

NURETH14-096

CFD MODEL OF CANDU CALANDRIA VESSEL RETENTION DURING SEVERE ACCIDENTS

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Abstract

A CFD model is developed for the calandria vessel retention of generic CANDU^{®1} reactors, including the Enhanced CANDU 6^{®TM2} (EC6^{®TM2}), the Advanced CANDU Reactor^{®3} (ACR-1000^{®3}), and the CANDU 6, during a postulated severe accident. The model is focused on the thermal hydraulics in a full-scale calandria vessel when terminal debris bed is formed during a loss-of-coolant accident, which is bounding in terms of potential challenge to calandria vessel integrity. The CFD model is benchmarked against MAAP4-CANDU analysis of ACR-1000. The results show that with ex-vessel cooling available, the core debris can be well contained inside the calandria vessel, demonstrating the successful in-vessel retention strategy in the ACR-1000 severe accident management.

1. Introduction

One of the CANDU reactor design principles is to prevent and mitigate severe accidents and to reduce severe accident consequences. Redundant fuel cooling mechanisms and multiple layers of barriers (preventing release of fission products) provide adequate time for the operators to halt accident progression and to achieve a controlled and stable state. In the unlikely event of a severe accident, CANDU plants are provided with additional features to maintain the containment integrity and limit the radioactive releases. By design, CANDU reactors have larger inventories of water (such as the primary coolant, emergency coolant, moderator, steam generator inventory, and others) that will be available to remove the heat from the core, providing ample time for operator actions. Therefore, the progression of core damage is slower compared to other reactor designs.

There are two broad categories of potential core damages in the CANDU reactor: limited core damage (LCD) and severe core damage (SCD). The LCD states involve mainly fuel damage, with the core maintained in essentially nominal configuration. The limited core damage accidents (LCDAs) are predecessors of the severe core damage accidents (SCDAs), and they are unique to pressure tube reactors. The CANDU design provides multiple, redundant means of terminating accident in the LCD states and thereby preventing further core degradation. The SCD states

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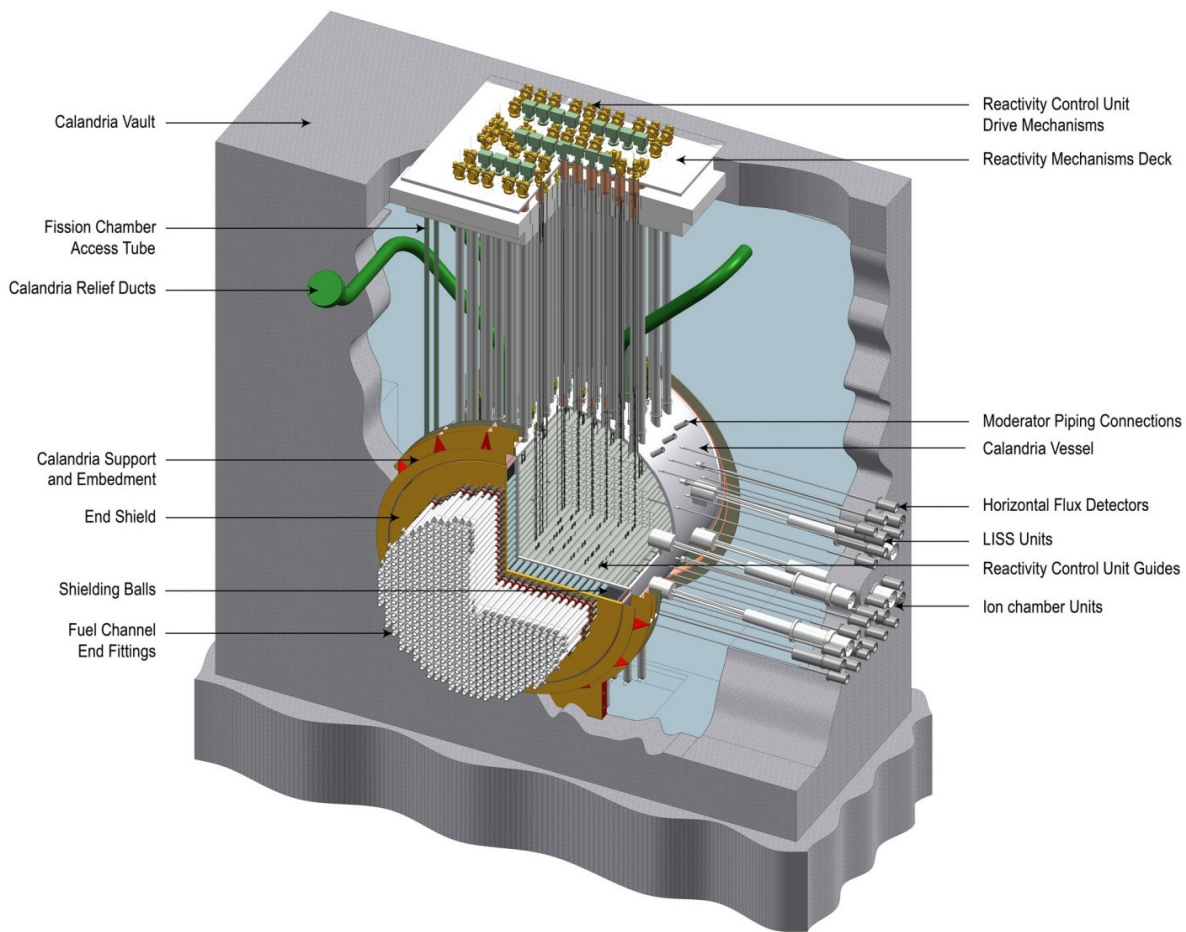


Figure 1 Calandria Vessel and Reactor Vault for ACR-1000

involve reactor core degradation (i.e., break-up of fuel channels and formation of core debris). The intention of CANDU type reactor design for severe accidents is to ensure retention of the core debris within the calandria vessel (in-vessel core damage, InVCD).

The CANDU reactors, including the EC6, the ACR-1000 (Figure 1), and the CANDU 6, feature horizontal fuel channels supported in heavy water moderator inside a calandria vessel (CV), which in turn is inside a reactor vault (RV) filled with light water. This unique core configuration renders the CV as an inherent “core-catcher” during a severe accident. The in-vessel retention (IVR), a severe accident management strategy, is achieved by removing decay heat through the ex-vessel cooling using the water in the large volume RV and shield cooling system and maintaining the CV integrity. This paper covers one aspect of modelling of the calandria vessel retention - the computational fluid dynamics (CFD) modelling of CANDU reactor calandria vessel integrity during severe accidents and compares the predictions with MAAP4-CANDU simulations, in particular for a bounding case of the postulated large, loss-of-coolant accident (LOCA) scenario.

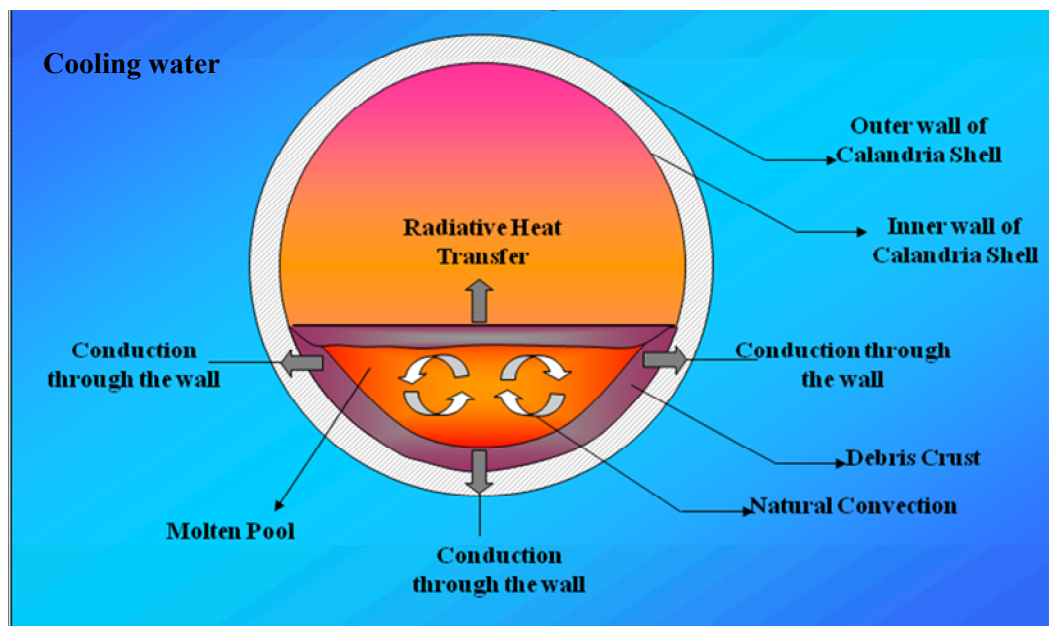


Figure 2 Schematic of Terminal Debris Bed and Heat Transfer Mechanisms

The fuel and fuel channel responses in sequence to the postulated large, out-of-core LOCA with consequential loss of long-term cooling system and loss of moderator heat sink involve the boil-off and loss of moderator inventory, uncovering and heat-up of calandria tubes of top rows, core disassembly, formation of suspended debris bed, massive core collapse, and subsequently, a terminal debris bed (Figure 2) formed at the bottom of the CV, which consists of a molten corium pool surrounded by a solid crust layer [1]. In this circumstance, various heat transfer mechanisms exist in the CV, including natural convection in the molten corium due to volumetric heat generation (decay heat), radiation from the upper crust to the CV wall and tubesheets, and conduction through the crust, CV wall and tubesheets.

A number of severe accident analyses have been performed for the above large LOCA scenario in CANDU reactors. Meneley et al. [1] developed a 1-D model for the transient heat-up of solid debris bed and a lumped-parameter model for the molten pool thermal behaviour and crust layer thickness. Quasi-steady-state conditions were assumed due to slow decay and heat flows to the end shields were ignored. Rogers and Lamari [2] extended the above models to account for the transient solid debris bed melting and the eventual solidification of molten pool, which filled the gap in the previous study [1]. Muzumdar et al. [3] performed sensitivity studies using a lumped-parameter molten pool heat transfer model and found that among material properties, the corium thermal conductivity is the most sensitive variable for the core retention capability. In support of level 2 probabilistic safety assessment (PSA), AECL also performed accident progression and consequence analyses for CANDU 6 ([4] and [5]) and ACR-1000 using the MAAP4-CANDU code and its early versions, which is a computer code intended to simulate the integral effects of interaction of various phenomena/physical processes upon accident progression. These analyses ([1]-[5]) have shown that during the large LOCA transients, the formation of terminal debris bed is bounding in terms of potential challenge to the CV integrity due to elevated CV wall

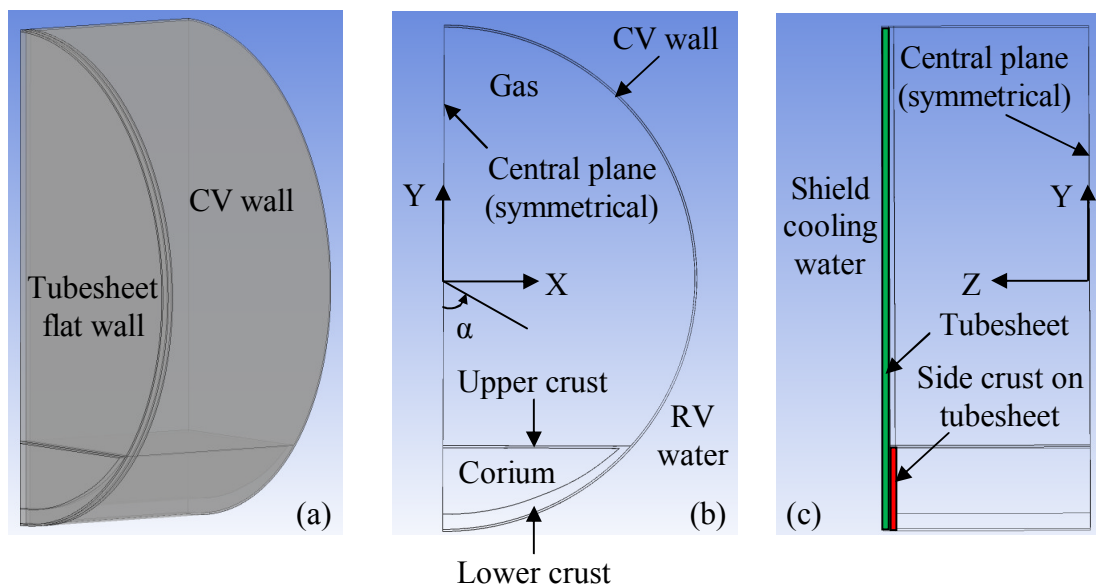


Figure 3 Flow Domain of CFD Model for a Quarter of ACR-1000 Calandria Vessel: (a) Isometric View; (b) Cross Section View; (c) Side View

temperature and heat flux. With the shield cooling fully functional, the CV wall temperature and heat flux are kept relatively low such that the wall strength is maintained and a departure from nucleate boiling is avoided on the outer wall, and thus the core debris is retained within the CV and would eventually resolidify. None of these studies, however, have solved for the buoyancy-driven molten corium flow. Instead, empirical correlations are used to determine the natural convection heat transfer from the molten pool to the surrounding crust.

In this study, a computational fluid dynamics (CFD) model is developed using ANSYS-CFX version 12 [6] in support of the IVR analysis of generic CANDU reactors. The model is capable of predicting the steady-state 3-D thermal hydraulics in a full-scale CV when the terminal debris bed is formed during a postulated large LOCA scenario, which is the most challenging phenomenon to IVR. The CFD simulation is benchmarked against MAAP4-CANDU analysis results of this particular stage of the severe accident for ACR-1000.

2. Development of CFD model

The focus of the CFD model is on the steady-state characteristics of the terminal debris bed of given geometrical configuration. This would allow for a more accurate prediction of the conjugate heat transfer in the terminal debris bed and the CV.

The CFD model is developed for the generic CANDU reactors by taking into account the key thermal hydraulic phenomena inside the CV based on mechanistic models. The application of this CFD model to the IVR analysis of a particular CANDU reactor design, i.e., the EC6, requires limited modifications only, such as the CV dimensions and the physical properties of the debris

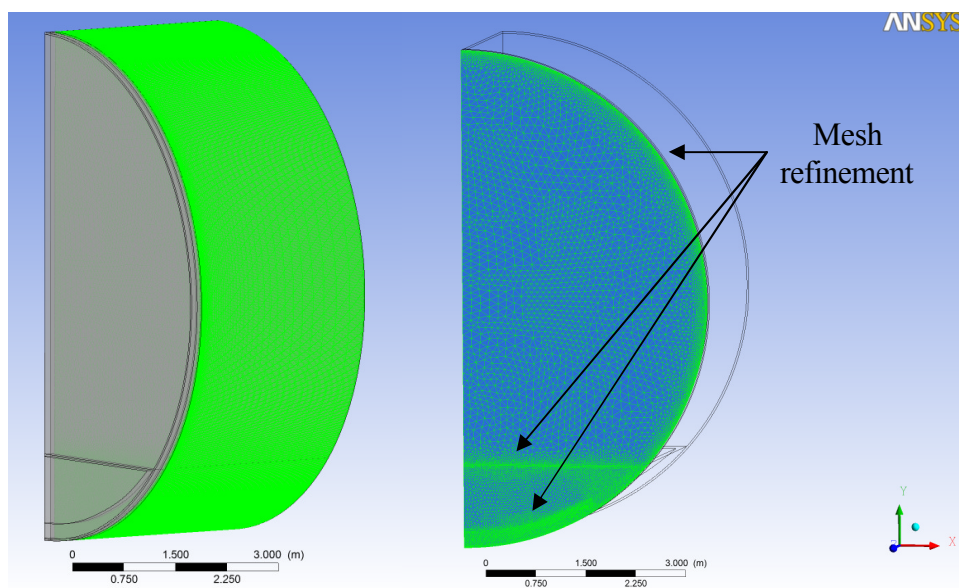


Figure 4 Illustration of Surface Mesh in CFD Model for ACR-1000 Calandria Vessel

core materials. The discretization strategy of flow domain, the physical models and the types of boundary conditions used in the CFD model remain essentially the same.

2.1 Flow domain and mesh

When shield cooling on both ends of the CV is available, the flow and heat transfer in the CV are considered symmetrical about two vertical, central planes independent to each other (at 90°). The CFD model of the full-scale CV is thus simplified to a quarter of it, as shown in Figure 3. The flow domain includes the CV wall, the tubesheet on one end of the CV, the terminal debris bed at the bottom of the CV, two symmetrical central planes, and the rest of the enclosed volume.

The terminal debris bed consists of a molten corium pool surrounded by an upper crust, a lower crust, and a side crust on the tubesheet inner wall. Generally, the crust layer thickness in the current model is first assumed to set up the model and start the simulation, and then iterated until the calculated crust-corium interface temperature is equal to the melting point.

The flow domain is discretized using the unstructured CFX-mesh tool. The CV is divided along its axial direction into three parallel slice-shape blocks, the core block consisting mainly of the molten corium and upper and lower crust layers, the tubesheet block, and the middle block for the side crust on the tubesheet. Each block is meshed separately and connected together, providing sufficient mesh resolution with controlled number of mesh elements (approximately 1.5 million). Dedicated mesh refinement is implemented (Figure 4) in the molten corium pool, crust and CV wall particularly the region close to the upper crust to capture the potential focussing effect, which is a phenomenon of localized higher heat loads onto the CV wall due to the presence of a thin crust layer. The mesh independence of the current model is examined by comparing the simulation results to those from refined meshes.

2.2 Physical models

The governing equations for the incompressible molten corium flow are the 3-D Navier-Stokes and the mass conservation equations. Natural convection is present within the molten corium as the CV is cooled on the outside and volumetric heat generation continues within the debris bed. The standard k - ε turbulence model with the scalable wall function and the Boussinesq buoyancy model are used for closure. A homogeneous volumetric heat generation in the debris bed is specified as the heat source.

The upper portion of the CV is assumed to be occupied by air, which is generally considered to be optically transparent. In this case, the radiation from the upper crust to the CV and tubesheet inner walls does not transfer much energy directly to the media. Thus, the discrete transfer model with surface to surface radiation transfer mode is used, which is suitable for modelling the enclosure radiative transfer with non-participating media.

2.3 Boundary conditions

The two central planes of the CFD flow domain are specified as symmetry surface. The heat transfer boundary conditions for the CV outer wall and the tubesheet flat wall (Figure 3) are given in accordance with those in the MAAP4-CANDU benchmark case. On the CV outer wall cooled by the RV water, the Yang's correlation [7] is used to determine the nucleate boiling heat transfer coefficient, and the water saturation temperature is specified corresponding to the calculated pressure in the RV. On the tubesheet flat wall in contact with the shield cooling water, the Rohsenow correlation [8] is used to determine the nucleate boiling heat transfer coefficient, and the water saturation temperature is specified corresponding to the calculated pressure in the shield cooling system.

3. Benchmarking of CFD model

The CFD model is benchmarked against MAAP4-CANDU analysis of ACR-1000 by comparing the predicted thermal behaviour of the CV wall when the terminal debris bed is formed. To facilitate the benchmarking exercise, the CFD model is set up with the crust layer thickness given by the MAAP4-CANDU benchmark case. No results of molten corium hydraulics are available from MAAP4-CANDU for comparison.

Figure 5 compares the CFD results of CV inner wall temperature and outer wall heat flux at the axial central plane of the CV ($Z = 0$ shown in Figure 3) to those from MAAP4-CANDU. The MAAP4-CANDU results are given at 15 nodes along the CV wall from the bottom (angle $\alpha = 0^\circ$) to the top (angle $\alpha = 180^\circ$), based on the assumption of 2-D heat transfer in the core. Both analyses show similar trend of CV wall thermal behaviour. Due to the natural convection inside, the CV wall temperature and heat flux in the debris bed region increase upwards from the bottom of the CV. The peak wall temperature of approximately 550 °K and heat flux close to 200 kW/m² occur before reaching the upper crust layer. These peak values are lower than the nominal service temperature of stainless steel (more than 1000 K) and the minimum critical heat flux (CHF) of approximately 300 kW/m² [9], therefore the deterioration in the CV wall strength is not a

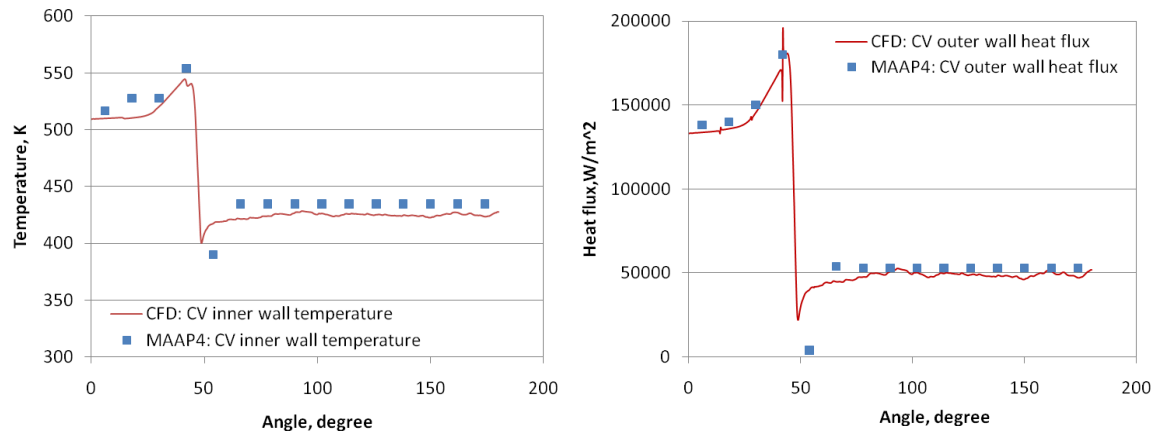


Figure 5 Comparison of Predicted CV Inner Wall Temperature and Outer Wall Heat Flux Between CFD Model at Axial Central Plane and MAAP4-CANDU

concern. The CV wall temperature and heat flux decrease dramatically over the upper crust layer region, and then remain almost constant in the air region except for the portion close to the crust due to less thermal radiation. The CFD model predicts a peak wall heat flux higher than MAAP4-CANDU, which is as expected because the latter uses very limited number of nodes, i.e., 15 nodes along the circumferential direction, resulting in results on an average basis.

4. Conclusions

A general CFD model is developed to predict the thermal hydraulics in the terminal debris bed and the conjugate heat transfer in the full-scale CV of generic CANDU reactors. The CFD model is benchmarked for the ACR-1000 CV and the results show that with the ex-vessel cooling available, the core debris can be well contained inside the CV during the postulated large LOCA scenario with sufficient margin, demonstrating the successful IVR strategy in the ACR-1000 severe accident management. The CFD model results of CV wall temperature can be used to provide input to the stress analysis of the CV. The application of this model to the IVR analysis of a particular CANDU reactor including the EC6 requires limited modifications only.

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