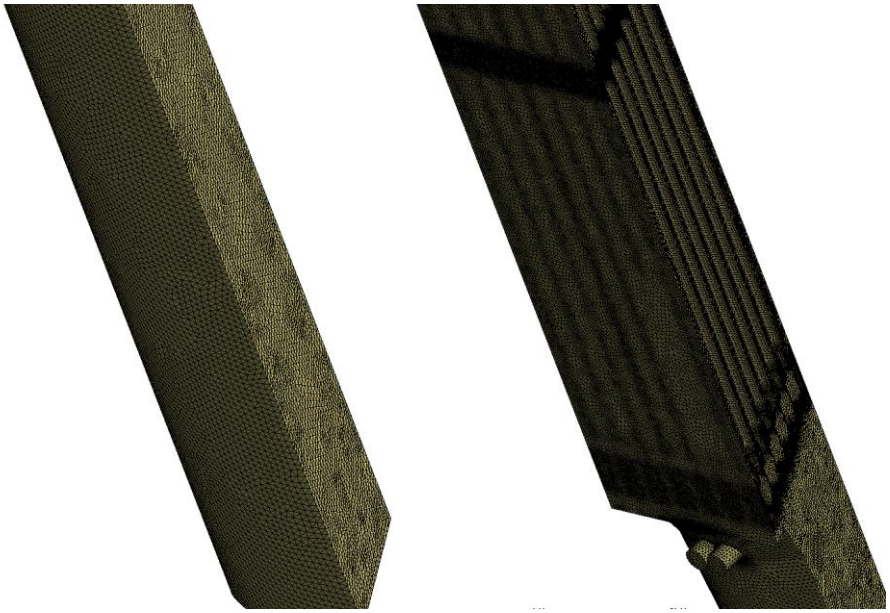
Since the model of the fuel assembly is very complex and contains numerous small parts, the model was meshed entirely. Additionally, to speed up the calculations it was decided to use shortened model of fuel assembly. Therefore model of fuel assembly was cut horizontally on 1.032m elevation from bottom. Shortened model includes fuel tailpiece, lower lattice and two lattices. Additionally, considering the fact that fuel assembly hexagon consists of 6 identical triangles which are symmetrical, only the 1/6 of fuel assembly was meshed.

The global mesh settings were chosen to create sufficient quality mesh, moreover the finer mesh was created in those regions (mostly tetrahedral grid cells), where some small details could possibly cause issues during calculation (

Figure **2**-Figure **4**).

The total number of elements was as following:

Domain	**Nodes**	**Elements**
Fluid	2963627	14653165



a) tailpiece b) lower lattice and lattice

Figure 2: Mesh of the sliced part of the fuel assembly

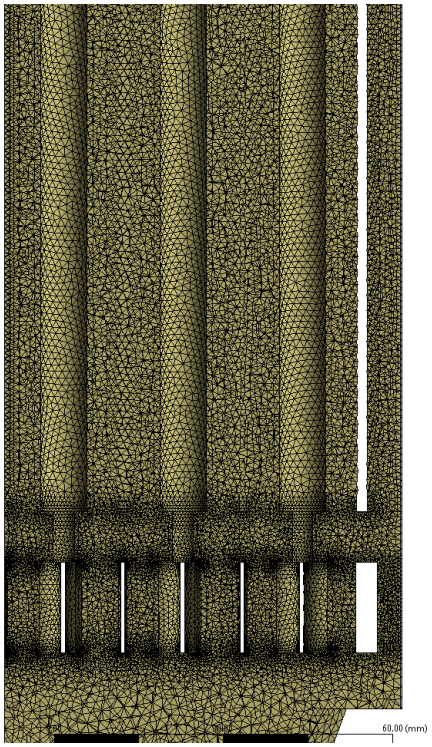


Figure 3: Mesh of the fuel assembly (lower lattice)

Figure 4: Mesh of the fuel assembly (top view)

The elements distribution was presented by showing the quantity and distribution of tetrahedral, hexagonal, wedge and pyramid mesh elements (Figure 5).

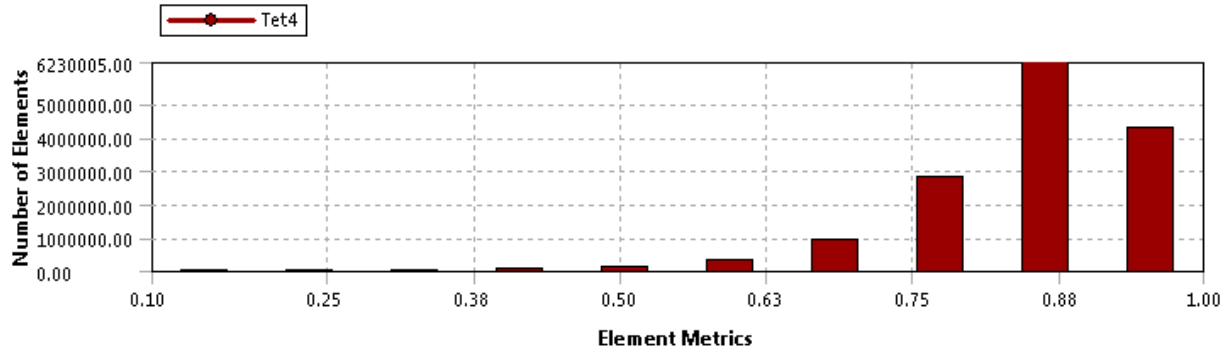


Figure 5: Global mesh element distribution

Domain

One domain was created for simulation of water inside fuel assembly. Material properties of the coolant were set according to the material model in material library. The buoyancy model was used with the buoyancy reference pressure equal to 782kg/m3 (which satisfies density of water at 12.26MPa and 267°C). The heat transfer mode was set to "Thermal Energy", which took into account the transport of enthalpy and included kinetic energy effects. The turbulence model was set to the Shear Stress Transport model. Shear Stress Transport model is recommended for high accuracy boundary layer simulations.

Initial and boundary conditions

Initial and boundary conditions for normal operation of the Armenian NPP and accident state with natural circulation were selected (Table 1) according to the technical specification of the Armenian NPP and accident analysis with full loss of reactor coolant flow due to tripping of the reactor coolant pump motors.

Table 1. Initial conditions of ANPP

Parameters	Normal operation	Natural circulation
Pressure in the upper point of the fuel assembly, MPa	12.26	12.62
Flow rate, kg/s through one fuel assembly	24.48	0.66
Inlet temperature of fuel assembly, °C	266	267
Inlet temperature of fuel assembly side holes, °C	266	267

The boundary conditions for simulation of normal operation of the Armenian NPP and accident state with natural circulation are presented in Table 2.

Heat flow due to power generation from fuel rod to coolant was modeled by introducing heat flow table to fuel rods of ANSYS model (Table 3).

Table 2. Boundary conditions for water domain

Location	Boundary type	Parameters	Normal operation	Natural circulation
All	Relative	Pressure, Pa	12.26E+6	12.62E+6
Inlet	INLET	Mass flow, kg/s	24.48	0.66
Outlet	OUTLET	Static Pressure,	0	0
Side Hole	Opening	Pressure, Pa	3198	Is closed
		Temperature, °C	266	

Table 3. Heat generation from fuel rod

Height	Normal operation, W/m2	Natural circulation, W/m2
0.472	0	0
0.595	2.6757E+05	4.7583E+03
0.718	3.5959E+05	6.3948E+03
0.841	4.0426E+05	7.1891E+03
0.964	4.2124E+05	7.4910E+03
1.0327	4.2615E+05	7.5784E+03

3 Results of analysis

Two ANPP conditions were considered in analysis – normal operation mode and natural circulation mode.

Normal operation mode

Pressure across fuel assembly is shown in Figure and Figure 6. In cylindrical tailpiece part of the assembly, starting from inlet and up to expansion part (0.0-0.26m) pressure is decreasing due to wall shear stress. Then, due to expansion pressure starts to rise before reaching elevation where fuel assembly side holes are located (0.4215m). After that pressure drop occurs due to outflow of coolant from side holes. Further expansion of flow results in pressure rise. After that, pressure is continuously decreasing due to wall shear stress and local resistance created by lattices. Overall pressure loss across fuel assembly is equal to 11.9kPa. Pressure loss in lower lattice is equal to 1.55kPa. In lattice 2 and 3 pressure losses are equal to 1.82kPa and 1.83kPa correspondingly.

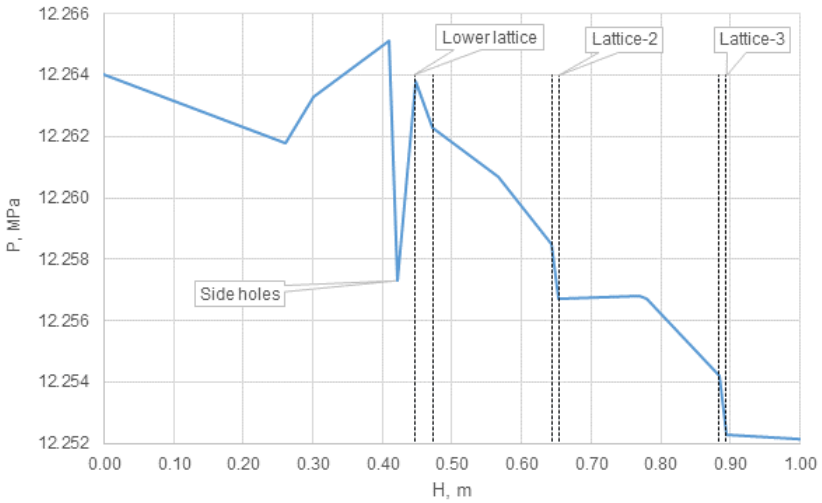


Figure:. Area average pressure across fuel assembly

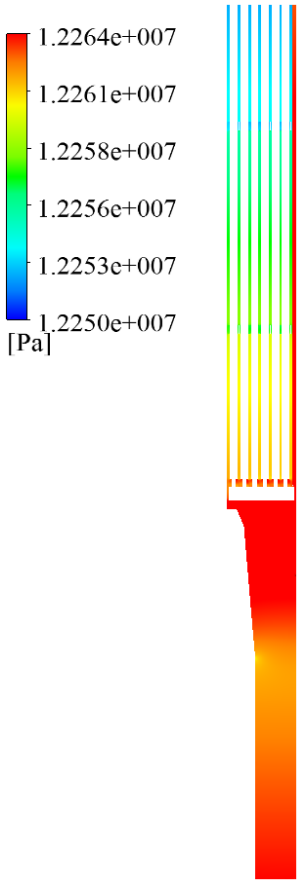
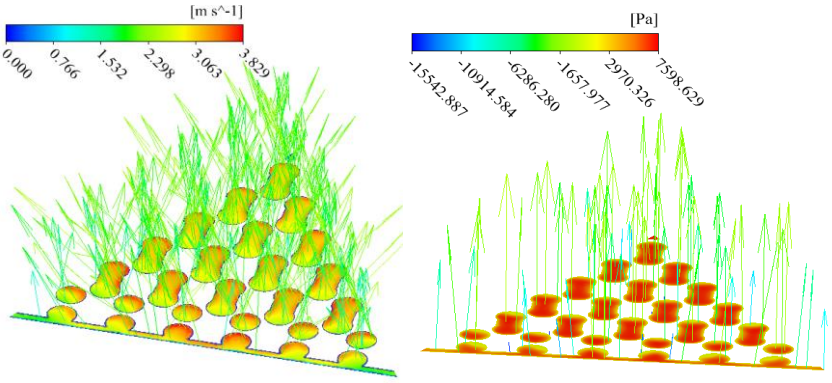
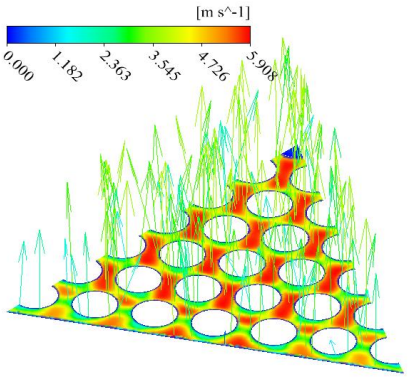


Figure 6: Pressure across vertical cross-section of fuel assembly

In region of lower lattice fluid the flow velocity becomes disturbed (Figure 7, a) which leads to high pressure losses in this region. However due to influence of lower lattice flow velocity vector directs in normal to lattice cross-section (Figure 7, b). At lower lattice exit the fluid velocity profile starts to develop (Figure 7, c). Similar process is taking place in the second and third lattices (Figure 8 and Figure 9).

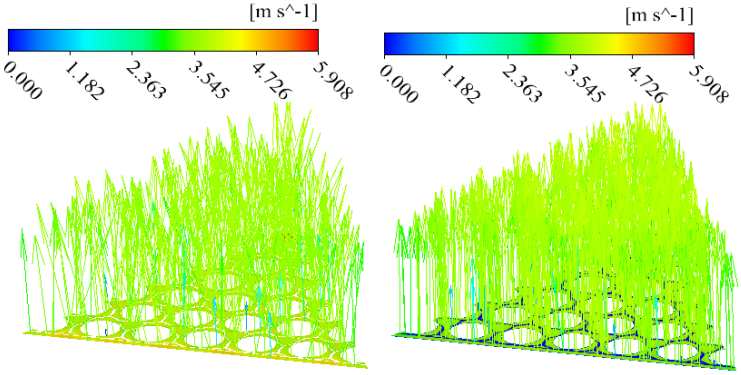


a) entrance of lower lattice b) center of lower lattice



c) exit of lower lattice

Figure 7: Velocity vector profile in lower lattice region of fuel assembly



a) entrance of second lattice b) exit of second lattice

Figure 8: Velocity vector profile in second lattice region of fuel assembly

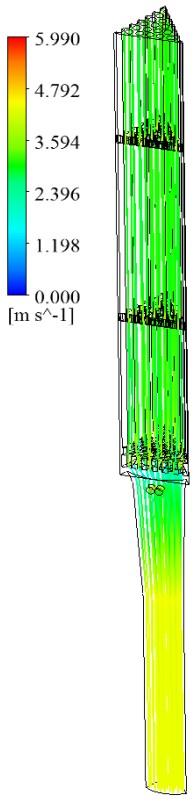


Figure 9: Fluid stream lines in fuel assembly

Natural circulation mode

Pressure across fuel assembly is shown in Figure 10. As can be seen from Figure 10 the pressure changes are mostly linear across fuel assembly length. The small deviation occurs in lattice. Linearity of pressure change across the fuel assembly is mainly conditioned by small velocity of flow which leads to smaller wall shear stress. Behavior of other parameters is similar to behavior at normal operation mode (Figure 11 – Figure 14). Overall pressure loss across fuel assembly is equal to 8.0kPa. Pressure loss in lower lattice is equal to 193kPa. In lattice 2 and 3 pressure losses are equal to 80kPa.

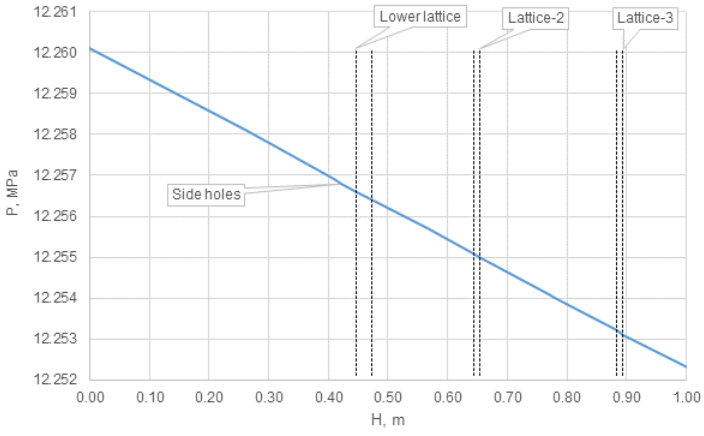
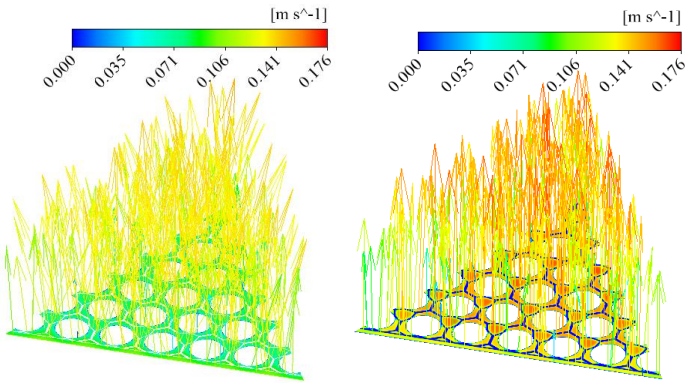
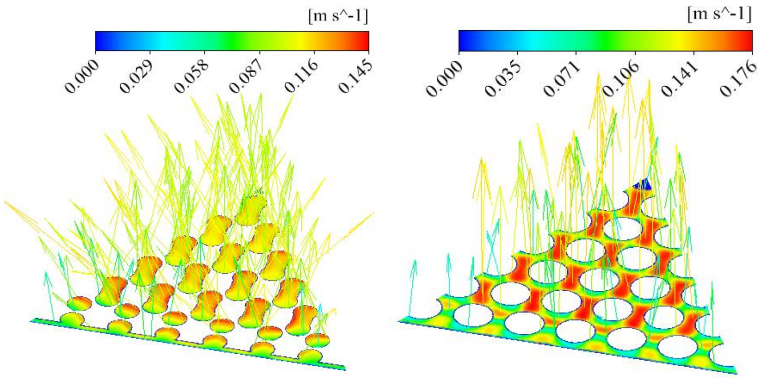


Figure 10: Area average pressure across fuel assembly



a) entrance of second lattice b) exit of second lattice

Figure 11: Velocity vector profile in the second lattice region of fuel assembly



a) entrance of lower lattice b) exit of lower lattice

Figure 12: Velocity vector profile in lower lattice region of fuel assembly

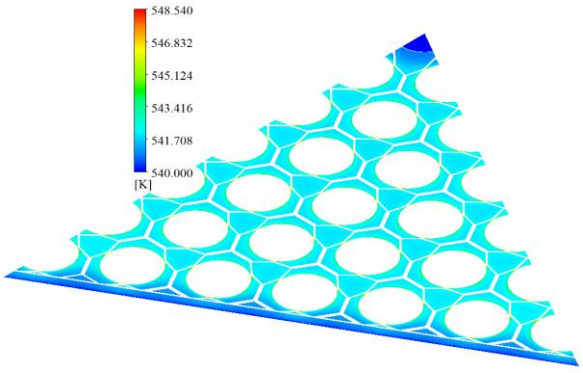


Figure 13: Temperature profile at cross-section of third lattice center of fuel assembly

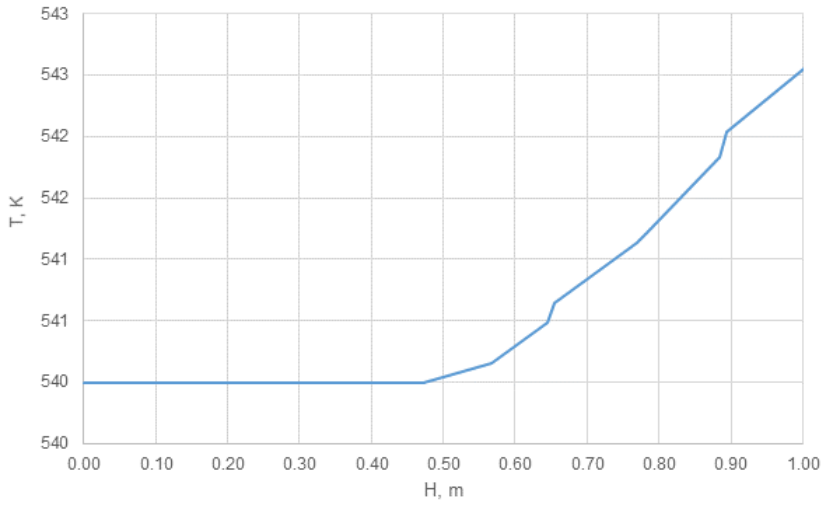


Figure 14: Area average temperature across of fuel assembly

4 Improvement of ANPP RELAP5 system TH code model

Fuel assembly RELAP5 model short description

To improve the ANPP RELAP5 system TH code model, and model of fuel assembly in particular, the separate model of fuel assembly was developed in compliance with ANSYS CFX model (Figure 15). The volume representing fuel assembly consists of 5 nodes. First two nodes represent the tailpiece part of FA, and 3 top nodes represent fuel part. To model heat generation a heat structure with constant heat source corresponding to power of one assembly was attached to hydraulic part. Parameters of time dependent volumes, which represent boundary conditions at fuel assembly inlet, outlet and side holes are selected in accordance with Table 1 and Table 2. Geometry of fuel assembly lattices was corrected based on to values received ANSYS model geometry development.

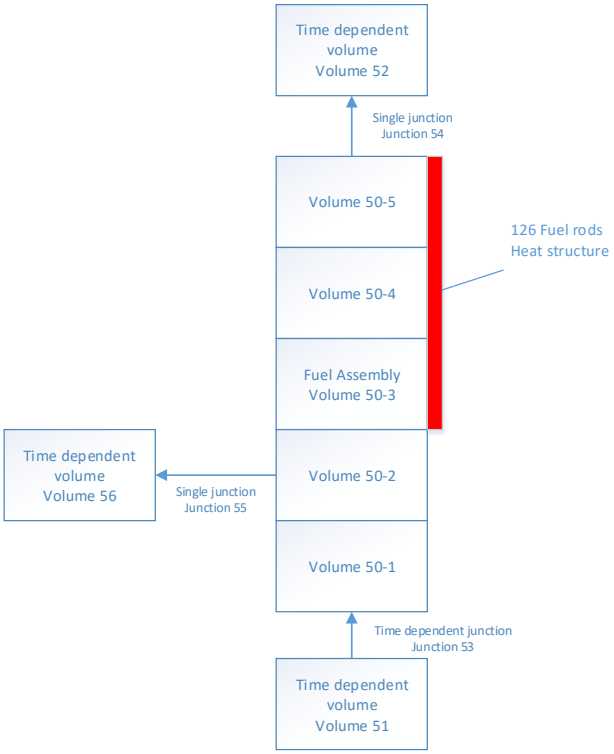


Figure 15: Nodalization of Fuel Assembly in RELAP5

Pressure head loss coefficient evaluation

For evaluation of lattice local resistance loss coefficient to use in RELAP5 model following equation was used.

$$\Delta P = \xi \frac{G^2}{2\rho A^2} + \rho g H \xrightarrow{yields} \xi = \frac{(\Delta P - \rho g H) 2\rho A^2}{G^2} \quad (1)$$

where: ΔP - pressure drop, ξ - local resistance coefficient, G - mass flow, ρ - density of coolant, A - flow area, and $\rho g H$ – stands for hydrostatic pressure.

Lattices local resistance loss coefficients using formula (1) were calculated for normal operation mode of ANPP. Results of ANSYS-CFX calculation from paragraph 3.1 were used for local resistance loss coefficient calculation. Results of calculation are presented in

Table **4**.

Table 4. Results of ANSYS calculation

Parameters	Lower lattice	Lattice 2	Lattice 3
Total pressure loss, kPa	1.55	1.82	1.83
hydrostatic pressure, kPa	0.192	0.0766	0.0766
Density, kg/m3	782	782	772
mass flow, kg/s	22.2	22.2	22.2
flow area, m2	9.31E-03	7.75E-03	7.75E-03
$\Delta P - \rho g H$, kPa	1.35	1.74	1.76
Local resistance coefficient	0.372	0.332	0.335

To verify local resistance coefficients values, calculation was performed by RELAP5 fuel assembly model where as an input mentioned coefficients were used. Results of calculation were compared with ANSYS CFX results (Figure **16**).

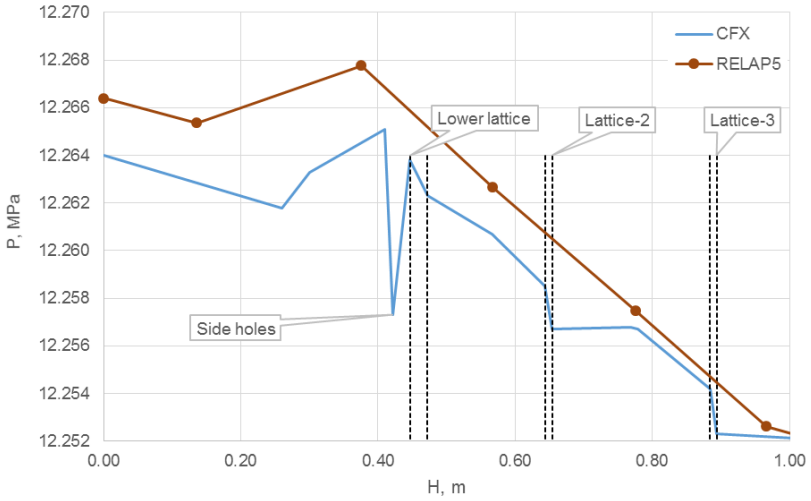


Figure 16: Comparison of pressure behavior estimated by CFX and RELAP5 codes

As can be seen from **Hata! Başvuru kaynağı bulunamadı.**Figure 16 the general behavior of pressure for both codes is similar. The reason for differences is the more precise calculation of resistance and corresponding turbulent flow effects in ANSYS. While in RELAP5 turbulent friction factor is given by the Zigrang-Sylvester approximation of the Colebrook-White correlation (see formula 2) which is applicable for cylindrical pipe [7]. In case of fuel assembly complex geometry (hexagonal) usage of this correlation overestimates the resistance due to turbulence.

$$\frac{1}{\sqrt{\lambda_T}} = -2\log_{10}\left\{\frac{\varepsilon}{3.7D} + \frac{2.51}{Re}\left[1.14 - 2\log_{10}\left(\frac{\varepsilon}{D} - \frac{21.25}{Re^{0.9}}\right)\right]\right\} \quad (2)$$

Conclusions

In the current study, the model of fuel assembly was developed for CFD analysis. One domain was created for simulation of the coolant inside fuel assembly. Heat generation from fuel rods was modeled.

Steady-state calculation for nominal state of ANPP and for condition with natural circulation was performed.

Results of analysis showed that during nominal state of ANPP fuel assembly lattices cause significant pressure losses. Calculation results for two lattices in different location showed that pressure drops in lattices are equal. However lower lattice creates comparable small pressure drops due to larger flow area.

In case of natural circulation pressure changes are mostly linear across the fuel assembly length. The small deviation occurs in lattices. Linearity of pressure changes across fuel assembly are mainly due to small velocity which leads to small wall shear stress.

Results of analysis showed that general behavior of pressure for both codes is similar. The reason for some differences is the more precise calculation of resistance and corresponding turbulent flow effects in ANSYS, while in RELAP5 turbulent friction factor is given by the empirical correlation which overestimates the resistance due to turbulence. The behavior of temperature is similar in both codes. The difference of 0.25 degrees exists, which is conditioned by coarse nodalization of RELAP5.

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