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Safety Assessment of Generic Safety Issues for CANDU-6 Reactors:
Analyses of Moderator Heat Sink Integrity

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ABSTRACT

During the loss of coolant accident (LOCA) in CANDU reactors, the pressure tube could contact its surrounding Calandria tube due to the increase of temperature, which leads to sustained Calandria tube dryout. In terms of safety analyses of CANDU reactors, it is concerned as one of major safety issues to maintain moderator subcoolability in the Calandria vessel against the postulated accidents. The Canadian Nuclear Safety Commission (CNSC), a regulatory body in Canada, categorized this issue as a general action item 95GAI05, *the temperature prediction for moderator integrity,* and recommended that a series of experimental works should be performed to verify the evaluation codes used for the design with the results of three-dimensional experimental data. In the present study, a simulation using a computational fluid dynamics (CFD) code has been conducted to predict the temperature distribution of the moderator in the Calandria vessel under a steady-state condition. In the simulation, the field data of Wolsong nuclear power plant were used with adequate recompilation for the study. It is found that the proposed analyses models can predict the moderator temperatures reasonably to the Calandria vessel. As a result of the CFD simulation, the moderator has the enough subcoolability to ensure the integrity of pressure tube.

1. INTRODUCTION

As for other water-cooled reactors, loss-of-coolant accidents (LOCA) in CANDU reactors can be the precursors to fuel damage, which can result in radiological consequences. However, the CANDU reactor has the unique features and the intrinsic safety related characteristics that distinguish it from other water-cooled thermal reactors. One of the safety futures is that the heavy water (D_2O) moderator is continuously cooled, providing a heat sink for the decay heat produced in the fuel if there is a LOCA and a coincident failure of the emergency coolant injection (ECI) system. Under such dual failure conditions, the hot pressure tube (PT) would deform into contact with the Calandria tube (CT), providing an effective heat transfer path from the fuel to the moderator.

Under conditions of high PT temperature and high coolant pressure following LOCA accidents, the PT could strain (i.e., balloon) to contact its surrounding CT (PT/CT contact). Following contact between the hot PT and the relatively cold CT, there is a spike in heat flux to the moderator surrounding the CT, which leads to sustained CT dryout. The prevention of CT dryout following PT/CT contact depends on available local moderator subcooling. Higher moderator temperatures (lower subcooling) would decrease the margin of CTs to dryout in the event of PT/CT contact. As for LOCAs with coincident loss of the ECI, fuel channel integrity depends on the capability of the moderator providing the ultimate heat sink. Although some computer codes such as 2DMOTH, PHOENICS, etc. were used to predict the moderator temperatures for these accidents, they were not adequately validated due to the uncertainty of temperature prediction. The CNSC requested to perform three-dimensional moderator test facility experiments with an aim to validate safety analysis tools.

The temperature profiles of moderator inside Calandria-like tank at SPEL (Sheridan Park Engineering Laboratory) were investigated and the predicted flow regimes of moderator were compared with those of the SPEL experimental results [1]. As a link of the previous work, three-dimensional analyses of fluid flow and heat transfer have been performed to assess thermal-hydraulic characteristics for the moderator simulation of the CANDU-6 nuclear reactor. In particular, the real data of Wolsong nuclear power plant in Korea was used and were recompiled adequately for the study. Moreover, the effects of heat load distribution and D_2O properties on the temperature distributions inside Calandria vessel have been also investigated. An objective of this study is, therefore, to establish a sound theoretical basis for the models and then verifying them systematically.

2. MODELLING DETAILS AND ASSUMPTIONS

The simulation of the moderator thermal-hydraulic behavior in the Calandria vessel has been conducted using a CFD code, FLUENT in the preceding work [1]. The temperature distributions of moderator inside Calandria-like tank at SPEL of the AECL

(Atomic Energy of Canadian Limit) were investigated. The predicted flow regimes of moderator were also compared with those of the SPEL experimental results. In addition, the characteristic flow regime map for the SPEL was proposed as a result.

In the present study, a CANDU-6 nuclear reactor has been simulated to conduct the three-dimensional thermal-hydraulic analyses for the moderator in the Calandria vessel under a steady-state condition with FLUENT code. The behaviors of moderator inside Calandria vessel were simulated for the typical CANDU-6 nuclear reactor as shown in the Figure 1. All dimensions are as close to the real Calandria vessel geometry [2]. The Calandria vessel is a cylindrical tank with a diameter of 7.6 m and a full length of 6 m. The moderator fluid is a heavy water, D_2O, circulating through eight inlet nozzles and discharging through two outlet nozzles. The inlet nozzles are symmetrically placed in x-y plane with respect to the vertical centerline but are asymmetric in a axial plane. A flowrate at the inlet nozzles is about 940 kg/s. The outlet ports are symmetrically located in the axial direction with respect to a mid-plane perpendicular to a z-axis but are asymmetrically placed towards the moderator pumps in the x-y plane.

In this study, the field data of Wolsong nuclear power plant were used with adequate recompilation for the study. Since the heat generation to the moderator fluid is about 100.2 MW of power from the plant data, the moderator fluid circulates in the Calandria vessel due to interaction between fluid inertia force and buoyancy force among the horizontal tube banks. As to the buoyancy effects, the Boussinesq approximation was, therefore, applied in this work.

In the Calandria vessel, there are 380 Calandria tubes, which displace about 12% of the Calandria vessel volume. Therefore, it is very difficult to simulate the heat load from 380 Calandria tubes respectively because of the limitation of the computer capability. In this study, 380 Calandria tubes were categorized into 9 groups in accordance with the ranges of coolant flowrate as shown in Table 1 and in Fig. 2.

For the thermal hydraulic analyses of CANDU moderator, the test matrix consists of five cases according to the input data such as the heat load and physical properties of D_2O as shown in Table 2. Comparison between constant heat load and 9-grouped heat loads was performed to investigate the effect of heat load distribution, i.e., (Case 1 Vs. Case 3, and Case 2 Vs. Case 4). Besides, the effect of moderator properties was also examined with comparison between constant and temperature-dependent D_2O properties.

For the numerical computation, the general purpose CFD code, FLUENT version 6.0, was used for the present study. The physical domain (geometry) of the Calandria vessel in a CANDU-6 reactor was meshed to generate both structured and unstructured grids respectively and the total number of grids is about 608,770 as shown in Fig. 3. The fluid flow is assumed to be steady, incompressible and single-phase. SIMPLEC algorithm is used to solve continuity equation, momentum equations, and energy equation coincidently. The standard k-ε turbulence model associated with the logarithmic wall function is used to predict turbulence generation and dissipation in the Calandria vessel. Buoyancy force is modeled using the Boussinesq approximation in such a way that density is assumed to be a linear function of temperature.

3. RESULTS AND COMPARISON

In the Calandria vessel, three flow patterns, i.e., momentum dominated flow, mixed type flow and buoyancy dominated flow are observed respectively with respect to the heat load and/or inlet flowrate, which were identified as the major parameters affecting the flow regime of moderator [1]. Table 3 shows the results of two models, i.e., porous media model and real geometry model. While the flow pattern inside the Calandria vessel using the porous media model is a momentum dominated flow as shown in Fig. 4, that of real geometry model used in Fig.5 is a mixture flow pattern between momentum dominated flow and buoyancy dominated flow. In general, the flow regime due to heat load and/or inlet flowrate can be identified by the dimensionless number (Ar), the ratio of inertia force to buoyancy force [1]. As to the condition of CANDU-6 reactors, Ar number is examined about 0.097 for Wolsong nuclear power plant and the flow pattern of moderator inside Calandria vessel is the mixed type fluid flow in the preceding study [1]. Figure 5 shows the predicted temperature distributions inside Calandria along the mid- and centerline plane and indicates that the flow regime is the mixed type flow. It is well agreed with those of predicted Ar number. Therefore, Ar number can be considered as a good indicator to identify the flow regime of moderator inside Calandria vessel if the inertia and the buoyancy forces are coexisted.

Figure 6 shows the comparison results for the four cases of the test matrix. The present analysis models can predict the moderator temperatures reasonably in the Calandria vessel, i.e., the predicted average temperatures of moderator are lower than about 70°C of the Final Safety Analysis Reports (FSAR) in the steady state condition. Therefore, the maximum temperature of moderator inside Calandria vessel is not high enough to saturate the moderator to the boiling. Therefore, it is seemed that the moderator can be maintained the enough subcoolability to ensure the integrity of pressure tube under the steady state condition as a result of the CFD simulation. However, it is indicated that there is somewhat differences between the results of two cases such as constant and temperature-dependent D_2O properties. This implies that the detail information sets for the heat load distribution of the 380 Calandria tube banks and D_2O properties are needed to predict the temperature distribution and the flow regime inside Calandria vessel with more accuracy,

4. CONCLUSION

Three-dimensional analyses of fluid flow and heat transfer have been performed to assess thermal-hydraulic characteristics for the moderator in the CANDU-6 reactors. The effect of heat load distribution and moderator properties has also investigated. The main conclusions are as follows;

- The flow pattern predicted with porous media model in the Calandria vessel is the momentum dominated flow. However, the predicted flow pattern with real CANDU-6 geometry is the mixed type flow, which agrees with the calculated dimensionless number, Ar.
- The present analyses models can predict the moderator temperatures reasonably in the Calandria vessel. From the result of the CFD simulation, it can be considered that the moderator has the enough subcoolability to ensure the integrity of pressure tube.
- To predict the temperature distribution and the flow regime inside Calandria vessel with more accuracy, the detail information sets for the heat load distribution of the 380 Calandria tube banks and D_2O properties are needed.

REFERENCE

[1] S. O. Yu, M. W. Kim, and H. J. Kim, “Three-Dimensional Analyses of Fluid Flow and Heat Transfer for Moderator Integrity Assessment in PHWR,” 22nd Nuclear Simulation Symposium, November, Ottawa, 2002.

[2] D. Koroyannakis, R. D. Hepworth and G. Hendrie, “An Experimental Study of Combined Natural and Forced Convection Flow in a Cylindrical Tank,” TDVI-382, AECL, 1983.

Table 1. 9 groups of heat load distribution

Group	Flowrate range, [kg/s]	Average flowrate, [kg/s]	Number, (EA)	Heat Load, [W/m^3]
1	~15	13.22	52	3,327,819.69
2	15~20	17.60	66	4,288,424.53
3	20~23	21.67	39	4,795,747.38
4	23~24	23.50	14	5,128,987.12
5	24~25	24.51	22	5,242,160.05
6	25~26	25.53	33	5,549,541.62
7	26~27	26.55	81	5,574,478.77
8	27~28	27.36	67	4,990,816.73
9	28~	28.29	6	4,832,732.80

Table 2. Test matrix of CFD code work

Case	Total Heat Load, [MW]	Inputs	
		Heat Load	D_2O Properties
Case 1	100.1814	uniform heat generation	density : Boussinesq approx others : constant
Case 2		uniform heat generation	density : Boussinesq approx others : function of temp.
Case 3		9 groups	density : Boussinesq approx others : constant
Case 4		9 groups	density : Boussinesq approx others : function of temp.
Case 5		uniform heat generation (porous media)	density : Boussinesq approx others : function of temp.

Table 3. Comparison between results with porous media model and real geometry

	Real Geometry (Case 4)	Porous Media Model (Case 5)
Flow Pattern	Mixed type flow	Momentum dominated flow
Average Temp., T_{avg} [°C]	62.23	56.90
Max. Temp., T_{max} [°C]	83.00	62.77
Outlet Temp., T_{out} [°C]	57.59	60.12

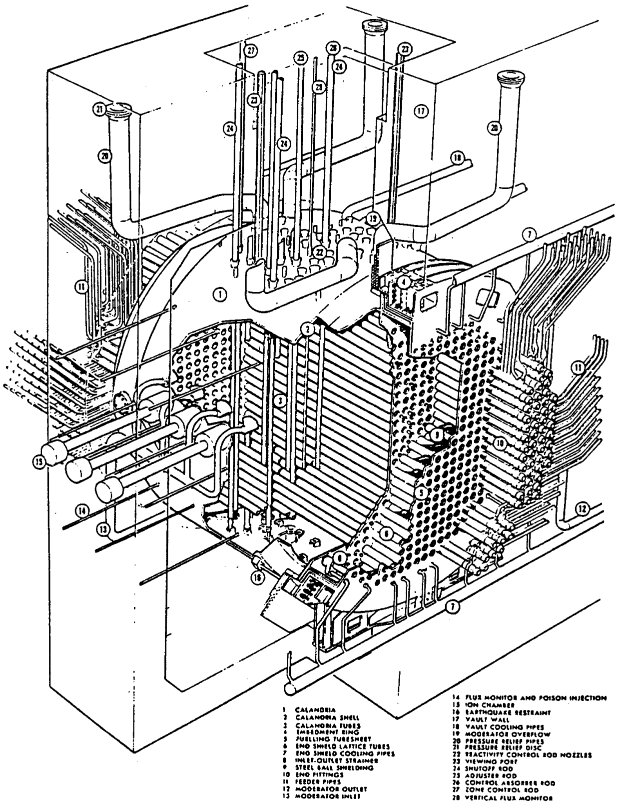
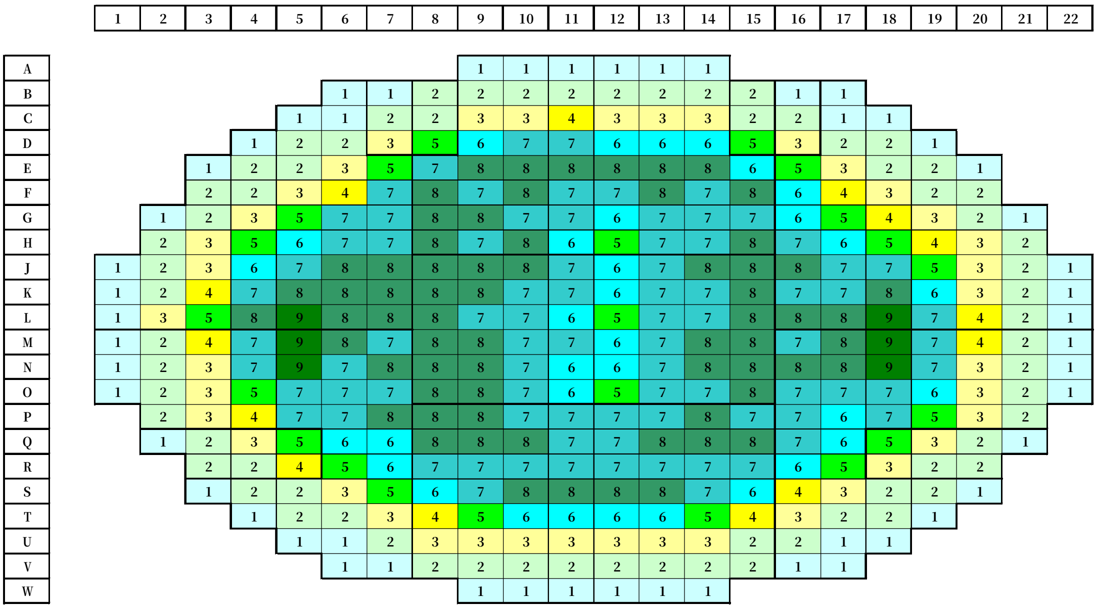


Figure 1. CANDU-6 nuclear reactor.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									1	1	1	1	1	1								
B						1	1	2	2	2	2	2	2	2	2	1	1					
C					1	1	2	2	3	3	4	3	3	3	2	2	1	1				
D				1	2	2	3	5	6	7	7	6	6	6	5	3	2	2	1			
E			1	2	2	3	5	7	8	8	8	8	8	8	6	5	3	2	2	1		
F			2	2	3	4	7	8	7	8	7	7	8	7	8	6	4	3	2	2		
G		1	2	3	5	7	7	8	8	7	7	6	7	7	7	6	5	4	3	2	1	
H		2	3	5	6	7	7	8	7	8	6	5	7	7	8	7	6	5	4	3	2	
J	1	2	3	6	7	8	8	8	8	8	7	6	7	8	8	8	7	7	5	3	2	1
K	1	2	4	7	8	8	8	8	8	7	7	6	7	7	8	7	7	8	6	3	2	1
L	1	3	5	8	9	8	8	8	7	7	6	5	7	7	8	8	8	9	7	4	2	1
M	1	2	4	7	9	8	7	8	8	7	7	6	7	8	8	7	8	9	7	4	2	1
N	1	2	3	7	9	7	8	8	8	7	6	6	7	8	8	8	8	9	7	3	2	1
O	1	2	3	5	7	7	7	8	8	7	6	5	7	7	8	7	7	7	6	3	2	1
P		2	3	4	7	7	8	8	8	7	7	7	7	8	7	7	6	7	5	3	2	
Q		1	2	3	5	6	6	8	8	8	7	7	8	8	8	7	6	5	3	2	1	
R			2	2	4	5	6	7	7	7	7	7	7	7	7	6	5	3	2	2		
S			1	2	2	3	5	6	7	8	8	8	8	7	6	4	3	2	2	1		
T				1	2	2	3	4	5	6	6	6	6	5	4	3	2	2	1			
U					1	1	2	3	3	3	3	3	3	3	2	2	1	1				
V						1	1	2	2	2	2	2	2	2	2	1	1					
W									1	1	1	1	1	1								

Figure 2. Heat load distribution rearranged into 9 groups with Wolsong NPP data.

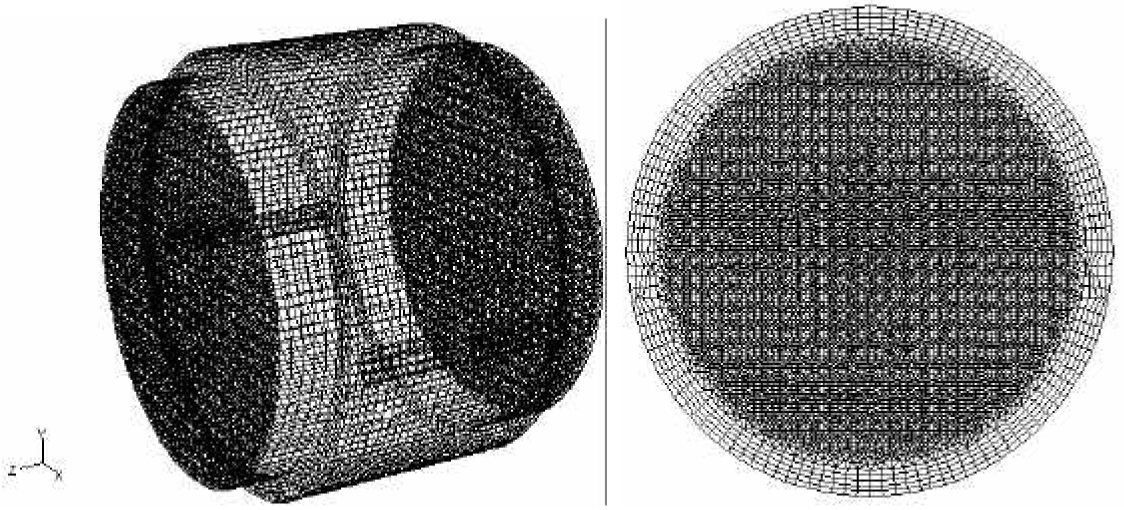


Figure 3. Computational domain of CANDU-6.

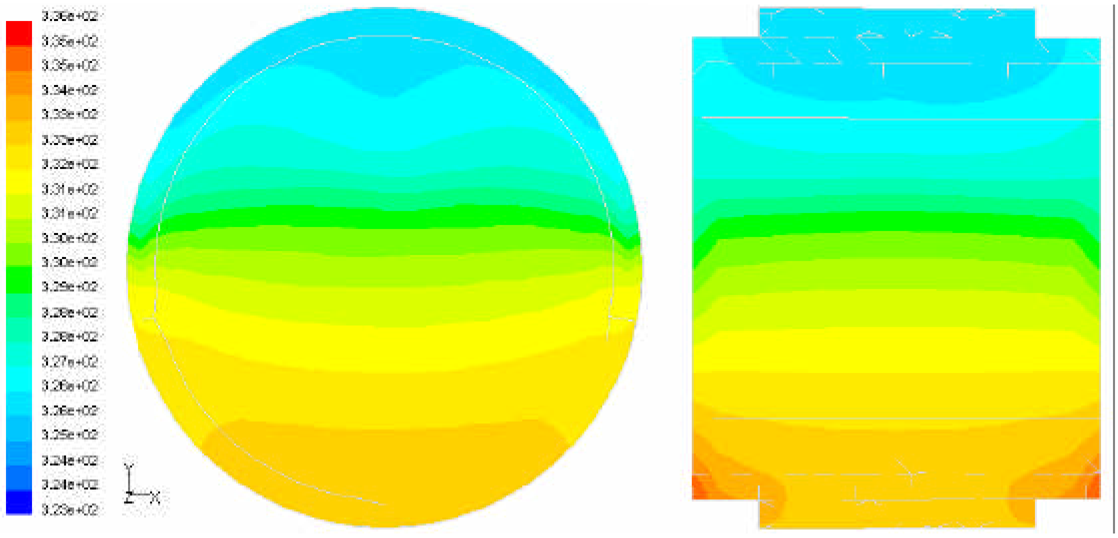


Figure 4. Temperature distribution predicted with porous media model (Case 5).

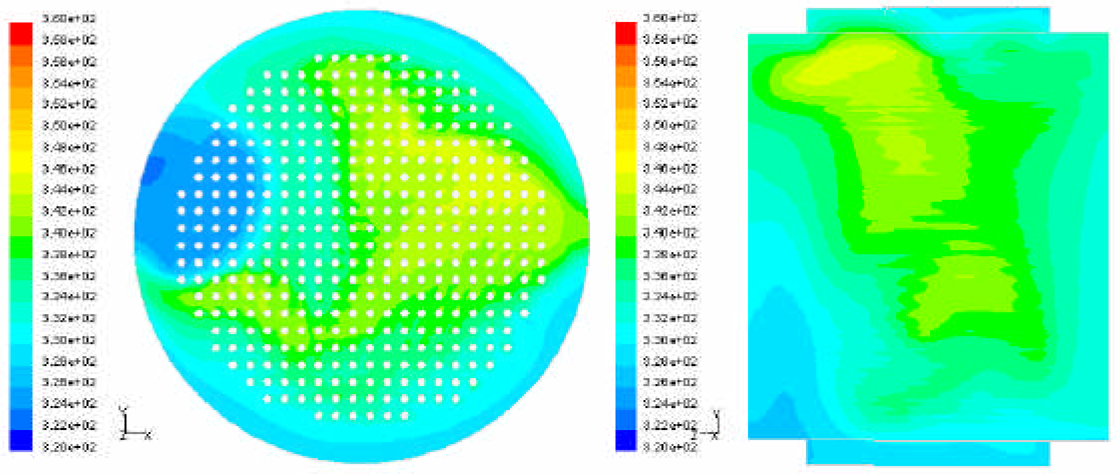
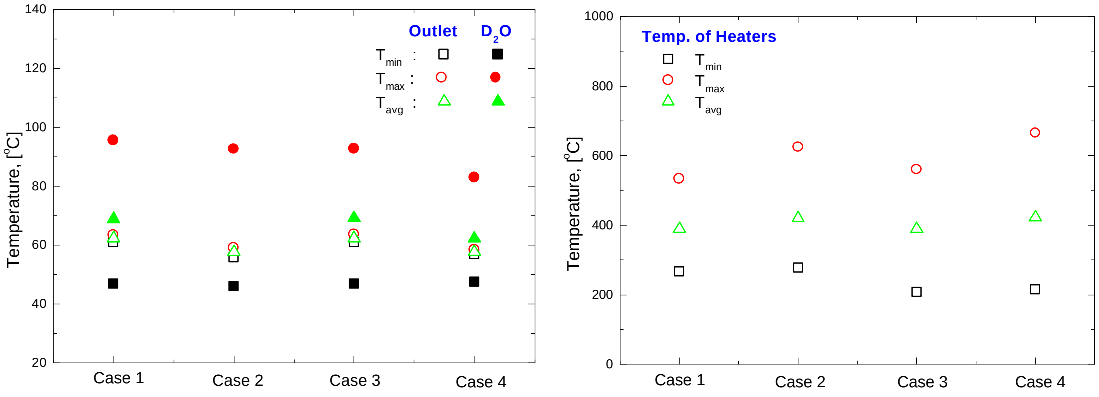


Figure 5. Temperature distribution predicted with real geometry (Case 4).



(a) moderator (b) heater

Figure 6. Comparisons of moderator and heater temperatures of real geometry.