Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2015

CATHENA Code Assessment for Pressure Tube and Calandria Tube Contact Phenomena

Hyoung Kyoun Ahn*, Chul Jin Choi, Jong Ho Choi
Safety Analysis Group, KEPCO-E&C, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, Rep. of KOREA
**Corresponding author:hkahn@kepco-enc.com*

1. Introduction

Ont of safety analysis code, Canadian Algorithm for THErmalhydraulic Network Analysis (CATHENA), has been validated against full-scale Contact Boiling Experiments conducted using specific channel power, pressure, and moderator subcooling as pre-test conditions [1]. The pressure tube (PT) and calandria tube (CT) temperatures, the extent of dryout and failures of the pressure tube or the calandria tube (if any) are the outcome of these experiments. Recently, an IAEA International Collaborative Standard Problem (ICSP) to provide contact boiling experimental data to participants for assessing the subcooling requirements for a heated pressure tube, plastically deforming into contact with the calandria tube during a postulated large break LOCA condition has been performed [2]. The test was conducted at the AECL facility shown in Figure 1. The CATHENA code assessment results against the experimental data distributed for the ICSP [3] are provided in this paper.

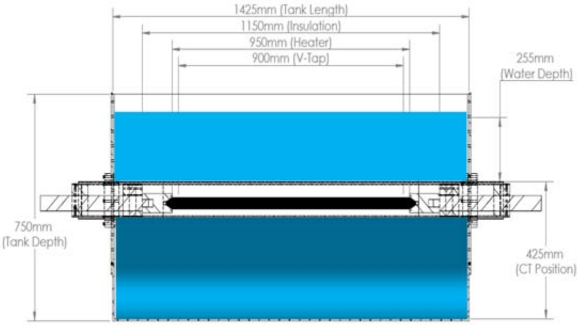

Figure 1. Experimental Apparatus for IAEA ICSP Test

2. Methods

CATHENA is an one-dimensional and non-homogeneous two-fluid thermal-hydraulic code. Heat transfer between fluid and solid or solid and solid could be modeled. The one of major heat transfer behavior includes radiation between heater and pressure tube. Conduction heat transfer between pressure tube and calandria is also addressed after pressure tube is deformed and formed ballooning. Convection heat transfer between calandria tube and water in moderator tank is rapidly driven after PT/CT contact.

2.1 Model

The experimental facility shown in Figure 1 is modeled by CATHNA with thermal-hydraulic component and heat structure for the fuel, argon gas, pressure tube, carbon dioxide gas, calandria tube and water tank. Carbon dioxide gas between pressure tube and calandria tube is modelled using a prescribed boundary condition for radiation or solid-solid contact models. Circumferential heat structure is composed symmetrically of 18 heater surfaces, 18 pressure tube surfaces and 18 calandria tube surfaces. It is noted that the volume of moderator water is arbitrarily increased to obtain reasonable calculation results.

2.2 Heat Transfer

Heater raises the surface temperature of pressure tube and temperature of argon gas in pressure tube. Pressure tube has been deformed by argon gas expansion. After pressure tube ballooned, pressure tube contacts with calandria tube. After contacting, heat transfer is rapidly increased to water. The temperature of water near the outer surface of calandria tube has distributed circumferentially. The temperature distribution induces the natural circulation near calrandria tube.

The ballooning deformation of the pressure tube caused by high pressure tube temperatures and internal pressure is calculated using the fuel deformation model in the CATHENA code. The contact conductance following PT/CT contact is modeled as follows: a step increase to a high initial contact conductance of 20.0 kW/m^2℃ for 1 seconds, and then a linear decrease in 1 seconds to a constant post-contact conductance of 1.0 kW/m^2℃. View factor matrices are used to calculate the radiative heat transfer between heat structures. The radiation emissivity of the heater, the pressure tube and the calandria tube is 0.9, 0.8 and 0.325 respectively. A set of pool boiling correlations on outside surface of the calandria tube in the water tank, which is composed of the modified Chen nucleate boiling, the Bjornard and Griffith transition boiling, and the Bromley film boiling, is used.

2.3 Assumptions

Followings are assumed in the CATHENA model.

- Axial power distribution is uniform.
- An offset from center of heater is neglected. Therefore, the radiative heat transfer from heater to inside surface of pressure tube is concentric and axisymmetric, and convective flow of argon gas within pressure tube is neglected.
- Multi-dimensional natural convective flow in the water tank is neglected.

3. Results

Sequence of event is shown in Table 1. In the CATHENA code, the ballooning deformation of the pressure tube is calculated using the Shewfelt equations. The model calculates the straining of each pressure tube model sector individually. Straining of the pressure tube is calculated until pressure tube/calandria tube contact. Subsequently, the model calculates the solid-to-solid heat transfer rates using a user specified contact conductance. It is predicted that the pressure tube is deformed at 63 seconds withe temperature of 540℃. Thereafter, it eventually contacts with the calandria tube at 73.8 seconds and the temperature of 798℃.

Table 1. Sequence of Event

Event	Time (seconds)	
	Experiment	Analysis
Turn Heater Power on	0	
Reach to Heater Power of 148 kW	20	
Start of Pressure Tube Deformation	N/A	63.0
Contact between PT and CT	71.3~74.7	73.8
Turn Heater Power off	141	

Temperatures in the pressure tube are shown in Figure 2. The calculated results are shown by solid line, while the experimental data show different temperatures at various locations. This behavior is owing to the concentric heater location and one dimensional heat flux in the water tank. The predicted circumferential variation is negligible. Heat-up of the pressure tube starts at later time than the experiment, but the rate of heat up is similar to the experiment. The peak temperature, which depends upon the contact timing between the pressure tube and the calandria tube, is slightly below the experimental data. Temperature is rapidly reduced due to the increased heat transfer just after the contact. However, temperature begins to gradually increase again because the heat transfer from the calandria outer surface to the water tank is insufficient to transfer the heat from the heater. After turning the heater power off, temperature decreases to the room temperature. It is noted that subcooling margin within the water tank is sufficient to keep the integrity of the pressure tube.

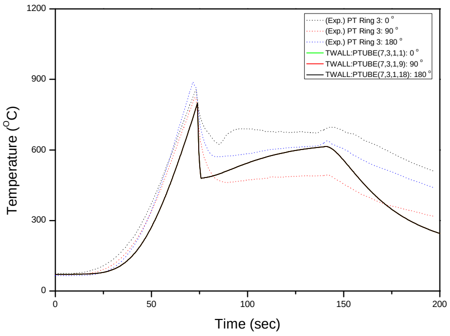

Figure 2. Temperature at pressure tube outer surface

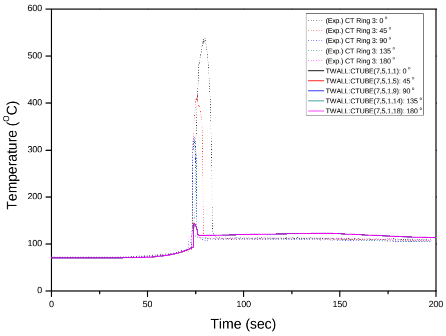

Figure 3. Temperature at calandria tube outer surface

Temperature transient in the water tank is plotted in Figure 4. The calculated temperature is maintained at a constant temperature of 70.5℃ since a large volume of 1,000 times of the water tank is used in calculations. The experimental data shows the upper part is hotter than the lower part, which is believed as a result of the natural convective flow in the tank.

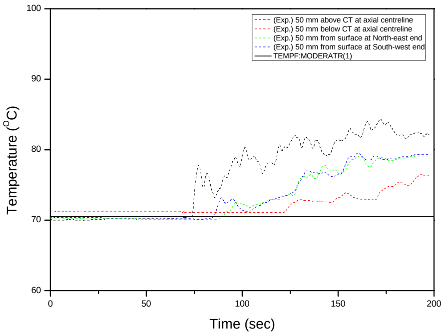

Figure 4. Temperature of water tank

A comparison of heat transfer between the heater, the calandria tube, and the water tank is shown in Figure 5. Before the contact, heat transfer from the heater to the pressure tube is higher than heat loss to the water tank because of adiabatic effect of the carbon dioxide gap. This unbalance of heat transfer results in the heat up and plastic deformation of the pressure tube. The ballooned pressure tube reduces the gap and eventually contact with the calandria tube. Heat transfer excursion occurs during several seconds just after contacting, thereafter the heat transfer to the water tank matches with the heat transfer from the heater. The heat transfer unbalance through the calandria tube occurs again after turning the heater power off.

The total heat transfer coefficient at the calandria tube outer surface is shown in Figure 6. The convective heat transfer coefficient at the calandria tube outer surface after contacting is relatively high. Temperature difference between the calandria tube outer surface and the water tank of about 40℃ and the temperature difference between the pressure tube and the calandria tube of about 400℃ is equivalent with the difference of heat transfer coefficient because the heat transfer is balanced each other. Therefore, the heat transfer coefficient of the calandria outer surface is evaluated as higher about 10 times higher than that of the pressure tube.

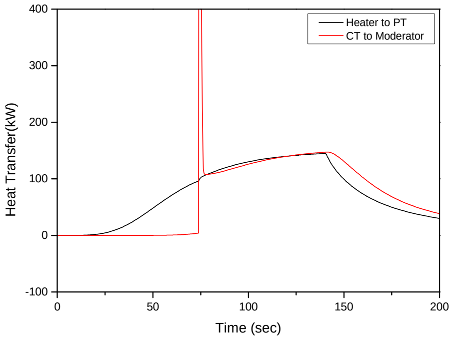

Figure 5. Heat transfer between components

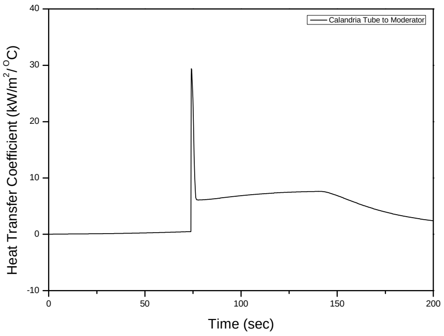

Figure 6. HTC from CT outer surface to water tank

The true strain calculated by the wall thickness change of the pressure tube is shown in Figure 7. The calculated strain of about 15% is in agreement with the theoretical value of 16% based on geometrical data. It is noted again that the calculated results are shown in a single line.

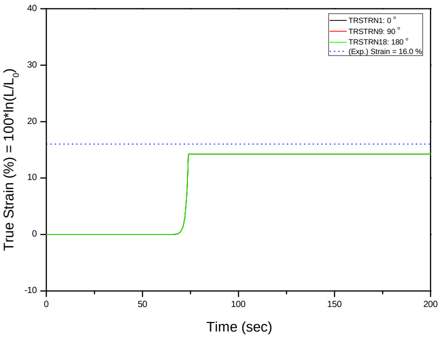

Fig. 7. True strain of pressure tube

4. Conclusions

The CATHENA code is used to simulate the experiment on pressure tube ballooning conducted at the AECL. The overall code's predictions show good agreements with the experimental data. The contact timing by the pressure tube ballooning is predicted accurately, however, it is found that the code largely underpredict the peak temperature at the pressure tube and the calandria tube. This discrepancy seems to be induced from multi-dimensional flow effects in the water tank. For more accurate calculations, detailed modeling of the water tank is required

REFERENCES

[1] H.Z. Fan, R. Aboud, P. Neal and T. Nitheanandan, Enhancement of the Moderator Subcooling Margin Using Glass-peened Calandria Tubes in CANDU Reactors, 30th Annual Conference of the CNS, May, 2009.

[2] T. Nitheanandan, Proposal for the IAEA International Collaborative Standard Problem on HWR Moderator Subcooling Requirements to Demonstrate Backup Heat Sink Capabilities of Moderator during Accidents, February 2012.

[3] P. Neal, Test Results for the IAEA International Collaborative Standard Problem on Heavy Water Reactor Moderator Subcooling Requirements, AECL Memo 153-126220-012-000, July, 2014.