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Analysis of pressure tube ballooning effect on a fuel channel failure of CANDU reactor using CAISER code

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1. Introduction

CANDU (CANada deuterium Uranium) reactor has novel geometry of the reactor core consisting of independent fuel channels (380) with pressure tube (PT) and calandria tube (CT) and failure of the fuel channels is key issue to evaluate the reactor safety under design basis accident or severe accident [1]. Ballooning of PT is related to the fuel channel failure at the early-phase of the severe accident for the CANDU reactor because when PT contacts to CT, significant conduction heat is transferred from PT to CT leading to the local dry-out under subcooled moderator [2]. Gap between the PT and CT is filled with CO_2 gas as an insulator during normal operation with 0.017 m gap distance [3].

PT ballooning and PT-CT contact phenomena were evaluated with International Collaborative Standard Problems (ICSP) test to both conduct the code comparison and benchmark the new contact-boiling experiment [4]. PT-CT contact by the PT ballooning results in an instantaneous dry-out phenomena at the CT under subcooled water.

The needs to simulate the PT ballooning and PT-CT contact phenomena have been raised for existing CANDU severe accident codes. MAAP-ISAAC code showed that PT ballooning results in faster fuel channel failure time [5]. RELAP/SCDAPSIM code reported the validation of the new contact-boiling experiment and detailed model for the ballooning and sagging [6]. With these backgrounds, present study is focused on the PT ballooning and its influence on the fuel channel failure time by simulating two representative problems (high-pressure and low-pressure accident) with CAISER code.

2. Methods and Results

2.1 Ballooning model in literatures

Ballooning of thin-wall tube means an increase of traverse or longitudinal strain by an increase of pressure and temperature inside the tube. High pressure and high temperature results in thermal expansion of the material and the decrease of wall thickness leads to the creep rupture failure. Traverse creep model of the pressure tube (Zr-2.5wt%Nb alloy) material and calandria tube (Zry) was suggested by R.S.W. Shewfelt [7,8]. Failure criteria based on the creep strain is generally reported as 20-38% for the pressure tube and 2% for the calandria tube, respectively [9].

(a) *Creep model for the pressure tube (PT)* [7]

(450 [°C] < T ≤ 500 [°C])

$$\dot{\varepsilon} = 1.3 * 10^{-5} \sigma^{9} \exp\left(-\frac{36600}{T}\right)$$

(500 [°C] < T ≤ 700 [°C])

$$\dot{\varepsilon} = 1.3 * 10^{-5} \sigma^{9} \exp\left(-\frac{36600}{T}\right) + 5.7 * 10^{7} \sigma^{1.8} \exp\left(-\frac{29200}{T}\right)$$

(700 [°C] < T ≤ 850 [°C])

$$\dot{\varepsilon} = 1.3 * 10^{-5} \sigma^{9} \exp\left(-\frac{36600}{T}\right) + \frac{5.7 * 10^{7} \sigma^{1.8} \exp\left(-\frac{29200}{T}\right)}{\left[1 + 2 * 10^{10} \int_{T1}^{T} \exp\left(-\frac{29200}{T}\right) dt\right]^{0.42}}$$

(850 [°C] < T ≤ 950 [°C])

$$\dot{\varepsilon} = 10.4 * \sigma^{3.4} \exp\left(-\frac{19600}{T}\right) + \frac{3.5 * 10^{4} \sigma^{1.4} \exp\left(-\frac{19600}{T}\right)}{\left[1 + 274 \int_{T2}^{T} \exp\left(-\frac{19600}{T}\right) (T - 1105)^{3.72} dt\right]}$$

(950 [°C] < T ≤ 1200 [°C])

$$\dot{\varepsilon} = 10.4 * \sigma^{3.4} \exp\left(-\frac{19600}{T}\right)$$

(b) *Creep model for the calandria tube (CT)* [8]

(T ≤ 850 [°C])

$$\dot{\varepsilon} = 22000 \left(\sigma - \sigma_i\right)^{5.1} \exp\left(-\frac{34500}{T}\right) + 140 \sigma^{1.3} \exp\left(-\frac{19000}{T}\right)$$

(c) *Creep model for the calandria tube (CT)* [10]

(T ≤ 800 [°C])

$$\dot{\varepsilon} = 7.2 * 10^{4} \sigma^{4.15} \exp\left(-\frac{34544}{T}\right)$$

(800 [°C] < T ≤ 1000 [°C])

$$\dot{\varepsilon} = 0.24 \sigma^{2.33} \exp\left(-\frac{12311}{T}\right)$$

(T > 1000 [°C])

$$\dot{\varepsilon} = 2.4 \sigma^{3.86} \exp\left(-\frac{15488}{T}\right)$$

2.2 Ballooning model in CAISER

CAISER code adopted the creep model for the pressure tube and calandria tube to evaluate the effect of the PT-CT contact at the fuel channel failures. General introduction of the fuel channel modeling for the CAISER code is available in the references [11-13].

Major assumption to simulate the PT-CT contact is summarized as below;

(i) Traverse creep model for the PT is selected by R.S.W. Shewfelt correlation [7] and grain-boundary sliding of the alpha- and beta-phase mode is assume d to be neglected: time-dependent term in model [14]. Traverse creep model for the CT is selected by DELOCA code [10] to consider the wide range of the temperature.

(ii) Failure criteria of creep-strain at the PT and CT is set as 20% and 2% strain, respectively. Thermal contact conductance between the PT and CT at the contact is assumed to be constant, 10,000 kW/m2-K [4]. Traverse strain of the PT and CT is calculated by their average temperature, which indicates uniform deformation without local distribution. Contact area between PT and CT is identical to inner surface area of CT.

(iii) Heat transfer model between calandria tube and moderator considers boiling phenomena. Critical wall superheat indicating the dry-out is assumed to be 20K, which is calculated from a pool boiling of a horizontal tube: N. Zuber for the critical heat flux and W.M. Rohsenow [15] for the nucleate boiling. Before the dry-out, heat transfer coefficient is 30,000 W/m^2-K (nucleate boiling). After dry-out, heat transfer coefficient is 250 W/m^2-K indicating a film boiling [9]. Wall thickness of the PT and CT is assumed to be constant (to be updated).

2.2 Transient analysis

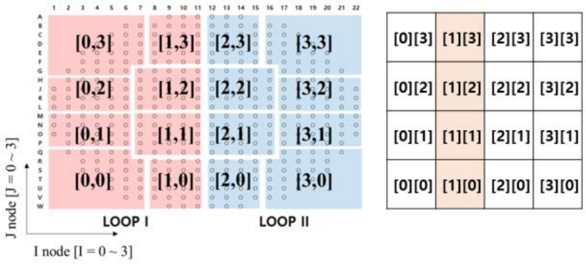

Fig. 1. [I][J][K] node system of 380 fuel channels modeling for CAISER code

PT-CT contact model of CAISER has been evaluated with two test conditions: high-pressure (10 MPa) and low-pressure (0.2 MPa) accident. Node number of CANDU fuel channels is [2][0-3][2] for [I][J][K] node system, where k-node is in a flow direction. CAISER code is considering various failure mechanism for PT and CT: Local temperature failure, Larson-Miller parameter (LMP) creep failure, Loss of ultimate strength failure and strain-limit creep failure. Failure of local temperature for PT and CT is 1800K and 1500K and difference between them indicates that CT have Zry-2 and relatively thin wall compared to the PT (Zr-2.5wt% Nb). Flow boundary condition inside PT is controlled after 1,000s as the zero mass flow rate at test conditions

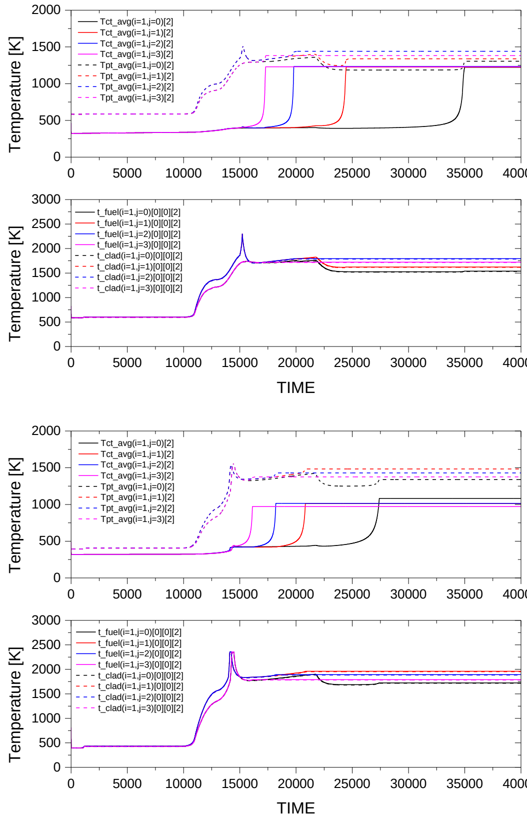

Fig. 2. Temperature of Fuel/clad, PT and CT *without PT/CT contact*: (top) high pressure and (bot) low pressure.

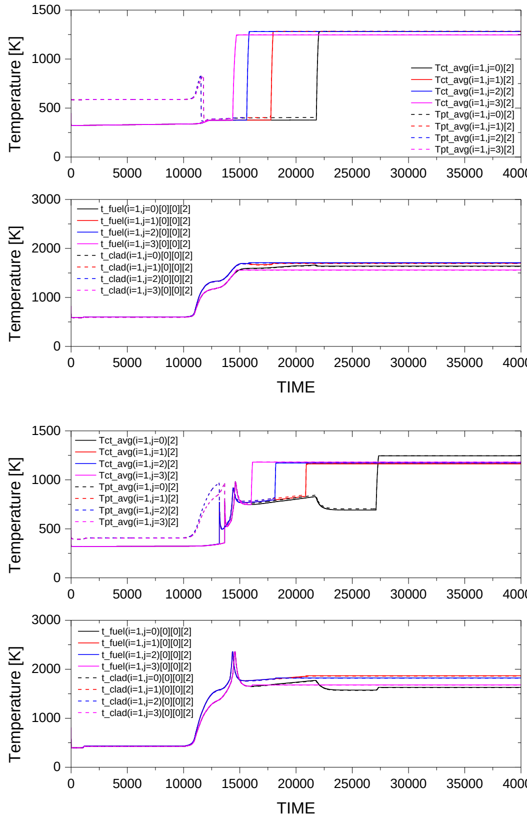

Fig. 3. Temperature of Fuel /clad, PT and CT *with PT/CT contact*: (top) high pressure and (bot) low pressure.

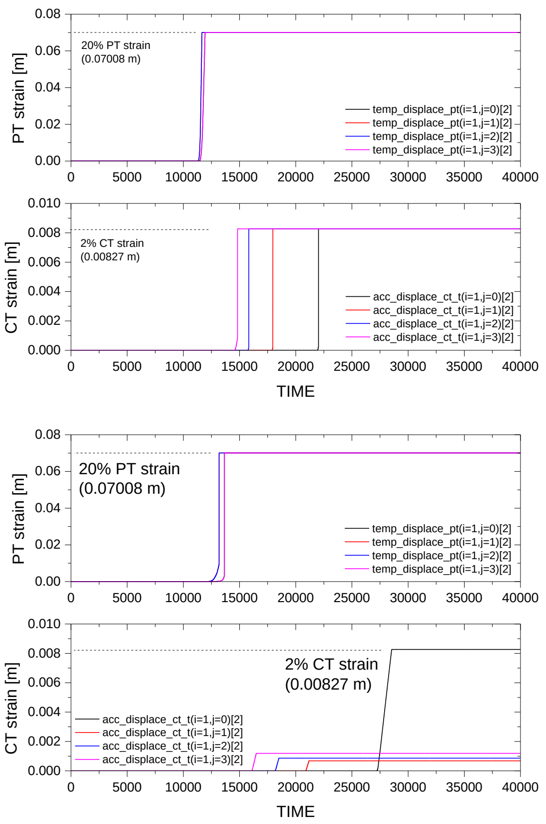

Fig. 4. Strain of the PT and CT under (top) high pressure and (bot) low pressure condition.

Depending on the consideration of PT ballooning, the temperature behavior of PT and CT significantly varied regardless of the pressure condition. In case of the PT-CT contact, temperature of the PT and CT behaves in a similar pattern after the contact. This is distinguishable to the '*without PT/CT contact*' case (Fig. 2-4); the PT temperature is generally governed by the coolant dry-out and the melting of the fuel/clad inside the PT, the CT temperature is strongly related to the moderator level.

Table. I. Failure mechanism of the 380 fuel channels

	Failure information	w/o ballooning		w ballooning	
		High P	Low P	High P	Low P
PT	Node	[2][2][0][4]	[2][2][0][4]	[2][2][4]	[2][2][4]
	Time [s]	12416	12903	11406	12144
	Temp [K]	1537	1800	355 (864)*	1020
	Mechanism	Creep (LMP)	Local (1800K)	Creep (Strain)	Creep (Strain)
CT (FC)	Node	[2][3][0][3]	[2][3][0][2]	[2][3][5]	[2][2][0][1]
	Time [s]	17226	16122	14615	14628
	Temp [K]	1332	1500	1297	1500
	Mechanism	Creep (LMP)	Local (1500K)	Creep (Strain)	Local (1500K)

It is noted that failure mechanism of the fuel channels (FC) is affected by the pressure condition (Table I). In case of the high pressure, FC is failed by the creep rupture failure. On the other hands, the low pressure condition results in the failure mechanism of the FC as the local temperature.

Under the low pressure condition, the strain-limit creep failure or *LMP* creep failure for CT are delayed and the local failure of CT is an earlier occurred, even though PT contacts to CT because of a small hoop-stress, σ = Pr/t, where P, r and T is pressure, radius of CT and wall thickness of CT, respectively. These results are identical to the general accident progress of the CANDU reactor [17].

3. Conclusions

Effect of the PT ballooning on the fuel-channel failure was evaluated with the CAISER code. Creep failure models of the PT and CT calculated the strain, which competes the existing failure criteria for PT and CT in CAISER code (local temperature failure, Larson-Miller Parameter Creep failure, Loss of ultimate strength failure, strain-limit creep failure).

Consideration of PT ballooning and PT-CT contact result in earlier failure time of PT and CT (20% for PT and 2% for CT) by strain-limit creep failure. PT and CT temperatures behaves in a similar pattern after the contact. Depending on the pressure condition, the increase of the wall superheat at the contact moment differs and this can be explained by the fuel/clad temperature inside of the PT. Regardless of the PT ballooning, the failure mechanism of fuel channel (i.e., CT) is identical at high (LMP-creep failure) and low pressure (local temperature failure) condition.

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