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CFD Investigation on Sagging Effects in CANDU Reactors

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1. Introduction

The CANDU reactor has 380 horizontal fuel channels, and the pressure tube in each channel consists of a fuel bundle comprising 37 fuel rods. As the nuclear reactor operates, pressure tubes deteriorate over time due to high temperature, high pressure, and high neutron irradiation. The most well-known aging effect is creep and sagging for pressure tube. When the creep and sagging for pressure tube occur, bypass flow is formed near the top of the pressure tube. Consequently, the flow rate within pressure tube decreases locally, and the fuel rod inside the pressure tube may experience the critical heat flux. Many studies have been conducted on pressure tube creep. However, most studies on pressure tube sagging were on structural characteristics related to pressure tube deformation, and there were scarcely any studies on thermal hydraulic phenomena.

This paper presents a study on the thermal-hydraulic characteristics of pressure tube sagging in CANDU reactors. Through this study, we analyzed key thermal-hydraulic parameters such as temperature, pressure, velocity, and void fraction, and examined their influence on the critical heat flux of fuel rods.

2. Analysis Model

2.1 Wall Boiling Model

Kurul and Podowski (1991) introduced the RPI wall boiling model. The wall heat flux for the RPI model is divided into three components: single-phase liquid heat flux, quenching heat flux, and evaporation heat flux. The bubble departure diameter is calculated using the correlation proposed by Tolubinsky and Konstanchuk. The wall nucleation site density is calculated using the correlation developed by Lemmert and Chawla.

2.2 Interfacial Momentum Transfer

Interfacial momentum transfer is modeled by the following forces. Drag force is modeled using the Grace correlation, which was developed for bubbly flows. Non-drag forces such as lift force, virtual mass force, and wall lubrication force are not included in this simulation. Turbulent dispersion force is modeled using the Favre-averaged drag model, which is based on the mass-weighted average of the interphase drag force.

2.3 Interfacial Heat Transfer

Interface heat transfer to liquid is modeled using the Ranz-Marshall correlation. Heat transfer to vapor at the interface is not modeled; vapor is assumed to be at saturation temperature. Interfacial mass transfer is directly associated with interfacial heat transfer.

2.4 Turbulent Model

The SST model is utilized to model the liquid turbulence. The Sato enhanced eddy viscosity model is employed to capture the effect of bubbles on liquid turbulence. For modeling turbulence in the vapor phase, the dispersed phase zero equation is utilized.

2.5Boundary Conditions

For this analysis, the Q7 channel power distribution shown in Fig 1, which is expected to have the largest sagging for the pressure tube, was selected. The boundary conditions for this analysis are as shown in Table I.

Table I: Boundary Conditions

Boundary Conditions	
Mass Flow Rate [kg/s]	12.01
Total Power [MW]	6.127 (Cosine Shape)
Inlet Temperature [K]	535.6
Outlet Pressure [MPa]	10

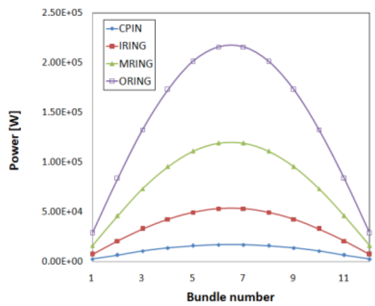

Fig. 1. Power Distribution at Each Different Fuel Ring

2.6 Grid Generation

The mesh sensitivity was analyzed using three cases, considering the accuracy and economic feasibility of the analysis. Table II shows the pressure drop and outlet temperature depending on the mesh size. As a result of the calculation, there was no significant change in the outlet temperature and pressure drop in the range of y+ 180~240. We chose case 2 for the simulation considering the analysis time and accuracy.

Table II: Mesh Case

CASE	Number of Nodes	Number of Elements	Pressure Drop	Outlet Temperature
CASE1	1564565	1368000	0.320248	580.773
CASE2	1954013	1710000	0.331294	580.803
CASE3	2213645	1938000	0.334385	580.854

3. Numerical Results

3.1 Average Bundle Temperature and Void Fraction

Fig 2 shows liquid temperature with different bundle power. The liquid temperature increases along the flow direction and the average maximum liquid temperature is predicted at the end of the channel. Fig 3 displays the average void fraction within the bundles. It can be observed that the onset of boiling occurs in the 6th bundle, and vapor gradually increases along the flow direction. The average void fraction for the pressure tube without sagging is relatively larger than for the pressure tube with sagging. This indicates that channel without sagging has better heat transfer performance compared to that with sagging. Fig 4 shows the average void fraction within the bundles with different thermodynamic quality. As the average void fraction increases, the thermodynamic quality also increases gradually. It can be seen that the coolant almost approaches a saturated condition near the end of the channel.

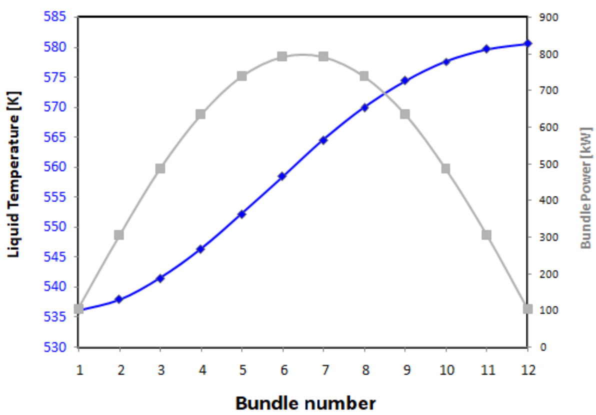

Fig. 2. Liquid Temperature in a Flow Direction with Different Bundle Power

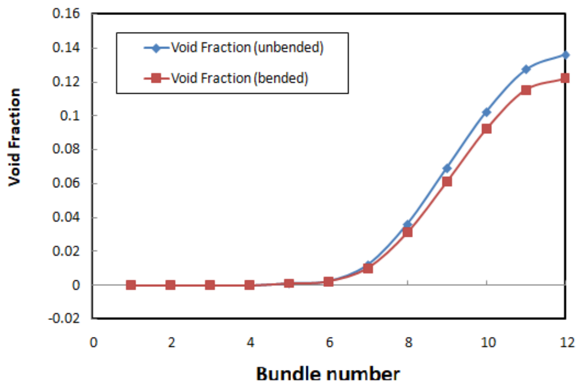

Fig. 3. Average Void Fraction within the Bundles

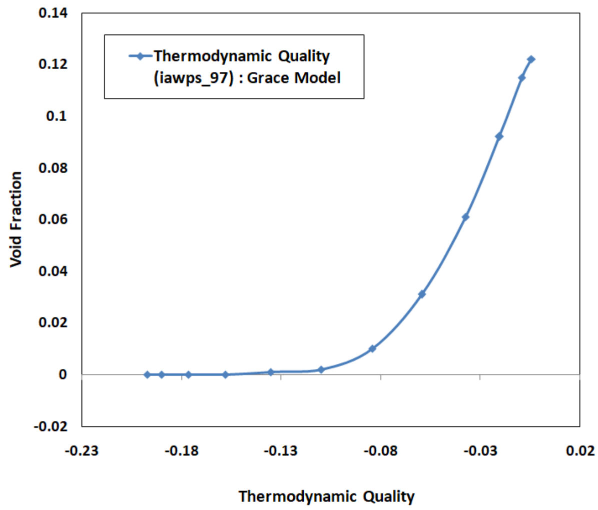

Fig. 4. Average Void Fraction within the Bundles with Different Thermodynamic Quality

3.2 Local Temperature of Fuel Bundle

Fig 5 shows a single channel in the flow direction. The data is extracted in cross section B-B of both the pressure tube with and without sagging, as the maximum peak vapor fraction is predicted in that section. Fig 6 and Fig 7 show the vapor fraction on the cross-section B-B for the pressure tubes. In both pressure tubes, the amount of vapor in central fluid region is larger than that of peripheral fluid region. The maximum void fraction is predicted near the bottom of the fluid region. And the maximum void fraction of the bottom fluid region inside the pressure tube with sagging is relatively smaller than that of the pressure tube without sagging.

Fig. 5. Single Channel in a Flow Direction for the Analysis

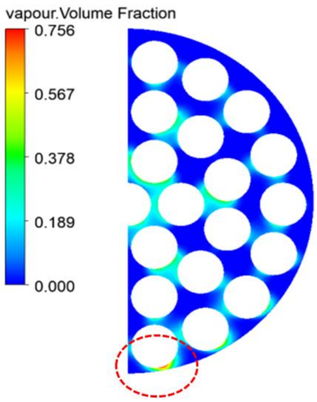

Fig. 6. Vapor Fraction for the Pressure Tube without Sagging in Cross Section B-B

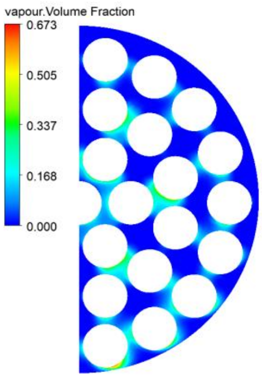

Fig. 7. Vapor Fraction for the Pressure Tube with Sagging in Cross Section B-B

3.3 Local Velocity of Fuel Bundle

Fig 8 shows the streamline profile of the pressure tube without sagging in cross section B-B. It is observed that recirculation is predicted near the narrow flow path of the lowest fluid region. It is believed that this flow stagnation by recirculation may interfere with coolant mixing, potentially affecting fuel rod integrity.

On the other hand, the streamline profile of the pressure tube with sagging in cross section B-B shown in Fig 9 indicates that no significant anomalies are observed in the fluid region at the bottom. This implies that the pressure tube without sagging has a relatively less favorable impact in terms of critical heat flux compared to that with sagging. Therefore, it is believed that the pressure tube with sagging will cause any issues, even after 20 years of aging.

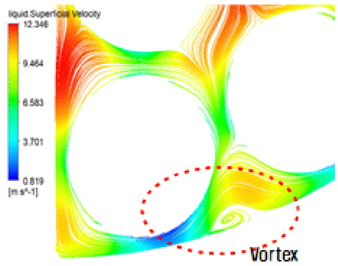

Fig. 8. Streamline Profile of Pressure Tube without Sagging in Cross Section B-B

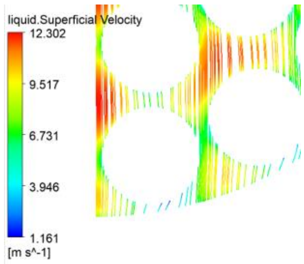

Fig. 9. Streamline Profile of Pressure Tube with Sagging in Cross Section B-B

4. Conclusions

The thermal-hydraulic phenomena were analyzed for pressure tubes with and without sagging using the wall boiling model.

In the case of the pressure tube with sagging, the average amount of bubbles decreased because the heat transfer was relatively reduced compared to the pressure tube without sagging. However, unusual phenomena such as flow stagnation near the lower fluid region were not observed. Therefore, the pressure tube with sagging is considered to be more favorable from the critical heat flux perspective.

This analysis only considers 20 years of pressure tube aging and requires additional study for the extended burnups in the future.

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