MODIFICATION OF CANDU 6 MODERATOR FLOW CONFIGURATION INSIDE CALANDRIA VESSEL FOR INCREASING AVAILABLE SUBCOOLING IN CASE OF SEVERE ACCIDENT

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This work represents the effort to improve the thermal-hydraulic characteristics of the moderator by developing a new design of the Calandria vessel containing some modifications in the moderator inlet/outlet flow configuration. The exact position of the inlet and outlet nozzles is determined by performing a sensitivity analysis. By implementing this new model, a stratified distribution of the temperature in the core region, increasing monotonically from the bottom to the top is expected to be obtained. Flow and temperature fields are expected to be stable, due to concordance of forced flow and buoyancy directions in the moderator.

Keywords: Nuclear Engineering, CANDU, CFD Modeling, Moderator Flow

1. Introduction

This paper describes the work of developing 3D CFD models using ANSYS CFX for simulating the flow circulation of the moderator in a CANDU 6 nuclear reactor and predicting temperature distribution inside the Calandria vessel under normal operation. The developed models contain a design change which modifies the moderator inlet/outlet flow configuration and which leads to increasing of the available subcooling in case of a severe accident.

The models are based on two models previously developed by the author, which were validated against the results obtained with MODTURC_CLAS during a training session at AECL Canada [1, 2].

The proposed model brings forward a new concept, the modification of the moderator inlet/outlet flow configuration inside Calandria vessel. The exact position of the inlet and outlet nozzles is determined by performing a sensitivity analysis. By implementing this new model, a significant increase of the available subcooling is expected, without introducing new design changes on the parameters of the moderator system.

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2. Description of ANSYS-CFX Models

The Calandria is a 6 m long horizontal cylindrical tank filled with heavy water (D_2O). The Calandria shell comprises a main shell with a diameter of 7.6 m and 4.01 m in length. At each end of this main shell there is a smaller diameter sub-shell with a diameter of 6.76 m and 0.97 m in length. Inside the Calandria, 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.

In a generic Candu 6, 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 centre plane, but they are not symmetrically located in the axial plane [3]. In Fig. 1, an image of an inlet nozzle is presented. These fan-shaped inlet nozzles have four compartments separated by walls placed at 22.5° angles [3,4]. 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.

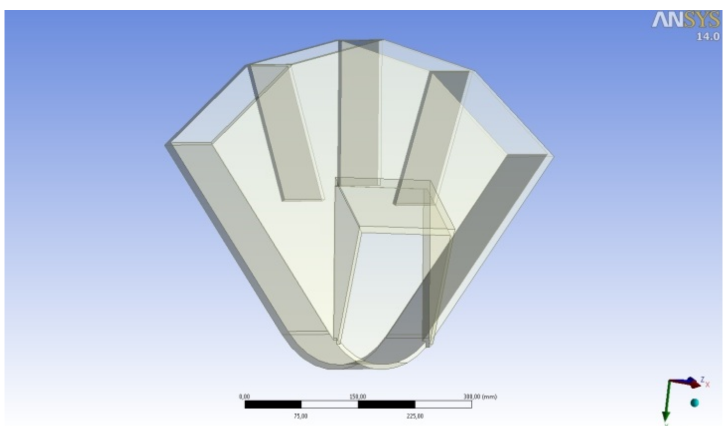

Fig. 1. Inlet nozzle configuration

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

In references 1 and 2 it could be observed that the highest temperature in the Calandria vessel was obtained in a part of the core. This is due to the interaction of buoyancy forces with the forced flow acting against each other. Therefore, it was considered necessary to study a way to make these forces act in the same direction within the core.

Thus, to improve the thermal-hydraulic characteristics of the moderator, a new model of the Calandria vessel was developed, containing design changes in the configuration of inlet and outlet nozzles of the moderator.

When modifying the configuration of the inlet and outlet of the heavy water, the target was that buoyancy forces would be consistent with the forces generated by the forced flow. Due to this objective, there is immediate need for the outlet nozzles to be positioned in the upper part of the vessel. The identified limitations which appear following the repositioning of the nozzles in the upper Calandria vessel are as follows:

- At the top of the vessel, the reactivity mechanisms are positioned. They are arranged symmetrically to the vertical center plane of the vessel and as presented in references 4 and 5, occupy the space within 30° on both sides of the central vertical plane. Due to this, the upper limit of the positioning is at 60° to the horizontal median plane of the Calandria.
- In the lower part of the vessel appears a limitation from the fact that for the proper cooling of the moderator, the channels located at the highest elevation have to be cooled by the primary current. These channels are located at 54° to the horizontal median plane of the Calandria; therefore, the outlet nozzles must be placed at a higher elevation.

Thus, the moderator outlet has to be positioned between 54° and 60° to the horizontal median plane of the Calandria. The exact positioning of the outlet nozzles will be identified following a sensitivity calculation which is presented in the next section.

In these models, four outlet nozzles are arranged symmetrically to the vertical central plane of the Calandria vessel, two on each side. This change is required in order to distribute the extracted flow over a larger area. In order not to change the moderator flow, the diameter of the nozzles was calculated at 0,157 m.

The eight inlet nozzles are redirected towards the bottom of the vessel, and repositioned in the upper region. Inlet nozzle shape and dimensions are identical to those of the generic CANDU. The exact positioning of the nozzles is determined as a result of a sensitivity calculation presented below. Their position should be chosen in order not to allow interaction of the cold flow entering the moderator with the hot jet leaving the moderator, but, in the same time there should be no portion of the Calandria vessel not covered by heavy water moderator between entry and exit of the moderator. A picture of the model is presented in Fig. 2.

By repositioning the inlet and outlet nozzles according to the considerations mentioned above, it is expected that the buoyancy forces and forced flow will have the same direction, and it is expected that the recirculation of the moderator will take place on the bottom of the Calandria vessel.

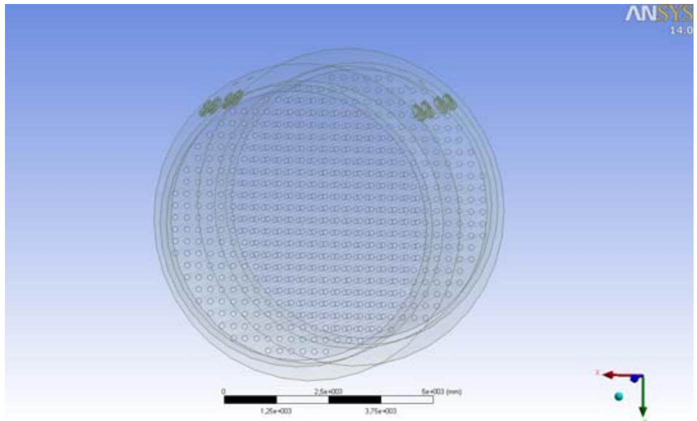

Fig. 2. Configuration of the inlet and outlet nozzles – Proposed Model

3. Simulation Conditions

The following conditions were applied to the model:

The total heat load considered is 100MW, of which 6,1MW in the reflector region and the rest in the core region [5]. Heat depositions in the solid components of 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 [1,2].

Calandria wall/tubesheets are thermally insulated (adiabatic condition). Also, the heat transfer inside of nozzle deflector is ignored [6].

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

The heavy water properties were collected from reference 7.

The mesh contains 1,292,750 elements and 1,206,185 nodes. The residual target RMS for the conservation equations was set at 1e-4.

4. Exact Positioning Of The Nozzles

To determine the position of the outlet nozzles a sensitivity calculation was made. This calculation took into account positioning of the outlet nozzles at angles between 54° and 60° to the horizontal median plane of the Calandria. In each case the position of the inlet nozzles was 10° downward.

Table 1 below summarizes the obtained results, highlighting the temperature, pressure and maximum velocities for each case considered.

Table 1.

Maximum parameters at different positions of the outlet nozzles

Outlet angle [°]	Inlet angle [°]	Max. Temperature [°C]	Max. Pressure [bar]	Max Velocity [m/s]
54	44	70,36	1,20115	13,719
55	45	69,701	1,24546	13,805
56	46	69,52	1,28219	14,226
57	47	70,046	1,26033	14,047
58	48	70,362	1,23775	13,832
59	49	70,624	1,22934	13,189
60	50	71,222	1,21636	12,924

It can be seen that the lowest outlet temperature is achieved when the outlet nozzles are positioned at an angle of 56° to the horizontal median plane of the Calandria. It can be seen that the temperature on the one hand, and the pressure and speed, on the other hand, vary in inverse proportion. It is noted that where the temperature is lower, the pressure and speed are higher, due to the fact that for certain positions of the outlet nozzle, some of the fuel channels are located in the main flow.

After determining the position of the outlet nozzles, a series of runs for the optimal positioning of the inlet nozzles were made. This took into account positioning angles between 41° and 51° to the horizontal median plane of Calandria. The results obtained are shown in Table 2.

Table 2.

Maximum parameters at different positions of the inlet nozzles

Outlet angle [°]	Inlet angle [°]	Max. Temperature [°C]	Max. Pressure [bar]	Max Velocity [m/s]
56	41	70,276	1,23919	13,499
56	42	70,189	1,27835	13,984
56	43	71,543	1,22291	13,662
56	44	69,707	1,22566	13,416
56	45	69,608	1,23855	13,671
56	46	69,52	1,28219	14,226
56	47	68,704	1,2921	13,896
56	48	70,318	1,23559	13,64
56	49	68,983	1,24316	13,97
56	50	69,907	1,24428	13,647
56	51	69,647	1,246	13,722

It can be seen that the lowest outlet temperature is achieved when the inlet nozzles are positioned at an angle of 47° to the horizontal median plane of the Calandria.

Thus, the optimum configuration of the modified Calandria vessel has the inlet nozzles positioned at an angle of 47° and the outlet at an angle of 56° to the horizontal median plane of the Calandria.

5. Results

Figs. 3 and 4 present the axial and radial temperature profiles in the center of the Calandria vessel for the chosen configuration, with the inlet nozzles placed at an angle of 47° and the outlet at an angle of 56° to the horizontal median plane of the Calandria.

It can be observed that the obtained temperature fields are stable and the core temperature increases monotonically in the vertical direction.

Buoyancy flow has the same direction as the forced flow, and not only that it accelerates the flow of the moderator in the Calandria vessel, but makes the horizontal temperature distribution much smoother as the main flow is headed to the outlet nozzles.

The calculated maximum temperature of the moderator is 68.704° C. This temperature is obtained at the top of the core in its center. This temperature is corresponding to a minimum subcooling temperature of 38.89° C. This results in an improvement of 14.51° C to Candu generic model [2].

In Fig. 5 the velocity fields are presented for the proposed model. Unlike Candu generic model, where the recirculation of the current was observed at an angle of 60° with respect to the horizontal median plane of the Calandria [1], for the proposed model, the reversal of the current is produced at the center-bottom of the Calandria vessel.

This makes the movement inside the vessel to be uniform and hot spots observed in Candu generic model, to disappear.

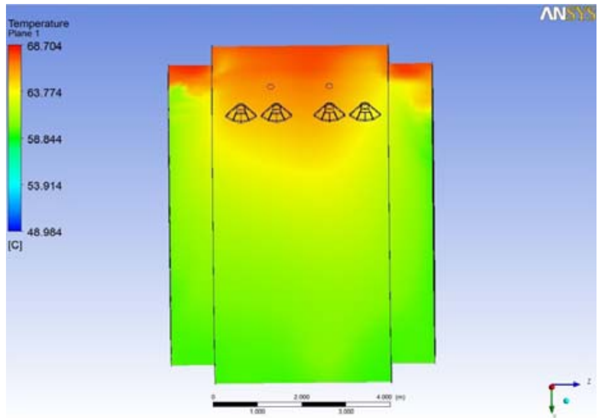

Fig. 3. Axial temperature distribution in the center of Calandria

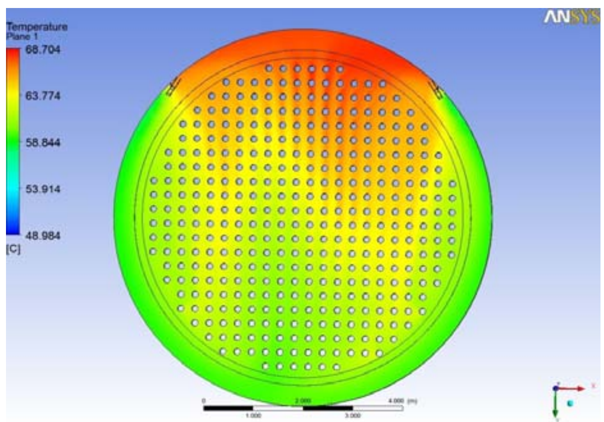

Fig. 4. Radial temperature distribution in the center of Calandria

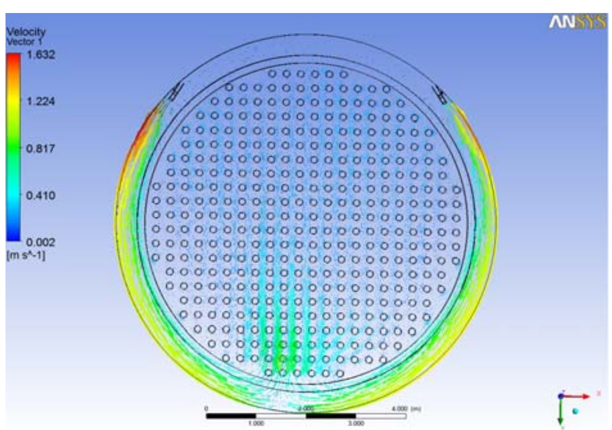

Fig. 5. Velocity fields in the center of Calandria

6. Conclusions

The objective of this study was to develop 3D CFD models for the simulation of moderator flow in a CANDU 6 reactor and to estimate the temperature distribution in the Calandria vessel in normal operation.

The authors propose with this paper a new model, which improves moderator performance and eliminates hot spots and thermal-hydraulic fluctuations occurring in the moderator. These improvements are achieved by modifying the flow configuration of the moderator inside the Calandria vessel.

The new configuration, proposed by the authors based on a sensitivity analysis, contains the inlet nozzles placed at an angle of 47° to the horizontal median plane of the Calandria, pointing downward, and the outlet at an angle of 56°.

By implementing this model, a significant improvement in the available subcooling was achieved [8], without introducing new changes to the parameters from the moderator system.

With this new model a stratified temperature distribution was achieved, and the temperature increases monotonically from the bottom to the top of the vessel.

The obtained flow fields are stable, and the temperature is also stable, due to the fact that buoyancy force within the core and forced flow directions in the moderator region are in concordance.

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