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CFD MODELING OF THE MODERATOR TANK OF A PHWR NUCLEAR POWER PLANT

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Abstract. A steady state CFD simulation of the moderator tank of Atucha II Nuclear Power Plant (a Pressurized Heavy Water Reactor PHWR) was performed. Three-dimensional (3D) detailed modeling of the tank was achieved including inlet and outlet ring-shaped distributors, the coolant channel (CC) tubes and the control and safety rod guide tubes. Two heat sources were taken into account: the conduction/convection from the coolant channels' fluid and the heat transfer by thermal neutron moderation. For the former, suitable boundary conditions (wall temperature) at the CC tube walls were arisen from 2D estimation of the conduction/convection heat through the coolant walls. The coolant temperature profile along each CC (obtained from a previous 1/3D model) along with correlations for the in-channel side convective coefficient were considered. The effective conduction coefficient was estimated by fitting the overall expected transfer power. For the latter, a homogeneoussource was implemented.

Simulations allowed a thorough understanding of the complex flow and the heat transfer phenomena, while acquiring useful information about the temperature distribution in the moderator. The most relevant conclusion is that the power transferred from the CCs to the moderator does not show linear dependence on the fission power but on the coolant temperature, which is very similar for all CCs. These results become of prime importance when defining more accurate boundary conditions for modeling the in-channel flow with a previously developed, in-house, 1/3D multidimensional model of the reactor pressure vessel (RPV). The 3D model developed is the starting point to carry on unsteady simulations in the moderator tank,such as reactor Safety Control Rod Axe Man (SCRAM), heat removal during a primary pump shut down or boron distribution during a fast shut down injection.

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1. INTRODUCTION

The Nuclear Power Plant (NPP) Atucha II (CNA II) is a pressurized heavy water reactor (PHWR) with a projected total thermal power of 2160 MWt and electric power of 745 MWe. At the moment this simulation was performed, CNAII has achieved criticality.

The reactor of CNA II has a primary circuit transporting the coolant (heavy water D_2O) which is in direct contact with the fuel rod cladding. This circuit is composed by two loops that transport the heat from the core to two steam generators, whereheat is exchanged to the secondary circuit (light water, H_2O).CNA II employs a fuel composed ofnatural uranium. Then, D_2O is also used for moderation purposes. The moderator is pumped into the moderator tank through four loops. In these loops, heat generated by thermal moderation and the heat loses from the coolant channel (CC) walls is extracted and used for pre heating the water of the secondary circuit.

The core has a vertical configuration housing 451 CC in the moderator tank. TheCCs's purpose is to remove heat generated by fission by means of a pressurized coolant flow.Each fuel bundle is composed of 37 fuel rods with 5.3 m of active length. Natural Uranium and Deuterium (heavy water) have been chosen as fuel and coolant, respectively. Also, moderation is accomplished by heavy water found in the moderator tank but, in this case, outside the CCs

The coolant circuit inside the RPVcan be divided into two main reservoirs, the downcomer and lower plenum and the upper plenum, both connected through the CCs.There exists also a bypass which transports less than 3% of the total flow. The coolant enters the RPV through two cold legs and goes down towards the lower plenum through the annular downcomerbetween the pressure vessel and the moderator tank walls. Figure 1shows a cross section view combining two cutting planes to visualize one hot leg and one cold leg of the RPV.After getting the lower plenum, the coolant flows through the CCs removing heat from cladding.Finally, the coolant leaves the RPV through two hot legs connected to the upper plenum.

The moderator tank is locatedin the central part of the RPV, housing the active length of the CCsas shown in Figure 1. The moderator enters the tank through four verticalducts which are connected to a ring-shaped distributor placed at the bottom side of the tank. It thenexits through a series of small orifices, which are placed along the ring´s circumferenceso that a homogeneous flow distribution is encouraged.

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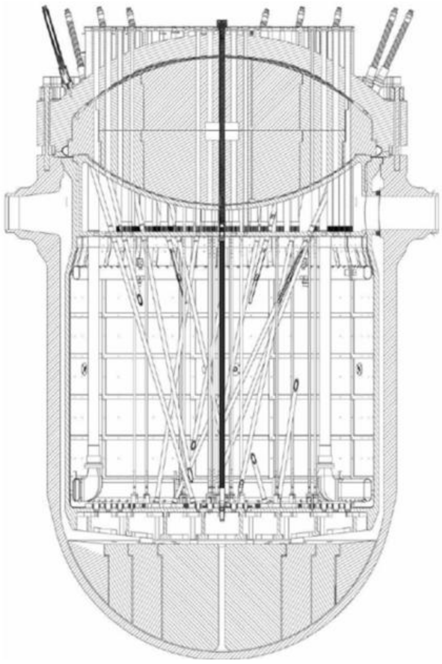

Figure 1: cross sectional cuts of the RPV.

The moderator flows upwards through the tank, covering completelythe CCs outer walls. Finally, it is collected though a ring placed at the top side of the tank from where it can then leave the RPV.

The moderator mass flow rate under nominal conditions is expected to be 880 kg/s andthe inlet and outlet temperatures are expected to be 140°C and 194°C respectively. On the other hand, the coolant inlet and outlet temperatures are expected to be 277°C and 314°C respectively. Due to the fact that the coolant has a higher temperature than the moderator, heat will be transferred through the CC walls.

The moderator is connected to the main coolant through a set of small orifices, which arefound between the top of the moderator tank and the upper plenum for pressure equalization. Thus, both fluids are at a similar pressure.

The moderator heats up by means of convection from the primary coolant and by neutron moderation. The heat transferred by convection from the CCs and the heat generated by neutron absorption are approximately %5.2 and %5 of the total NPP thermal power.

In this work, a full 3-dimensional model of the moderator tank of CNA II is developed. Transient single-phase non isothermal flow is solved by taking into account the fission heat transfer from the CC walls and the heat generated by neutron moderation under steady state normal conditions.These results will be useful at introducing more accurate boundary conditions to anin-house 1/3D model of the RPV (Ramajo et al., 2013). The present work corresponds to a preliminary estimation of moderator temperatures and velocities in the moderator tank during steady state normal conditions.

2. COMPUTATIONAL MODEL

Figure 2 shows the geometry of the moderator tank. For clarity, the 451 CCs were not included in the figure. The inlet ring distributor placed at the bottom of the tank is divided

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into 4 quadrants. Each quadrant has 18 orifices on its upper surface. The diameter of these orifices ranges from45 to52 mm. The fluid entering each quadrant from one of the four inlet ducts is restricted from flowing around one quadrant of the ring.

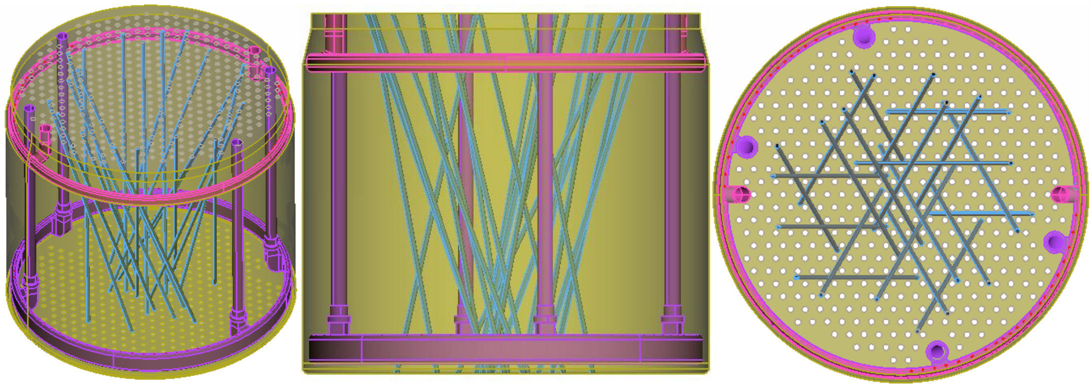

Figure 2: views of the moderator tank geometry.

The collector outlet is placed at the upper side of the tank. In this case, the ring is divided into 2 isolated parts, each one connected to one outlet duct. The outlet ring has 88 orifices which arenon-equidistantto eachother, having an average diameter of 45.18 mm. In order to reduce the amount of mesh elements, the flow inside the ducts and the rings was not solved and the total inlet mass flow was homogeneously divided throughout all orifices. Moreover, the lances for boron injection of the shutdown system were not included in the computational model.

Figure 3 shows views of the volume and surface mesh around the distributor ring. The moderator tank houses several rod bars corresponding to the control and shut down system. All these bars cross the tank at close proximity to the CCs with inclination angles ranging from 20° to 25°.

The computational model was discretized using ANSA® 13.1 package.Especial refinement was done in those regions where the control rods werecloser to the CCs. The flow inside of the inlet and outlet ducts and the distributor and collector rings was not solved. 26.845.085 tetrahedrons were required for the whole domain. The maximum aspect ratio was 7 and the average and the maximum non-orthogonality were 15.9 and 60.4 respectively. The maximum skewnesswas 0.7.Due to the complex geometry of the model the mesh convergence analysis was unable to be performed.On the one hand, the implementation of mesheswhich are coarser than the currently used,result inpoor definition of the geometry. On the other hand, refined meshes were far more difficult to be solved with the available computational resources.

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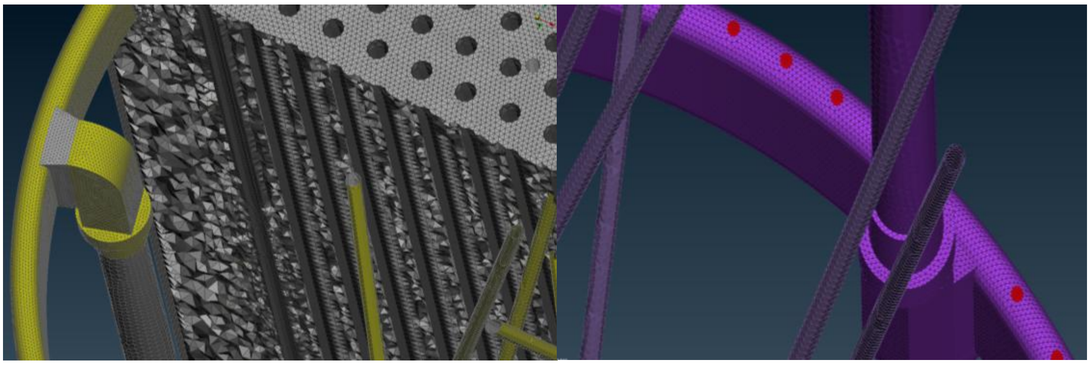

Figure 3: views of the inlet distributor and the outlet collector of the moderator tank.

Because of the non-homogeneous neutron distribution along the core, the mass flow rate of the CCs must be defined in order to remove the different fission power of the CCs. In this sense, the core was divided into five hydraulic zones (HZ), where the CCs of one HZ should have approximately the same mass flow rate. This is obtained by introducing an inlet flow restrictor at the bottom end of the CC. The 451 CCs were grouped following the real HZ division, thus imposing different boundary conditions for the heat transfer from the coolant to the moderator. Figure 4 shows the HZ mapand the corresponding computational model.

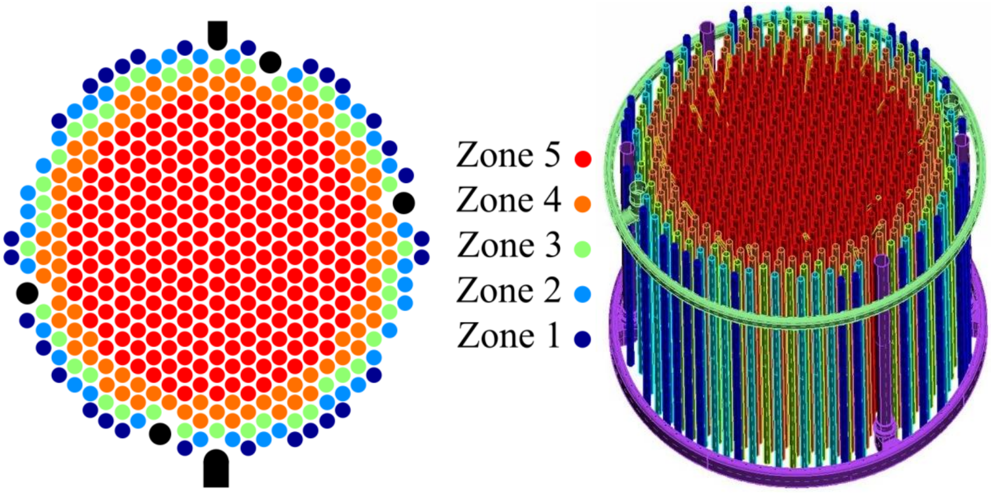

Figure 4: Hydraulic zones distribution

The nominal mass flow rateof moderator was imposed at the patcheswhichrepresent the orifices of the distributor ring. In addition to that, outlet static pressure boundary condition was set for the patches which represent the orifices of the collector ring. Regarding the thermal equation, axial temperature profiles (constant in time) were imposed at the CC walls to take into account the convective heat transfer from the coolant to the moderator.

3. GOVERNING EQUATIONS

Simulations were carried out using the open source toolbox OpenFOAM® (Open Field Operation and Manipulation) [OpenFOAM]. The OpenFOAM Toolbox is a free, open

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source CFD software package, released under the GNU General Public License. OpenFOAM has parallel computing capabilities, which provide the opportunity to simulate engineering problems such as the one considered in this work.

The continuity and momentum equationswere coupled with the thermal equation by including buoyancy effects with the Boussinesq approximation.These set of equations were solvedusing the *bouyantBoussinesqPimpleFoam* solver from the OpenFOAM toolbox version 2.2.x. Thissolver is a transient solver for buoyant, turbulent and incompressible flow. This solver hasbeen widely employed for natural convection problems and it has beenused by the authors to simulate natural convection flow in a cubic cavity among others academic geometries. Results are in agreement with experimental data and numerical simulations (carried out with Fluent®for other authors) reported in open literature for a wide range of Rayleigh numbers. More details about this can be found in corzo et al. (2011).

The constant-density filtered continuity equation takes the following form:

$$\frac{\partial \overline{u}_j}{\partial x_j} = 0 \qquad (1)$$

Although the continuity equation is presented, the solver does not actually calculate it; instead, a pressure Poisson equation that enforces continuity is solved. The momentum equation can be written as:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_j \overline{u}_i)}{\partial x_j} = -\frac{\partial}{\partial x_i}\left(\frac{\overline{p}}{\rho_0}\right) + \frac{1}{\rho_0}\frac{\partial}{\partial x_j}\left(\tau_{ij}\,\tau_{tij}\right) + \frac{\rho}{\rho_0} g_i \qquad (2)$$

where g_i is the gravity acceleration, τ_{tij} is the turbulent stress tensor, and τ_{ij} is the stress tensor due to molecular viscosity given by the following expression

$$\tau_{ij} = \mu\left[\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial \overline{u}_k}{\partial x_k}\right)\delta_{ij}\right] \; (3)$$

where ▯ is the molecular viscosity and δ_{ij} is the dyadic tensor. Rewriting leads to:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_j \overline{u}_i)}{\partial x_j} = -\frac{\partial}{\partial x_i}\left(\frac{\overline{p}}{\rho_0} + \frac{2}{3}k\right) + \frac{\partial}{\partial x_j}\left\{v_0\left[\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial \overline{u}_k}{\partial x_k}\right)\delta_{ij}\right] - R_{ij}^{D}\right\} + g_i\left(1 + \frac{\overline{\rho} - \rho_0}{\rho_0}\right) \; (4)$$

The last term in the right hand side of Eq. 4 is the buoyant term, which in this work is computedfor the solver by applying the Boussinesq approximation. Under the sub-grid scale hypothesis and using Boussinesq approach, Eq. 4 can be rewritten as:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_j \overline{u}_i)}{\partial x_j} - \frac{\partial}{\partial x_j}\left\{v_{eff}\left[\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}\left(\frac{\partial \overline{u}_k}{\partial x_k}\right)\delta_{ij}\right]\right\} = -\frac{\partial \overline{p}}{\partial x_i} + g_i\left[1 - \beta\left(\overline{T} - T_0\right)\right] \qquad (5)$$

wherev_{eff} is the effective kinematic viscosity and β is the coefficient of thermal expansion. In this work, an average constant coefficient for β was estimated as:

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$$\beta = \frac{1}{V}\frac{\partial V}{\partial T} = \rho\frac{\partial}{\partial T}\left(\frac{1}{\rho}\right) \to \overline{\beta} = \overline{\rho}\,\frac{\Delta\left(\frac{1}{\rho}\right)}{\Delta T} = \left(\frac{\rho_1+\rho_0}{2}\right)\frac{\frac{1}{\rho_1}-\frac{1}{\rho_0}}{T_1-T_0} \qquad (6)$$

As regards to the dynamic and thermal properties of HW, suitable polynomial functions with pressure and temperature as independent variables were implemented. The polynomials were constructed using fit tools from OCTAVE® package based on the RELAP5® database for heavy water at a pressure of 115bar and a temperature range from 130 to 200°C:

$$\rho(p,T) = 203.3 - 1.977\text{x}10^{-5}\,\text{p} + 4.725\,\text{T} + 3.455\text{x}10^{-13}p^2 + 2.359\text{x}10^{-8}\text{p T} - 0.006273T^2[kg\,m^{-3}] \quad (7)$$

$$\mu(p,T) = 0.001079 - 1.128\text{x}10^{-25}p - 2.987\text{x}10^{-6}\text{T} - 4.415\text{x}10^{-33}p^2 + 3.836\text{x}10^{-28}\,\text{p T} + 2.231\text{x}10^{-9}T^2[\text{Pa s}] \quad (8)$$

$$C_p(p,T) = 26350 + 1.871\text{x}10^{-4}\,\text{p} - 95.85\,\text{T} + 4.248\text{x}10^{-14}p^2 - 3.988\text{x}10^{-7}\,\text{p T} + 0.1039\,T^2[Jkg^{-1}C^{-1}] \quad (9)$$

The energy balance is solved in terms of the temperature equation as:

$$\frac{\partial\overline{T}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{T}\overline{u}_j\right) = \frac{\partial}{\partial x_k}\left(\alpha_{eff}\frac{\partial\overline{T}}{\partial x_k}\right) + S_E \qquad (10)$$

whereS_E is a volume source term andα_{eff} is the effective thermal diffusivity which accounts for the molecular and turbulent thermaldiffusion:

$$\alpha_{eff} = \frac{v_0}{Pr} + \frac{v_t}{Pr_t} \qquad (11)$$

In Eq. 11$Pr = Cp\mu_0/k$ is the Prandtl number and $Pr_t = Cp\mu_t/k_t$is the turbulent Prandtl number which was assumed to have a constant value of 0.7.

The turbulent closure equation was obtained from Large Eddy Simulation (LES). The Smagorinsky model was employed.

The PIMPLE (hybrid PISO-SIMPLE) method was used for pressure-velocity coupling. A maximum of 6 outer iterations were imposed for PISO loop.

The convergencecriterion of linear solvers was $5\text{x}10^{-5}$. For energy equation a Preconditioned Biconjugate Gradient (PBICG) was used and around 17 iterations were required to meet the convergence criteria. Regarding the linear pressure equation, a Generalized Geometric-Algebraic Multi-Grid (GAMG) was chosen with a maximum of4 iterations to reach convergence.

The set of governing equations were solved using distributed parallel computing in a Beowulf cluster using a total of 20 cores from 4 multicore XeonW3690 3.47 GHz (1 x 6 cores), 16 GbRAM. Transient simulations were performed with adjustable time step keeping the maximum Courant Number below5.

The temperature profile corresponding to each HZ was obtained by taking the average axial profiles for all CCs within each HZ. Heat transfer was estimated by considering the convective heat transfer between the coolant and the inner side wall of the CCs, the conduction along the CCs,the convective/conductive heat along the D_2O gap between the CCs and the foiling,the conduction along the foiling thickness and finally, the convective

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transfer between the foiling walls and the moderator. This preliminary estimation has to be corrected in order to obtain the expected moderator temperature at the outlet.
For cylindrical geometry, all the mentioned types of heat transfer can be summed up to giveaneffectiveheat transfer conductivity as:

$$k_{eff} = \frac{\pi}{\frac{1}{h_{in}\,d_1}+\frac{\ln\frac{d_2}{d_1}}{2\lambda_z}+\frac{\ln\frac{d_3}{d_2}}{2\lambda_a}+\frac{\ln\frac{d_4}{d_3}}{2\lambda_z}+\frac{1}{h_{out}\,d_4}} \quad (12)$$

where h_{in} is the convective coefficient between the coolant and the inner walls of the CCs, h_{out} is the convective coefficient between the foiling and the moderator, λ_z is the zircaloy conduction coefficient (λ_z= 13.6 W/mk) and λ_a is an effective heat transfer coefficient for the D_2O gap (λ_a=2.44 W/mk) for a moderator average temperature of 170°C.
The diameters $d_1$and d_2, are the inner and outer diameters of the CCs and d_3 and d_4 are the inner and outer diameters of the foiling sheet respectively.
The left hand side of Figure 5 shows a sketch of the temperature profile between the coolant and the moderator.

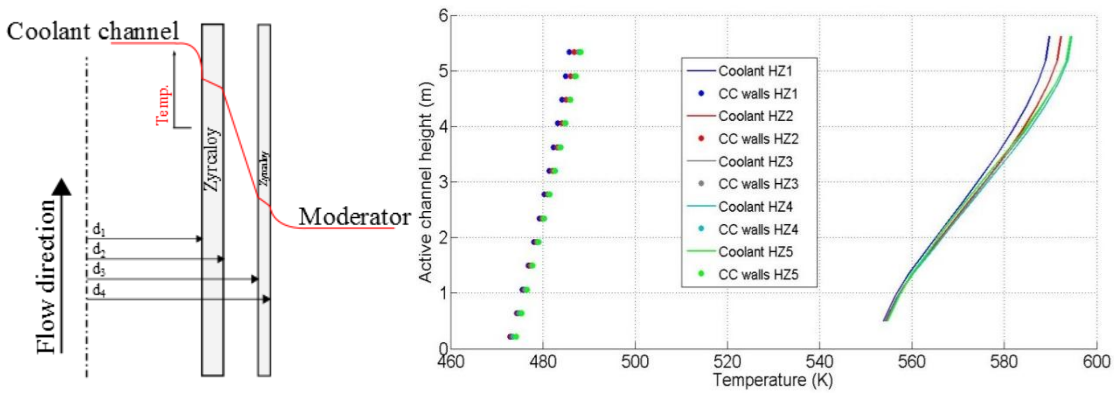

Figure 5: Left: Radial heat transfer model. Right: Temperature profiles for the coolant and the CC walls for the five HZs

The convection coefficient h_{in} was estimated using the following equation:

$$h_{in} = \frac{Nu\,\lambda_{cc}}{D_H} \quad (13)$$

whereλ_{cc} is the conduction coefficient for coolant D_2O (λ_{cc}=0.4855 W/mk for the coolant average temperature of 295°C), D_H is the hydraulic diameter of the *CC* (D_H = 9.48x10^{-3} m) and *Nu* is the Nusselt number estimated for single-phase internal turbulent flow using the Dittus-Boelter equation:

$$Nu = 0.023Re^{0.8}Pr^{n} \text{ for } Re>10000,\ 0.6>Pr>160 \text{ and } l/D_H>10 \quad (14)$$

In Eq. (14)*n* was assumed to have a constant value of 0.4,*Re* and *Pr* are the Reynolds and the Prandltnumbers, which are calculated for each *HZ*as:

$$Re = \frac{\rho U D_H}{\text{?}} \quad and \quad Pr = \frac{Cp\,\text{?}}{\lambda cc} (15)$$

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In Eq. (15) the dynamic properties for D_2O are locally estimated from Eq. (7), (8) and (9). Regarding the heat transfer across the D_2O gap, the pure heat conductivity is increased by convection motion giving and apparent heat conductivity λ_a which can be related with the Grashof (*Gr*) and Prandlt numbers for vertical flat plates:

$$\frac{\lambda_a}{\lambda_{gap}} = 1 + \frac{0.119(GrPr)^{1.27}}{GrPr + 1.45x10^4} \text{with} Gr = \frac{\rho l^3 \beta (T_w - T_\infty)}{?} \quad (16)$$

whereλ_{gap} is the heat conduction of the moderator in the gap (for simplicity $\lambda_{gap}$is assumed to have a value equal to λ_{cc}), l is the CC length (l = 6.122 m), T_w is the surface temperature and T_∞ is the bulk temperature. A unique value for all HZs was employed due to the fact that the temperature difference between the coolant and moderatoris nearly the same. Therefore, λ_a was assumed to be 2.44 W/mk.
Finally, the convection heat transfer from the outer of the foiling walls to the moderator was estimated as:

$$h_{out} = K_T (GrPr)^{1/3} \frac{\lambda_{cc}}{D_H} \qquad (17)$$

whereK_T is the heat transfer coefficient which was assumed to have a value of 0.13.
Once the effective heat transfer conductivity $k_{eff}$is estimated with Ec. (12), the total heat loss is calculated as:

$$\dot{Q}_{tot} = \sum_{i=1}^{5} \dot{Q}_i = k_{eff\,i} l (T_i - T_{mod}) \, (18)$$

In Ec. (18), T_i is the temperature vector along the HZ i. T_{mod} is a characteristic moderator temperature (it was assumed to have a value of 194 °C). The calculation of Eq. (18)leads to a total loss equal to 4.8% of the total fission power,which is closer than the expected from design. This preliminary verification can be taken as an assessment of the calculus methodology of k_{eff}. Then, the temperature of the foiling outer wall (the boundary condition for the CFD model) can be estimated as:

$$T_{i_w} = T_i - \frac{\dot{Q}_i}{k'_{eff\,i}} \qquad (19)$$

where$k'_{eff\,i}$ is the effective heat transfer conductivity without considering the term concerning the outer convective heat transfer (last term in the denominator in Eq. 12).
The foiling outer wall temperature profile for each HZ is shown in the right hand side of Figure 5. Note that far from the expected, the estimated profiles are similar for all HZs despite the different fission power release. It must be remembered that this preliminary estimation was obtained from the coolant temperature profiles previously calculated with our 1D code (Ramajo et al., 2013) by considering that each CC transfers %5 of its fission power to the moderator. The total heat transfer from the CCs to the moderator is close to 5 % of the full power. From the present estimations the transferred heat is similar for all CCs of the five HZs indicating that abovementioned heat might not be proportional to the fission power. In order to better estimate the coolant temperature profile, this assumption shall be replaced by a heat flux distribution approach obtained from the presentmodel. Therefore, it should be expected that the coolant temperature in central HZs would become higher than the currently obtained under the assumption of loses are proportional to the

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fission heat release. Also, it should be noted thatthe moderator heat-up caused by neutron moderation was implemented by means of a homogeneousvolumetric source.

4. RESULTS AND DISCUSSION

Results were visualized with ParaView®. Figure 6 shows the velocity magnitude of the inlet jets (for clarity only half of the total inlets are shown). The jets follow a vertical trajectory from the distributor to the collector, close to the tank wall. The maximum jet velocityis around 6 m/s but it reduces to around 2 m/s once the flow leaves the orifices and it reduces around 1 m/s as the flow approaches the top of the tank.

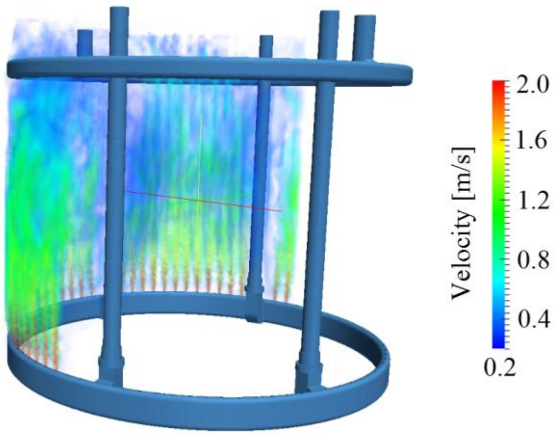

Figure 6: Velocity magnitude of the inlet jets leaving.

The vertical velocity is displayed in Figure 7over horizontal planes cutting the moderator tank. It can be seen that the flow is directed upwards close to the moderator tank walls and downwards at the center. Forced flow caused by the jet inlets dominates over natural convection.

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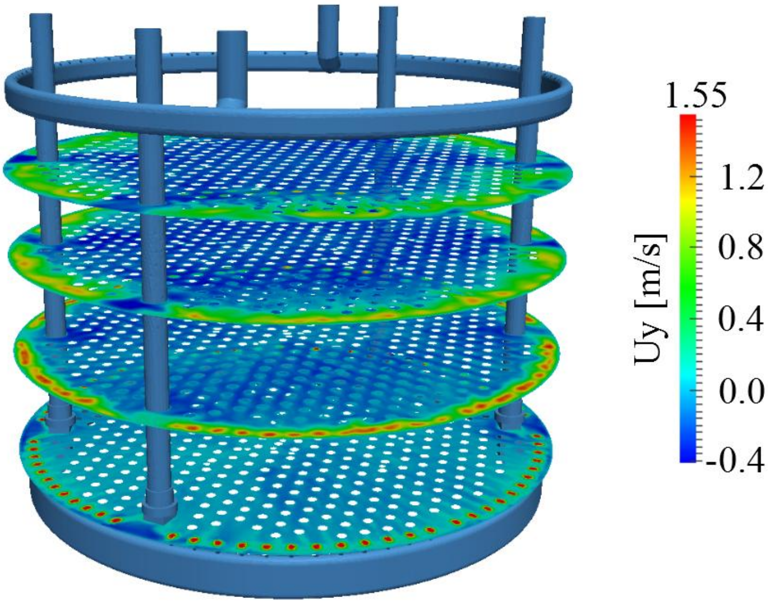

Figure 7: Vertical velocity over horizontal planes cutting the moderator tank.

In Figure 8, temperature is visualized over four horizontal planes cutting the moderator tank. The temperature stratification caused by the poor mixing between the central and peripheral zones of the tank can be observed in this figure.

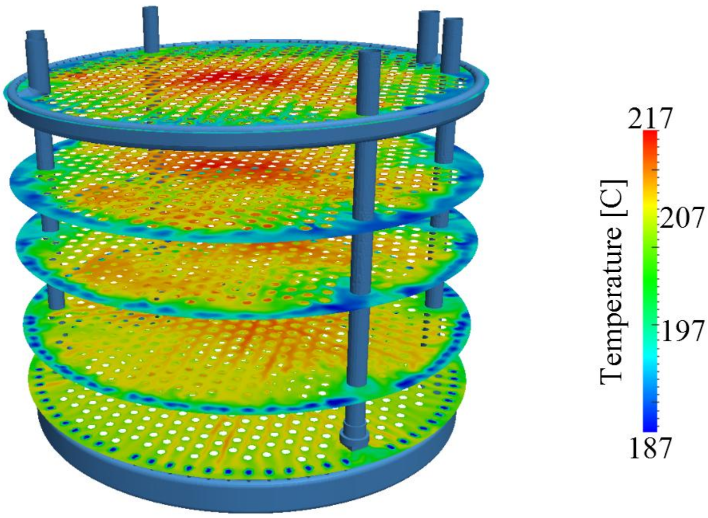

Figure 8: Temperature of the moderator over four horizontal planes cutting the tank.

The temperature pattern over a vertical plane cutting the moderator tank is shown in Figure 9. Temperature difference becomes greater than 50°C from the central tothe

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periphery of the tank. It can be observed the scarcely influence of the inlet jets over the temperature pattern. The inlet jet close to the orifices can be observed in detail in Figure 9. The inlet fluid enters at 140°C. Surrounding the orifices, a faster temperature increment is observed. Then, the cooler jets continue rising toward the collector without suffer noticeable temperature increments.

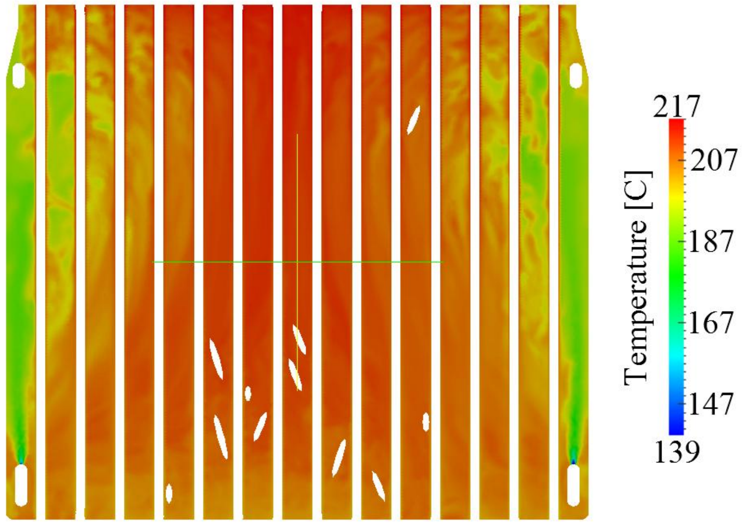

Figure 9: Temperature of the fluid over a vertical plane cutting the moderator tank.

5. CONCLUSIONS

In this work a computational simulation of the thermal-hydraulic flow inside the moderator tank of Atucha II NPP was carried out using OpenFoam. Results allowed to understand the dominant effect of the inlet distributor over the natural convection on the global flow distribution. For the given boundary conditions, forced flow caused by the inlet jets dominates over natural convection.The heat flux from the coolant channels to the moderator was estimated based on previous temperature simulations of the coolant circuit. These simulations indicated that the heat loses are similar for all the hydraulic zones, despite the fact that fission power is almost three times higher for the central zone. Thermal stratification was evidenced, mainly caused by the low mixing induced by the inlet jets.

GLOSSARY

NPP: Nuclear Power Plant.
CNA: Nuclear Power Plant Atucha.
PHWR: Pressurized Heavy Water Reactor.
PWR: Pressurized Water Reactor.
0D: zero-dimensional.

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1D: one-dimensional.
3D: three-dimensional.
CC: Coolant Channel.
HZ: Hydraulic zone.
RPV: Reactor Pressure Vessel.
MFR: Mass Flow Rate.
NPP: Nuclear Power Plant.
CFD: Computational Fluid Dynamics.
LES: Large Eddy Simulation.
LOCA: Loss Of Coolant Accident.
HW: Heavy Water.
PISO: Pressure Implicit with Split Operator
SIMPLE: Semi-Implicit Method for Pressure-Linked Equations
PIMPLE: Hybrid PISO/SIMPLE algorithm.
VFM: Volume Finite Method.
D_H: Hydraulic diameter.
U: Velocity.
p: Pressure.
T: Temperature.
ρ: Density of D_2O.
g: Gravity acceleration.
h: Enthalpy.
$\bar{\bar{\tau}}$: Stress tensor.
μ: Dynamic Viscosity of D_2O.
κ: Thermal Conductivity.
S_E: Energy Sink/Source.
μ: Dynamic viscosity of D_2O.
μ_t: Turbulent viscosity.
G_t: Turbulence production.
η: Wall roughness.
λ_{cc}: Conduction heat coefficient of D_2O for the average coolant temperature.
λ_z: Conduction heat coefficient of zircaloy.
λ_a: Effective conduction heat coefficient for the foiling gap.
λ_{gap}: Conduction heat coefficient of D2O for the moderator at the foiling gap.
h_{in}: Convective coefficient at the inner walls of the CC.
h_{out}: Convective coefficient at the outer walls of the foiling.
$\dot{Q}$: Heat transfer rate.
Re: Reynolds number.
Pr: Prandlt number.
Gr: Grashof number.
Nu: Nusselt number.
k_{eff_i}: Effective heat conductivity from the coolant to the moderator.
k'_{eff_i}: Effective heat conductivity without consider the outer convective transfer.
T_∞: Bulk temperature for the Grashof number.
T_w: Surface temperature of the foiling outer walls.
T_{mod}: Bulk temperature of the moderator.

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l: Length of the CCs.

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