Transactions of the Korean Nuclear Society Virtual Autumn Meeting
October 21-22, 2021

Analysis of Fuel Channel Failure Mechanism of CANDU-6 Using CAISER Code

Keun Sang Choi*, Jun-young Kang, Dong Gun Son, Yong Mann Song and Jun Ho Bae
Intelligent Accident Mitigation Research Division, Korea Atomic Energy Research Institute,
Daejeon, 34057, Rep. of Korea
**Corresponding author: ksc307@kaeri.re.kr*

1. Introduction

CANDU (CANadian Deuterium Uranium) type reactor has 380 horizontal fuel channels inside its calandria tank, and each fuel channel consists of 12 fuel bundles in a row with 37 fuel rods in a pressure tube and a calandria tube.

CAISER (**C**ANDU **A**dvanced **I**ntegrated **SE**ve**R**e accident code) is a computational code for CANDU severe accident analysis. CAISER can simulate fuel channel failure phenomenon solving energy balance equation including heat transfer (conduction, convection, radiation) inside fuel channel, oxidation heat of steam-Zircaloy reaction, and energy transport caused by mass relocation of fuel channel material[1]. Present study focused on fuel channel failure mechanism of conceptual problem with high pressure and low pressure severe accidents.

2. Methods and Results

2.1. Methodology

CAISER consists of two modules; a fuel channel module and a calandria tank module. Fig. 1 shows CAISER node structure. Along with these cross-sectional nodalization schemes, CAISER splits the reactor longitudinally with notation of [k]. The number of nodes for each module is defined by users and details for CAISER node structure can be found in Ref. [1, 2].

There are three fuel channel failure modes in CAISER; (1) local temperature failure, (2) creep rupture failure, and (3) beam structure failure. As shown in Table 1, numerical simulations are conducted for high pressure(CP-HP) and low pressure(CP-LP) conditions for this study.

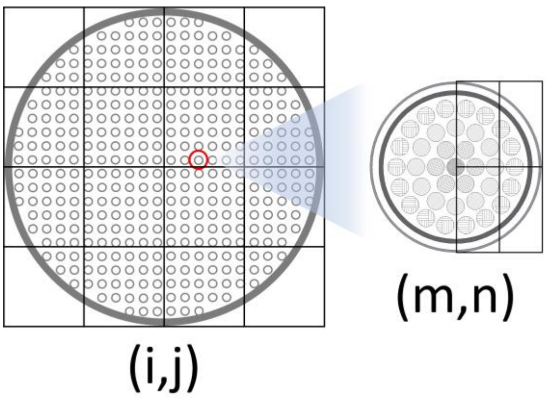

Fig. 1 Node structure of CAISER

Table 1 Calculation condition for present study

Case name	CP-HP	CP-LP
RIH pressure [MPa]	10	0.2
Number of calandria tank nodes [i][j]	[4][4]	
Number of fuel channel nodes [m][n]	[2][2]	
Number of longitudinal nodes [k]	[6]	
Pressure tube(pt) local temperature failure condition	$T_{pt} \geq 1800$ K	
Calandria tube(ct) local temperature failure condition	$T_{ct} \geq 1500$ K	
Sagging failure condition	$\left(\frac{H_{sag}}{H_{FC}}\right) \geq 0.5$	
Creep failure condition	DCC ≥ 0.99	

2.2. Fuel channel failure mechanism

In the severe accident condition, a fuel channel of CANDU can deform and fail according to temperature and pressure conditions. These temperature and pressure conditions are varied with a severe accident condition such as SBO, LOCA.

A pressure tube can deform and fail due to circumferential temperature gradient which is caused by a local conduction between a molten core material and a pressure tube[3]. Although a pressure tube can be ballooned in a high temperature and pressure condition, it is not considered in this study.

A calandria tube is thinner than a pressure tube. It means it is not as durable as pressure tube against high temperature and pressure. In normal condition, the temperature of a calandria tube is not high because the gap between pressure tube and calandria tube is insulated with 70 kPa gaseous CO_2 and moderator in a calandria tank acts as an ultimate heat sink. But if a pressure tube is fails, a conduction heat transfer by molten clad and a calandria tube will be occurred. Then the integrity of a calandria tube is largely dependent on a heat transfer to moderator. If moderator is present as an ultimate heat sink, the heat generated inside fuel channel can be removed and the calandria tube can be intact. But if moderator level decreases, overall heat transfer of uncovered fuel channel decreases and the calandria tube becomes vulnerable.

As mentioned earlier, CAISER are considering three kinds of fuel channel failure modes. The failure criteria of each mode have been decided through the existing research results and sensitivity analysis. Three fuel channel failure modes are described in the below.

2.2.1. Local temperature failure mode

CAISER nodalizes a pressure tube and a calandria tube as a circumferential nodes. The circumferential temperature gradient is caused by stratification of the coolant in the channel and conduction heat transfer by molten and relocated corium[3] with a pressure tube. The condition for local temperature failure used in this study is shown in Table 1.

2.2.2. Creep rupture failure mode

Y. Zhou et al.[4] have developed the Larson-Miller parameter for materials of the pressure tube and the calandria tube. The correlation is been implemented in CAISER for calculation of creep rupture failure.

2.2.3. Beam structure failure mode

If moderator cannot act as a heat sink, fuel rods, pressure tube and calandria tube will heat up, which leads to an entire fuel channel sagging by the loss of its strength [5]. The sagging of fuel channel is modelled [6] based on P. M. Mathew et al. [7]. In this study, the fuel channel is assumed to fail if a sagging deformation exceeds the half of fuel channel height (= diameter).

2.3. Simulation result

As described in Table 1, numerical simulations have been conducted with different pressure conditions. The fuel channel failure time and the failed node numbers are shown in Table 2 and 3 under a high and low pressure accident condition, respectively. The first failure time among three kinds of failure modes is highlighted in bold Italic and yellow-colored background.

Under a high pressure accident condition, the first fuel channel failure has been occurred by creep rupture mechanism because the creep rate is significant under a high pressure. While, under a low pressure accident condition, the first fuel channel failure has been occurred by a local temperature criterion because of the conduction heat transfer between a relocated molten corium and a pressure tube or a calandria tube.

A pressure tube failure is occurred first in j = 1 and 2 (central nodes) while a calandria tube failure is occurred first in j = 3 (top node), namely, top node as shown in Table 2 and 3. Since a horizontal and vertical power distribution of CANDU is considered in this study, central nodes are high power nodes and top node has less power than central nodes. As a result, the first pressure tube failure is occurred dependently on thermal power of channel while the first calandria tube failure is occurred dependently on a moderator level as shown in Fig. 2 and 3.

When referring to Ref. [3], the sagging of fuel channel tends to occur in low pressure condition and this is in accordance with the result that no first fuel channel failure by sagging appeared, as shown in Table 2 and 3.

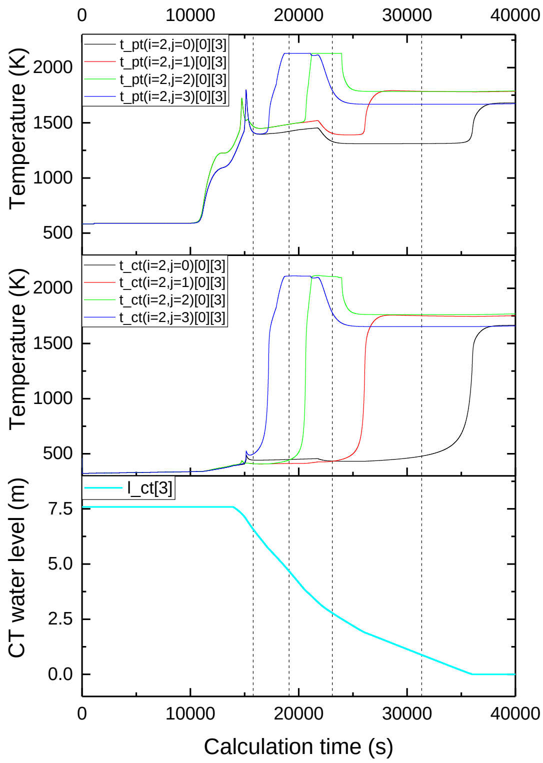

Fig. 2 Simulation result of CP-HP

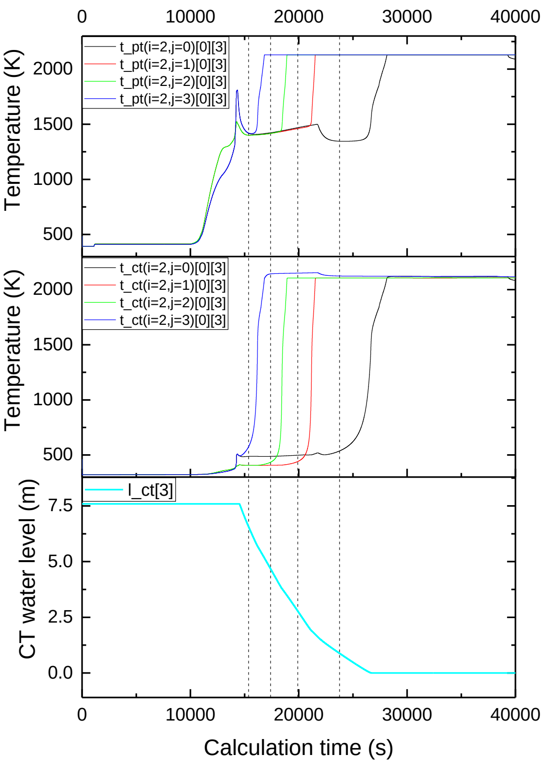

Fig. 3 Simulation result of CP-LP

Table 2 Summary of calculation result of CP-HP

Case		CP-HP	
Mode \ Tube		Pressure tube	Calandria tube
Local temp	Failure time	13050.5 s	17254.5 s
	Node number ([i][j][k])	[1][1][5] [1][2][5] [2][1][5] [2][2][5]	[1][3][3] [2][3][3]
	Node temperature	1798.97 K	1501.29 K
UTS (Sagging)	Failure time	-	17343.5 s
	Node number ([i][j][k])	-	[1][3][2] [2][3][2] [1][3][3] [2][3][3]
	Node temperature	-	1617.36 K
Creep	Failure time	***12399.5 s***	***17217.5 s***
	Node number ([i][j][k])	[1][1][4] [1][2][4] [2][1][4] [2][2][4]	[1][3][3] [2][3][3]
	Node temperature	1306.68 K	1335.27 K

Table 3 Summary of calculation result of CP-LP

Case		CP-LP	
Mode \ Tube		Pressure tube	Calandria tube
Local temp	Failure time	***12858.5 s***	***16189.5 s***
	Node number ([i][j][k])	[1][1][4] [1][2][4] [2][1][4] [2][2][4]	[1][3][2] [2][3][2]
	Node temperature	1799.08 K	1505.63 K
UTS (Sagging)	Failure time	-	16333.5 s
	Node number ([i][j][k])	-	[1][3][2] [2][3][2] [1][3][3] [2][3][3]
	Node temperature	-	1739.45 K
Creep	Failure time	16622.5 s	16486.5 s
	Node number ([i][j][k])	[1][3][2] [2][3][2]	[1][3][2] [2][3][2]
	Node temperature	1947.34 K	1838.72 K

3. Conclusions

Two conceptual problems of severe accident for CANDU-6 with different pressure conditions are analyzed by CAISER. Thermal behavior of fuel channel has been analyzed with a consideration of a failure mechanism of fuel channel.

In a high pressure condition, creep rupture tends to firstly occur because the creep rate is significant under a high pressure condition. While, in a low pressure condition, local temperature failure tends to firstly occur because of the direct contact heat transfer between a relocated molten corium and a pressure tube or a calandria tube. In the meantime, a fuel channel failure by entire fuel channel sagging is dominant in low pressure condition.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (Ministry of Science, ICT, and Future Planning) (No. NRF-2017M2A8A4017283).

REFERENCES

[1] J. H. Bae et al., Theory manual of CANDU Advanced Integrated SEveRe accident code (KAERI/TR-7734/2019), 2019.
[2] J. H. Bae et al., Modeling and Simulation of CAISER for CANDU Accident Progression, 39th Annual Conference of the Canadian Nuclear Society, Ottawa, Canada, 2019.
[3] IAEA, Analysis of Severe Accidents in Pressurized Heavy Water Reactors(IAEA-TECDOC-1594), 2008
[4] Y. Zhou et al., Short-term rupture studies of Zircaloy-4 and Nb-modified Zircaloy-4 tubing using closed-end internal pressurization, Nuclear Engineering and Design, 2004.
[5] F. Zhou et al., Development and Benchmarking of Mechanistic Channel Deformation Models in RELAP/SCDAPSIM/MOD3.6 for CANDU Severe Accident Analysis, Nuclear Science and Engineering, 2018.
[6] D. Son et al., SAGGING MODEL OF CALANDRIA TUBES IN SEVERE ACCIDENT FOR THE CAISER CODE, 39th Annual Conference of the Canadian Nuclear Society, Ottawa, Canada, 2019.
[7] P. M. Mathew et al., Severe Core Damage Experiments and Analysis for CANDU Applications, SMiRT 17, 2003.