Development of a CATHENA Fuel Channel Analysis Model for a Fuel Channel with Axial Variation of Radial Pressure Tube Creep in a Stratified Two-Phase Flow Condition

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1. Introduction

A two-phase heat transfer phenomena in the fuel bundle strings located in a horizontal pressure tube with an axial variation of the radial creep, especially under a low stratified two-phase flow condition such as encountered in the CANDU reactor under the later stage of the blowdown phase of a LBLOCA, involves a complex heat transfer nature. This includes the conduction in the fuel rods, pressure tube, convection in the vapor and liquid regions, and radiation between the fuel rods exposed in the steam and the pressure tube, pressure tube and calandria tube. As these three modes of heat transfer has to be treated in a combined way, modeling the heat transfer phenomena inside the fuel bundle under the stratified flow during the later stage of LBLOCA blowdown has been one of the most challenging tasks in the CANDU safety analyses. The main reason for this hot attention is that it closely related to the integrity of the pressure tube. In this study a heat transfer model for handling this situation is developed, implemented and under preliminary testing of the analysis results. The analysis result up to now is encouraging and the validation of the model developed is ongoing. The major motivation of this study is to evaluate the conservatism of the current CANDU safety analysis methodology for a fuel channel with an axial variation of the radial creep of the pressure tube as easily experienced in the aged CANDU plant as it assumes the centerline of the fuel bundle string is the same as that of the pressure tube.

2. Major Improvement of the New Model

The major backbone of the fuel channel heat transfer model of CATHENA[1] for a stratified flow is (a) find the height of the water level using the void fraction, (b) find the convective heat transfer coefficient on the surfaces of the heat structures depending on the fraction exposed to the steam, (c) calculate the view factors among the segmented parts of the heat structures and use them to find the radiation heat transfer coefficient. Combining all these three modes of heat transfer for the same heat transfer surfaces without apriori knowledge of the flow regime and heat transfer topology requires a careful and detailed segmentation of the heat structures. To carry out these tasks, a computer program of computing the relative location of the fuel rods with respect to the pressure tube centerline and the water level. Then the way how to compute the fraction of the submerged part of each segment of the heat structures is developed, and validated against a benchmark results whose accuracy is proved already. Based on these results, the CATHENA crept fuel channel model input is prepared, i.e., the interlinked network of the segments of the heat structures are set up, and the necessary inputs for the combined heat transfer calculation are prepared. Once these preliminary works be completed, the heat transfer model calculates the heat fluxes for different mode on the same surface in such a way that energy is conserved. The thermalhydraulic boundary conditions imposed are the channel inlet and exit pressures, the inlet flow enthalpies of each phase, void fraction, the cooling condition of the calandria tube outside. As for the modeling of the fuel bundle strings, the 37 fuel rods are treated individually. Axially the whole fuel channel of about 6 m are divided into 12 segments both hydraulically and heat structure-wise. The schematic configuration of the fuel bundle of 28 element and the pressure tube, and calandria tube is depicted in the Figure 1 as an illustration.

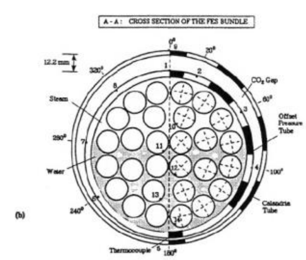

Fig.1. CATHENA Solid Structure Model and Radiation Model for Standard 28-Pin Fuel

3. Surface-to-Surface Radiation Model

The computation method is a lumped-system approximation for gray diffuse surfaces contained in an enclosure. The assumptions of this method are that:

- The fluid in the enclosure neither emits nor absorbs radiant thermal energy.

- Reflectance from a surface is neither a function of incident nor reflected direction nor of radiation frequency.
- Temperature, reflectance, and radiosity are constant over each surface.

The view factors from each surface to all other surfaces must sum to 1. Also, to conserve energy, the area times view factor for each surface i to any other surface j must equal the area of j times the view factor from j to i. The view factor was calculated using MATRIX code [2] which was validated and widely used for CATHENA application.

4. CATHENA Simulation Results and Discussion

A simple test problem is formulated and tested. Initially the W-10 channel of 4.0 MWth was simulated at a full power steady state condition. And then in order to make the final steady state condition as the stratified two phase flow condition, the inlet pressure was decreased very close to the exit header pressure of 10.033 MPa, 10.219MPa, and the channel power was also decreased to 60% of the initial full power from t= 1500sec, and kept the same until the final steady condition is reached.

The profile of the radial creep of the pressure tube was assumed to be center peaked cosine shape, and the typical axial and radial power shape of W10 channel of CANDU-6 was applied. As a result, a steady state two phase flow condition was formed with the quality gradually rise along the axial direction and a stratified flow formed at the last 3 fuel bundle locations. The radiation heat transfer model was utilized to simulate the two-phase heat transfer among the fuel rods and pressure tube at this stratified flow condition. The view factors among these thermal structures were calculated separately using the MATRIX code developed for CATHENA code. A typical modeling feature of the fuel channel for the study is shown in Figure 2, and the final steady state result at the 12^{th} axial bundle location from the inlet out of 12 bundles in a channel is depicted in Fig. 3.

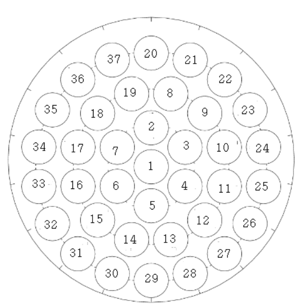

Fig.2. Numering of the Fuel Rods in the Crept Fuel Channel Model for Aged Plant Simulation.

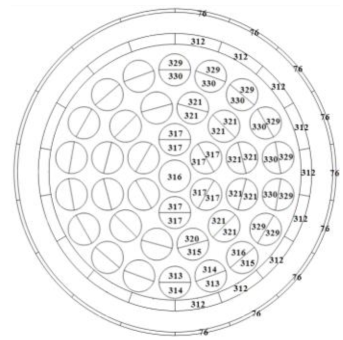

Fig.3. Predicted Fuel and PT/CT Temperatures at the 12^{th} Bundle Location for W10 Channel under the Stratified Two-Phase Flow Condition

The incorporation of the full ledged 37 element CANDU standard fuel with 2 segments for the complex heat transfer under the blowdown phase two-phase flow including the stratified flow condition seems satisfactory as the simulation results at different void fraction meets the commonsense physics. However further detailed validation of the results against the applicable experimental results for the aged fuel channels will be carried out. Also the necessity of further detailed modeling of the circumferential variation of the fuel rods as well as the pressure tube temperatures need to be checked for the best practical use of this model for the safety analyses in a massive quantity.

REFERENCES

[1] CATHENA MOD-3.5d Theory Manual, 153-112020-STM-001, Rev.0, December 2005, AECL.

[2] MATRIX 1.05, A Stand-Alone Preprocessor Utility for CATHENA Users, J.B. Hedley, AECL, Oct. 1999.