IMPROVEMENT OF THE THERMALHYDRAULIC CHARACTERISTICS IN THE CALANDRIA VESSEL OF A CANDU 6 NUCLEAR REACTOR

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This paper describes the work of developing two 3D CFD models using ANSYS CFX for simulating the flow circulation of the moderator in a CANDU 6 nuclear reactor. The first model presents the calandria vessel of the CANDU 6, with the actual location of the inlet nozzles and outlet ports. The second model presents a new design of the calandria vessel containing some modifications in the moderator inlet/outlet flow configuration aiming to improve the thermalhydraulic characteristics in the calandria vessel. This work represents the effort to improve the thermalhydraulic characteristics in the calandria vessel and obtain a more uniform temperature distribution in the core region.

Keywords: Nuclear Engineering, Candu Reactor, CFD Modeling, Moderator Flow, Moderator Temperature Distribution

1. Introduction

A CANDU nuclear power plant utilizes controlled fission in the reactor core as a heat source to supply steam and electrical power. The CANDU is a reactor of the pressure tube type that utilizes natural uranium fuel and heavy water as a coolant and moderator.

The reactor comprises a stainless steel horizontal cylinder, which is called Calandria and contains heavy water (D_2O) moderator at low temperature and pressure, reactivity control mechanisms and 380 fuel channels. Each fuel channel is approximately 6 m long and contains 12 fuel bundles.

Pressurized heavy water coolant is circulated through the fuel channels. The coolant carries the heat to steam generators, where it is transferred to light water to produce steam. The coolant leaving the steam generators is returned to the inlet of the fuel channels. The steam produced in the steam generators is used to drive the turbine generator to produce electricity.

Neutrons produced by nuclear fission are moderated (slowed) by the D_2O in the Calandria. The moderator D_2O is circulated through systems that cool and

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purify it and control the concentrations of soluble neutron absorbers used for adjusting the reactivity. [1,2]

For assessing the flow in the Calandria, two models were developed and compared. Both models use the porous media approach, in which the flow around individual Calandria tubes is not modeled in the analysis, and a pressure loss coefficient is applied.

The first model presents the Calandria vessel of the CANDU 6, with the actual location of the inlet nozzles and outlet ports.

The second model presents a new design of the Calandria vessel containing some modifications in the moderator inlet/outlet flow configuration aiming to improve the thermalhydraulic characteristics in the Calandria vessel.

The main objective of this paper is to simulate the flow of the moderator in the Calandria vessel and to estimate the local subcooling of the moderator inside Calandria vessel under normal operational condition for both models and to compare the obtained results.

2. CANDU 6 Moderator System

In accordance with reference 4, the heavy water moderator and the main moderator system have the following functions:

- To moderate the energy of the fast neutrons;
- To evacuate the heat produced in the moderating process;
- To act as a medium for the dispersion of the chemical substances used for the reactivity regulation;
- To evacuate the heat from the core after a Loss of Coolant Accident (LOCA) combined with the unavailability of Emergency Core Cooling System (ECCS).

The main moderator system is a low pressure, low temperature, closed D2O circuit that is operated independently of the high pressure, high temperature primary heat transport system.

In a CANDU 6 moderator system, cool D2O moderator is supplied to the Calandria through nozzles that penetrate the wall of the Calandria shell just below its mid-height. The flow is heated up in the Calandria vessel, and extracted through two outlet ports at the bottom of the Calandria vessel, as presented in Fig.1. It can also be seen that the moderator which flows from two outlets is mixed in a header and passes through either of two 100% capacity moderator pumps, subsequently being cooled via two parallel 50% capacity heat exchangers. The cooled flow is returned to the Calandria through inlet nozzles. The moderator inlet nozzles are designed to promote proper moderator flow to all areas of the Calandria vessel and to prevent direct impingement of the incoming moderator via deflectors onto the Calandria tubes [3].

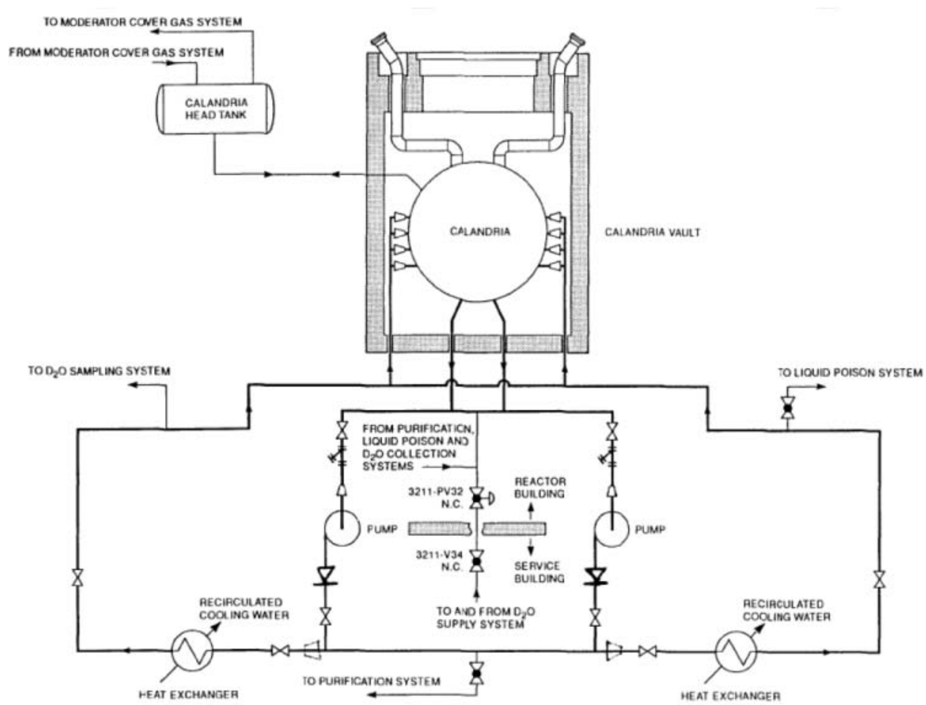

Fig.1. CANDU 6 Moderator system

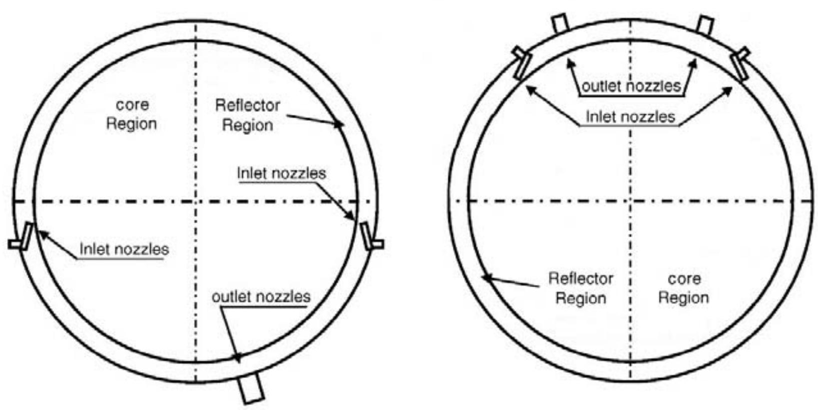

Fig.2. Schematics of the Calandria vessel models showing the configuration of the inlet and outlet nozzles

3. Description Of Ansys-CFX Models

The Calandria is a 6 m long horizontal cylindrical tank filled with heavy water (D2O). The Calandria shell comprises a main shell with a diameter of 7.6m and 4.01m in length. At each end of this main shell there is a smaller diameter sub-shell with a diameter of 6.76m and 0.97m in length. Inside the Calandria, a total of 380 Calandria tubes span the Calandria shell horizontally on a 286 mm square pitch to form a circular lattice array. In addition, there are a number of horizontal and vertical reactivity mechanisms.

The moderator geometric model developed using Ansys CFX consists of the Calandria vessel, inlet nozzles and outlet ports.

It can be observed in Fig.2 that the in the first model the actual configuration of the Calandria vessel is represented, meanwhile in the second one a new design of the Calandria vessel containing some modifications in the moderator inlet/outlet flow configuration is presented.

These two models are detailed in the following paragraphs.

In the first model, which presents the actual configuration of the CANDU 6 Calandria vessel, the heavy water moderator/reflector enters the Calandria vessel through eight inlet nozzles pointing upward in 14° angle from the vertical direction. The inlet nozzles are placed 4 on each side of the Calandria, just below its mid-height, symmetrically in the axial center plane, but they are not symmetrically located in the axial plane [6]. In Fig.3, an image of an inlet nozzle can be observed. These fan-shaped inlet nozzles have four compartments separated by walls placed at 22,5° angles [3,6]. The main role of these diffusers is to provide forced flow to the top of the reactor core region. The moderator exits through two 304.8 mm lines at the bottom of the shell, as shown in Fig.4.

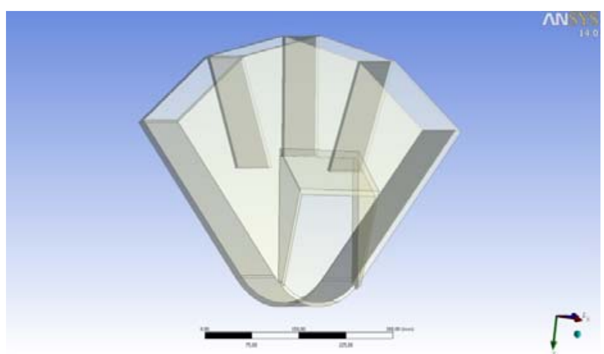

Fig.3. Inlet nozzle configuration

In the effort to improve the moderator performance and minimize the hot spots and thermalhydraulic fluctuations, the moderator inlet/outlet flow configuration are redesigned in the second model.

The eight inlet nozzles are re-oriented to face down and relocated in the upper portion of Calandria vessel. The design of the inlet nozzles is the same as in the first model. The inlet nozzles are relocated at 46° angle above Calandria mid height. Four instead of two outlet ports, located above the inlet nozzles, provide flow extraction from the vessel. Similar to the inlet nozzles, the outlet ports are laid out symmetrically with respect to the vertical cylinder center plane. The outlet nozzles are relocated at 56° angle above Calandria mid height.

This position was chosen based on the following judgment: it was considered that by positioning the inlet and outlet nozzles like this, the fuel channels situated in the top row are expected to be covered by the major flow.

By relocating the inlet and outlet nozzles as presented above, the conflict of flow momentum and buoyancy in the core region is expected to be eliminated and the recirculation in the lower portion of Calandria vessel is expected to take place.

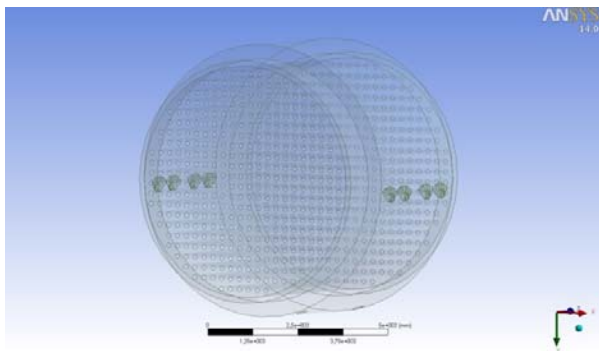

Fig.4. Calandria vessel in the first model

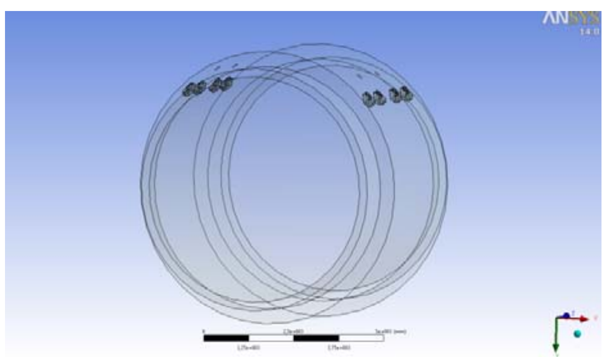

Fig.5. Calandria vessel in the second model

In the analysis performed using the porous media approach, flow around individual Calandria tubes is not modeled. The effect of the Calandria tube matrix on flow distribution is approximated by using the porous media concept in which the reduction in flow volume is accounted for by defining a porosity as the volume occupied by the fluid divided by the total volume. In this case the porosity is 0.83. The fluid momentum loss as it passes over the channels is taken into account by considering a pressure loss coefficient.

The geometric models presented in Figures 4 and 5 were divided in two regions, representing the reflector and the core. For CANDU reactors the reflector is represented by the moderator located between the external fuel channels from the core and the Calandria vessel, as presented in Fig.2.

The reflector is considered to be a fluid domain, and, in accordance with references 2 and 4 the total heat generated in the reflector is 6.1 MW. This heat is distributed uniformly in the domain.

The core is considered a porous domain. Momentum sources can be used to model isotropic and directional losses in porous regions. The fluid momentum loss as it passes over the channels is calculated using empirical drag model:

$$S = -C_D \rho \frac{u^2}{2} \tag{1}$$

where CD is the pressure loss coefficient (PLC), ρ is the density and u is speed (magnitude of the velocity). The formula for the pressure loss coefficient is the following:

$$C_D = A_{cd} f(\theta) \frac{\gamma^2 Re^{B_{cd}}}{D_{row}} \tag{2}$$

where Acd and Bcd are the experimental determined coefficients and have default values of 4.54 and -0.172, respectively. Drow is the channel to channel distance in the flow direction (lattice pitch) and γ is the porosity.

Re is the Reynolds number and is calculated from:

$$Re = \frac{\rho |u| \gamma D_{tube}}{\mu} \tag{3}$$

where Dtube is the Calandria tube diameter and μ is the fluid dynamic viscosity. f(θ) is a yaw-angle correction factor and Drow is a function of lattice pitch and yaw-angle. The yaw-angle θ is the flow direction with respect to the Calandria tubes and is close to unity and Drow is the lattice pitch (0.286 m).

After solving equations (1), (2) and (3) mentioned above, the momentum loss resulted in the following form:

$$S = A u^{2-0,172} \tag{4}$$

where A is a constant. This equation can be approximated to identification with the following 2nd degree equation:

$$S = A(0.785u^2 + 0.183u) \tag{5}$$

In accordance with reference 5, the momentum loss through an isotropic porous region can be formulated using permeability and loss coefficients as follows:

$$S_{M,x} = -\frac{\mu}{K_{perm}} U_x - K_{loss} \frac{\rho}{2} |U| U_x$$
$$S_{M,y} = -\frac{\mu}{K_{perm}} U_y - K_{loss} \frac{\rho}{2} |U| U_y \tag{6}$$

$$S_{M,z} = -\frac{\mu}{K_{perm}} U_z - K_{loss} \frac{\rho}{2} |U| U_z$$

Where Kperm is the permeability and Kloss is the loss coefficient. The linear component of this source represents viscous losses and quadratic term represents inertial losses.

The source may alternatively be formulated using linear and quadratic resistence coefficients substituting two coefficients CR1 and CR2 as follows:

$$C_{R1} = \frac{\mu}{K_{perm}} \text{ and } C_{R2} = K_{loss} \frac{\rho}{2} \quad (7)$$

Taking into account equations (5), (6) and (7), the values for CR1 and CR2 can be easily observed.

The heat generated in the reactor core region is not uniformly distributed as in the reflector region, as it depends on the neutron flux. According to reference 2, for a cylindrical reactor, like CANDU 6, the neutron flux distribution has the following form:

$$\frac{\varphi}{\varphi_{max}} = J_0\left(2{,}405 \frac{r}{R'}\right) cos \frac{\pi z}{H'} \quad (8)$$

Where φ represents the neutron flux, φmax the maximum neutron flux, J0 the Bessel function of first kind, R' the extrapolated radius of the reactor, H'the extrapolated length of the reactor.

Taking into account that the reactor power is proportional with the neutron flux, and for a CANDU reactor, the ratio Pmed/Pmax is 0,82 in the radial direction and 0,71 in the axial direction, giving a global ratio Pmed/Pmax of 0.582, the reactor power can be expressed as:

$$P = 0.582 P_{max} J_0\left(2{,}405 \frac{r}{R'}\right) cos \frac{\pi z}{H'} \quad (9)$$

The Bessel function is approximated with a 4th degree equation, giving the spatial distribution of the power. By dividing the core power (93.9 MW) to the volume of the reactor core, the power density in the core is introduced in the core region.

4. Simulation Conditions

The following conditions were applied to both models:

The total heat load considered is 100MW, of which 6,1MW in the reflector region and the rest in the core region. Heat depositions in the solid components in Calandria vessels, such as the Calandria wall, reactivity mechanisms, and inlet nozzles, are included in the total heat load to the moderator, in addition to the direct energy depositions in the moderator and heat transfer from Calandria tubes.

The total inflow is 940 l/s, distributed equally between the eight inlet nozzles. The assumed inlet temperature is 49°C.

Calandria wall/tubesheets are thermally insulated (adiabatic condition). Also, the heat transfer inside of nozzle deflector is ignored.

The same inlet temperature is assumed to all eight inlet nozzles.

The heavy water properties were collected from reference 7.

For the first model the mesh contains 773,065 elements and 371,879 nodes. The residual target RMS for the conservation equations was set at 1e-5.

For the second model the mesh contains 779,481 elements and 365,415 nodes. The residual target RMS for the conservation equations was set at 1e-5.

5. Results and comparison

Figs. 6 and 7 represent the axial and radial temperature distribution in the center of Calandria obtained with the first model representing the generic CANDU 6. Under normal operating conditions, one can observe that the calculated maximum temperature of the moderator is 83.21°C. This temperature is obtained in the upper center region of the core, which corresponds to a minimum subcooling of 24.38°C.

Figs. 8 and 9 show the predicted 2-D axial and radial temperature profiles in the center of Calandria for the CANDU 6 modified model. It can be seen that the flow and the temperature distributions are stable.

Flow is mainly vertical and temperature is monotonically increasing in the vertical direction in the core region. Buoyancy, with flow in the same direction, not only accelerates the flow circulation but also smoothes the horizontal temperature distribution in the core region, as flow is rising.

The calculated maximum temperature of the moderator is 69.95°C. This temperature is obtained in the upper center region of the core, which corresponds to a minimum subcooling of 37.64°C. Therefore it can be observed that the improvement in soobcooling is very significant, 13.26°C.

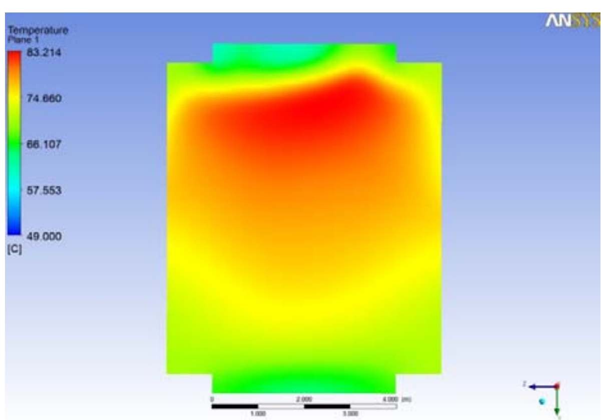

Fig.6. Axial temperature distribution in the center of Calandria – CANDU 6

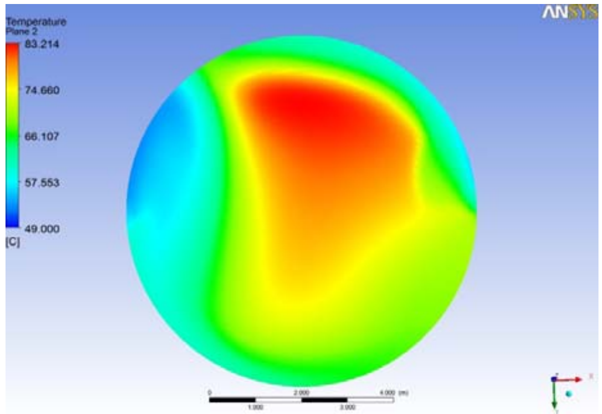

Fig.7. Radial temperature distribution in the center of Calandria – CANDU 6

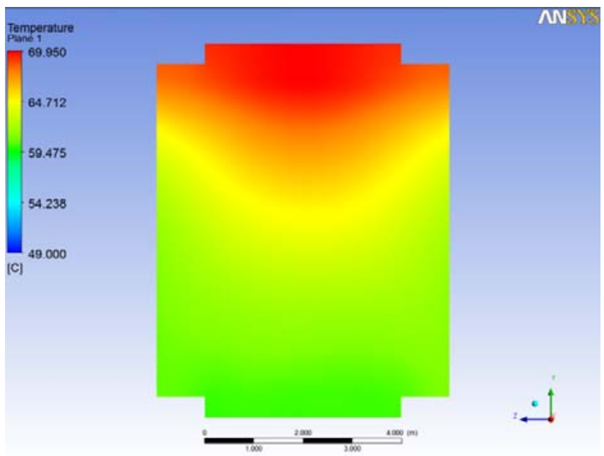

Fig.8. Axial temperature distribution in the center of Calandria – CANDU 6 Modified

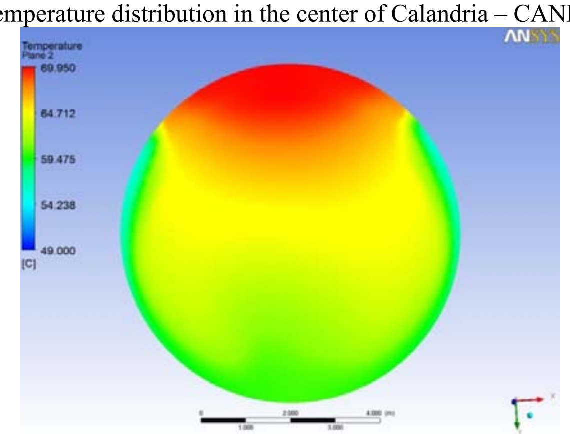

Fig.9. Radial temperature distribution in the center of Calandria – CANDU 6 Modified

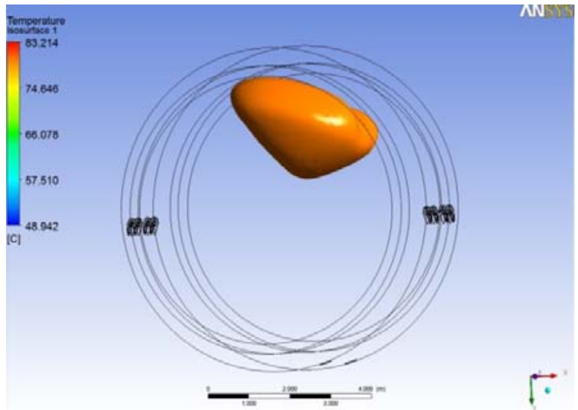

Fig.10. 3D distribution of temperatures above 80°C – CANDU 6

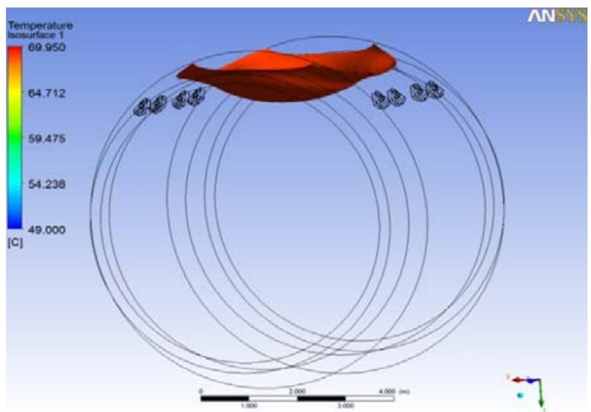

Fig.11. 3D distribution of temperatures above 69°C – CANDU 6 Modified

For the first model, an isosurface is presented in Fig.10, which shows the temperatures above 80°C. It can be observed that the hottest spot is located in the upper area of the core region. The spot is not located in the centerline of the Calandria. This is due to the interaction between the buoyancy forces and the inlet jet momentum forces.

In Fig.11, which represents the isosurface of temperatures above 69°C for the second model, it can be seen that the horizontal temperature distribution in the core region is very smooth. This is due to the fact that the buoyancy and the flow are in the same direction.

Fig.12 shows the velocity fields in the center of Calandria for the first model. The reversal of the jet occurs at an angle of about 60° over the horizontal centerline, in one side of the Calandria. It also can be observed that the velocities in the core region are very small compared to those from the reflector region. This is due to the fact that in the porous domain the hydraulic resistance appears.

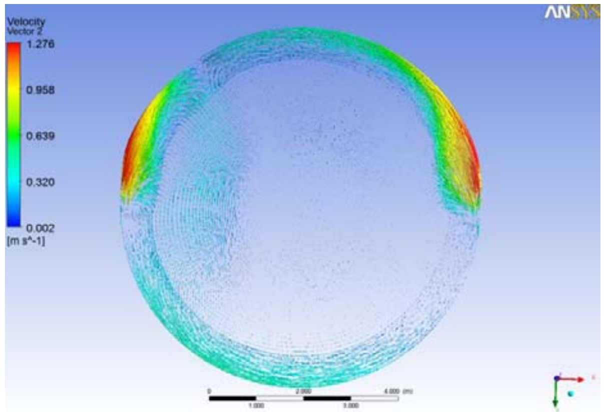

Fig.12. Velocity fields in the center of Calandria - CANDU 6

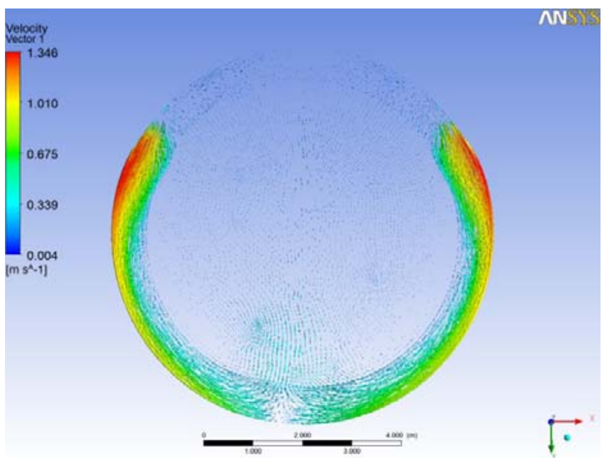

Fig.13. Velocity fields in the center of Calandria - Candu 6 Modified

In Fig.13 the velocity fields for the second model can be observed. The results show that the recirculation center is in the lower portion and near the edge of the core region.

It can be seen that the configuration change of moderator inlet/outlet flow results in more symmetric velocity and temperature distributions and less fluctuation compared to the traditional CANDU 6 design. This model minimizes the occurrence of hot spots and improves the thermalhydraulic characteristics in the Calandria vessel. Inflow jets at both sides along the Calandria cylinder wall collide at the vessel bottom, turn upward and move into the core region.

6. Conclusions

Starting from reference [8], two models for the Calandria vessel were developed, in order to simulate the flow of the moderator and to estimate the local subcooling of the moderator inside Calandria vessel under normal operational condition. The results obtained with the two models were compared.

There is a significant improvement in available subcooling with the modified CANDU 6 design. This result is obtained without other the moderator enhancements. For the second model, there were no hot spots in the core region, like those observed in CANDU 6 model. The temperature in the core region is stratified, increasing monotonically from the bottom to the top.

Flow and temperature fields are stable, due to concordance of forced flow and buoyancy directions in the core region.

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