Prediction of Moderator Temperature under 35% RIH Break LOCA with LOECC in CANDU Calandria Vessel

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1. INTRODUCTION

A CANDU reactor has the unique safety features with the intrinsic safety related characteristics that distinguish it from other water-cooled thermal reactors such as a PWR. One of the safety features is that the heavy water moderator is continuously cooled, providing with a heat sink for the decay heat produced in the fuel when there is the LOCA with the coincident failure of the emergency coolant injection (ECI) system. Under such a dual failure condition, the hot pressure tube (PT) would deform into contacting with the calandria tube (CT), providing with an effective heat transfer path from the fuel to the moderator. Following PT/CT contact, there is the spike of the heat flux in the moderator surrounding the CT, which could lead to sustained CT dryout. The prevention of the CT dryout depends on available local moderator subcooling. Higher moderator temperature (or lower subcooling) would decrease the margin of the CTs to dryout. As for LOCAs with coincident loss of the ECI, fuel channel integrity depends on the capability of the moderator as an ultimate heat sink.

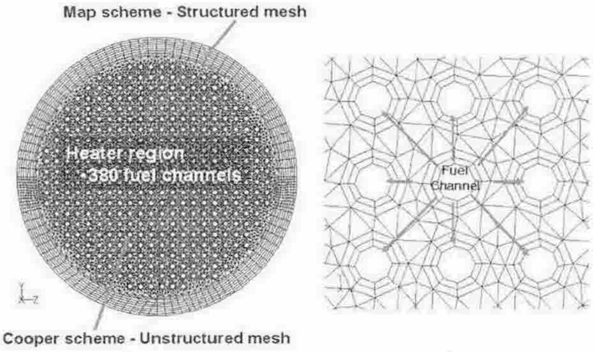
In this regard, the Canadian Nuclear Safety Commission (CNSC) had categorized the temperature prediction for the moderator cooling integrity as a general action item (GAI) and had recommended that a series of experimental works should be performed to verify the evaluation codes comparing with the results of three-dimensional experimental data. However, although a couple of computer codes were used to predict moderator temperature prediction for those problems, they could not be adequately validated due to the uncertainty of temperature prediction.

In this work, the temperature prediction under the transient condition of LOCA with loss of emergency core cooling (LOECC) in a CANDU reactor is conducted using the optimized calculation scheme from the previous work [1].

2. METHODS AND RESULTS

2.1 Numerical Model

A Calandria vessel of the CANDU-6 has the shape of the cylindrical tank, 6 m long and 7.6 m in diameter at its widest point [2]. In the core region, there are 380 calandria tubes (OD=0.131m) and a number of reactivity mechanisms. The 8 inlet nozzles pointing upward are installed at the middle of each sidewall of Calandria symmetrically in the axially center-plane, but are asymmetrically placed axially. The 2 outlet ports are symmetrically located axially but are asymmetrically placed in the axially center-plane.



(a) (b)

Figure 1. Mesh for calculation of CANDU-6.

Figure 1(a) shows the computational mesh on the front plane to analyze the fluid flow and heat transfer characteristics inside the Calandria vessel. In the core region, all the fuel channels are modeled in such a way to analyze as a real geometry, since fuel channels plays the flow resistance to influence the heat transfer and the flow field. The internal flow is simulated using the standard k-ε turbulence model associated with logarithmic wall treatment to model turbulence generation and dissipation rate within the vessel. As to the inner wall surface of Calandria vessel, an adiabatic boundary condition is applied. The buoyancy effects are accounted for density change assumed as the Boussinesq approximation.

The flow field inside Calandria vessel is simulated using the computational fluid dynamics code, FLUENT. The conjugated heat transfer analysis method is used to calculate the convective heat transfer of fuel channel surface so as to match the fluid-wall interface conditions adequately. To solve the governing equations, computational domain is discretized into finite control volumes (about 830,000 cells) using the unstructured meshes mostly for fine calculation except the surfaces of fuel channels. The fuel surfaces within boundary layer are modeled as the structured fine meshes for calculating the turbulence generation and dissipation rate in accuracy. In addition, to consider the channel wall effect, 5 grid layers are applied, as shown in Fig. 1(b). In the calculation, the iteration is progressed until the absolute sum of dimensionless residuals in the numerical solution of governing equations is less than 10^{-3}.

2.2 Transient Analysis

The steady-state condition of normal operation for a CANDU-6 reactor was obtained for the initial condition of the transient analyses in the previous work [1]. Figure 2 shows the typical total heat load profile to moderator in the transient condition of 35% RIH break LOCA with LOECC. It shows that some of the pressure tubes in the critical pass (i.e. downstream of the break pipe) contact with the Calandria tubes between about 20 and 40 sec, and the contact takes place again at the rest of the pressure tubes in the broken loop between 40 and 2000 sec thereafter. Based on 40 sec, the transient condition is separated as the Blow-down Phase (up to 40 sec) and the Post-blowdown Phase (after 40 sec). And the heat loads of the moderator are identified with the heat sources; (i) fission product decay heat, radiation heat, and γ-ray/ neutron direct heat, and (ii) the heat flux due to PT/CT contact.

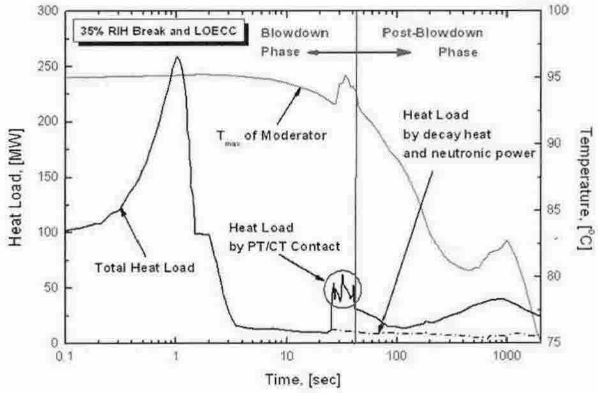


Figure 2. Heat load profiles and resultant temperature during transient.

After reactor trip initiated, the increase of void generation due to the leakage of primary coolant during LOCA without ECC injection induces the power pulse caused by void reactivity. The sharp peak of heat load to the moderator takes place at about 1 sec and the total amount of the heat load to moderator is about 250 MW. However, the effect of the heat load due to the power pulse is not concerned because the heat sink capability of the moderator is large enough compared to the effect of this pulse. As shown in Fig. 2, while a slight increase of the maximum temperature is observed due to large increment of power pulse, the flow pattern is maintained the same as that of the normal operation, i.e., the mixed type flow. During the time span of 1 ~ 20 sec after LOCA, PT/CT contact does not occur and the temperature of moderator is decreasing continuously until PT/CT occurs. The heat load generated in blow-down phase consists of two heat sources; (i) one is the fission product decay heat and neutronic power, which is exponentially decreasing, and (ii) the other is the conductive and convective heat transfer from PT/CT contact in the critical pass. Around 20 sec, the large amount of heat load generated shortly from the fuel channels due to PT/CT contact and the maximum local temperature of moderator is about 95.2°C Therefore, the moderator could be maintained subcooled condition without boiling since the maximum temperature is lower than the saturation temperature. In the post-blowdown phase (after 40sec), the PT/CT contact could be taken place in each of the 190 channels of the broken loop (critical core pass as well as non-critical core pass). During the post-blowdown phase, the total heat load is not large enough to cause the moderator to boil and is continuously decreasing.

3. CONCLUSION

To investigate the thermal-hydraulic characteristics of moderator flow inside Calandria vessel of CANDU-6, the numerical simulation using CFD code has been performed for the transient condition of LOCA with LOECC. As a result of this study, boiling is not predicted during transient. In conclusion, since the moderator within Calandria vessel has enough coolability as the ultimate heat sink, the fuel channel integrity can be maintained and assured.

REFERENCES

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