DELOCA, COMPUTER CODE SIMULATING OF CANDU FUEL CHANNEL BEHAVIOR IN LOCA

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DELOCA computer code is software developed as an interactive program in Visual Basic 5 to simulate the thermo-mechanical behavior of CANDU fuel channel under postulated LOCA conditions, to simulate pressure tubes ballooning phenomenon. The modeling of temperature transient conditions for both pressure and calandria tubes, moderator and also the material properties dependence *versus* temperature are the most important features of the code. DELOCA code is used in this paper to simulate the fuel channel response at transient conditions that are described by heating rate of inside pressure tube surface. The temperature rate values used were: 1, 5, 10, 15, 20, 25, respective, 50°C/s. Also, DELOCA is used to perform a fuel channel analysis taking into account a postulated accident conditions for RIH 5%.

Key words: LOCA, ballooning, pressure tube.

1. INTRODUCTION

The CANDU-6 reactor design is based on the natural uranium fuel and heavy water as moderator and reactor coolant. The pressure tube from each fuel channel, manufactured from Zr-2.5%Nb alloy, contains the primary cooling agent and the fuel bundles and it allows the refueling process during reactor operation. A distinctive feature of CANDU (CANada Deuterium Uranium) design consists of the separation between coolant and moderator by an interstitial gap between pressure tube (PT) and calandria tube (CT), which is filled with an annulus inert gas [1]. There is the possibility to detect any leakage in the gap by monitoring of annulus gas moisture and, consequently, to monitor the loss of coolant.

The deformation of pressure tube is quite sensitive on the magnitude of internal pressure at high temperatures and on its overheating rate as well. In some loss of cooling accidents (LOCA), at high internal pressure and temperatures, the pressure tube can deform diametrically until its contact with surrounding calandria tube is reached. Sometimes this phenomenon is referred as pressure tube ballooning [2]. The local contact produces the heat removal to the moderator, and the heat transfer rate depends on the contact conductance and heat transfer regime

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established at calandria external surface. If the heat flux exceeds the critical heat flux for specified fuel channel the calandria tube will dry out. Since the post-dry out heat transfer coefficient is very low [3], the calandria tube would be effectively insulated on its outer surface, so its temperature would rapidly increase.

The modeling of pressure tubes ballooning phenomenon requires mathematical implementation of the suitable models to simulate the both mechanical and thermal behavior. DELOCA code has been developed to compute the moment of contact between the two tubes (PT and CT) and also the heat flux released in moderator through the contact zone. The DELOCA program was previously checked with a similar computer code, CONTACT 1 [4], with a good agreement [5].

Other tests were carried out with CATHENA code, which is a one-dimensional thermal hydraulic computer code designed for the analysis of two-phase flow and heat transfer in piping networks [6]. With aid of CATHENA computer code the analysis of the event sequences which occur during a postulated loss-of-coolant accident in a CANDU reactor have been done. However, the manipulations of both codes (CONTACT1 and CATHENA) are quite annoying due to complexity of the input and output files.

DELOCA code is developed in Visual Basic 5, with a friendly user interface which allows that the input data to be introduced directly and explained on user interface [7]. The code computes the pressure tube stress state of the and infers the radial strain of tube at various instants of time.

The paper describes the contact moments which are obtained with DELOCA computer code by considering a loss of cooling accident of type RIH 5% (Rupture of Inlet Header).

2. DELOCA CODE - MODEL DESCRIPTION

DELOCA code has been developed to simulate the mechanical behavior of pressure tube during pre-contact transition, and mechanical and thermal behavior of both pressure and calandria tubes after contact event.

The input data are: transient temperatures of pressure tube on inner surface, transient of the incident heat flux, the internal pressure transient, initial geometry characteristics of the channel assembly and the moderator temperature.

The geometrical model consists (Figure 1) in a fuel channel divided in twelve axial cylinders, and each axial cylinder is further divided in twelve circumferential sectors. The axial elements correspond at the twelve fuel bundles. Due to geometrical symmetry, only a half circumference of an axial cylinder is considered divided in 6 circumferential sectors, as is depicted in Figure 1. The partition into radial elements is displayed in Figure 2, with 19 elements in pressure tube, 10 elements in calandria tube and 1 element for the gap between pressure and calandria tube.

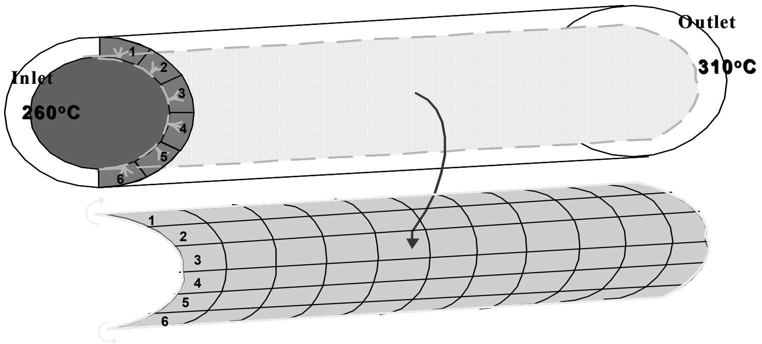

Fig. 1 – The model geometry used for 3-D simulation and circumferential and axial segmentation of fuel channel

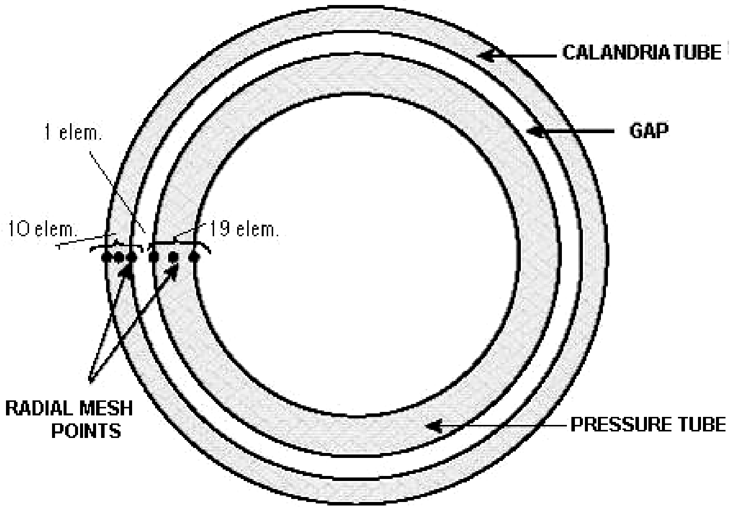

Fig. 2 – The radial segmentation of fuel channel.

Mathematical modeling of overheating transients for fuel channel consists of few models which are able to describe the deformation of tubes, their stress state, and the heat transfer by conduction trough cylindrical walls. Thermal properties of the materials and the calculation of heat removed by the interface between calandria tube and moderator were also implemented.

The modeling of ballooning deformation supposes that total strain is a cumulative result during heating up by incorporating the thermal creep strain and grain size changes due to hoop stresses developed in the pressure tube, generated by internal pressure. Worth to mention is the fact that the total strain rate for pressure tube (Zr-2.5%Nb alloy) and for calandria tube (Zy-2 alloy) have particularly expressions for certain temperature intervals. Thus, the relationships for pressure tube deformation rate are [8]:

$$\dot{\varepsilon}_t = \dot{\varepsilon}_\alpha + \dot{\varepsilon}_{gb} = 1.3 \times 10^{-5} \sigma_t^{9} \exp(-36600/T) + \\ + \frac{5.7 \times 10^{7} \sigma_t^{1.8} \exp(-29200/T)}{\left(1 + 2 \times 10^{10} \int_{t1}^{t} \exp(-29200/T) dt\right)^{0.42}} \tag{1}$$

for 723K ≤ T < 1123K, and

$$\dot{\varepsilon}_t = \dot{\varepsilon}_\beta + \dot{\varepsilon}_{gb} = 10.4 \sigma_t^{3.4} \exp(-19600/T) + \\ + \frac{3.5 \times 10^{4} \sigma_t^{1.4} \exp(-19600/T)}{\left(1 + 274 \int_{t2}^{t} \exp(-19600/T)(T-1105)^{3.72} dt\right)^{0.42}} \tag{2}$$

for 1123 K ≤ T < 1473 K.
where t1, t2 – the instants of time when T_1=700°C, respective T_2=850°C in [s], and σ_t is hoop stress in [MPa].

For calandria tube, the creep equations used in DELOCA code are [7]:

$$\dot{\varepsilon}_t = 7.2 \times 10^{4} \exp(-34544/T) \sigma_t^{4.15}, \quad \text{for } T \le 1073 \tag{3}$$

$$\dot{\varepsilon}_t = 0.24 \exp(-12311/T) \sigma_t^{2.33}, \quad \text{for } 1073 < T \le 1273 \tag{4}$$

$$\dot{\varepsilon}_t = 2.4 \exp(-15488/T) \sigma_t^{3.86}, \quad \text{for } 1273 < T \tag{5}$$

The post-contact hoop stress in pressure tube wall is [7]:

$$[\sigma_t]_{PT} = \frac{(P - P_C) \cdot r_{PT}}{w_{PT}} \tag{6}$$

where: P_C - contact pressure; r_{PT} - radius of pressure tube; w_{PT} - thickness of pressure tube.

The heat transfer model is focused on the transient removal of heat to the moderator, in radial direction, from the inner pressure tube surface to the outer surface of the calandria tube.

The Fourier equation for heat conduction in cylindrical coordinates [9] is:

$$\rho \cdot C_p \frac{\partial T(r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda(r) \frac{\partial T(r,t)}{\partial r} \right) \tag{7}$$

where: c_p – heat capacity, ρ – density, T – temperature, t – time, λ – thermal conductivity.

In DELOCA code, equation (7) is solved by finite difference method for composite walls. The gap between the pressure tube and calandria tube is account as a very thin layer (<1 μm) characterized by a thermal contact conductance starting from contact event. The heat transfer is assessed by solving the heat transfer equation for conduction across the multilayer system, taking into account the temperature dependence of thermal properties. The mesh number in pressure and calandria tube is different and also the time increments in the thermal and mechanical solutions; the last one depends on the pressure tube strain rate.

Boundary conditions are established for each interface: between two adjacent elements of tubes, between outer surface of calandria tube and moderator and between calandria and pressure tubes. Initial conditions are characterized by null gradients of temperature in tube walls, the starting instant of time for heat transfer being the contact one. The contact event between the ballooned pressure tube and calandria tube is followed by a heat transfer at the interface between calandria tube outer surface and moderator.

The heat flux depends on the heat transfer regime at interface depending on the calandria tube temperature. DELOCA uses five types of regime: liquid natural convection, nucleate pool boiling, critical heat flux, transition from nucleate boiling to stable film boiling, stable film boiling. Different and appropriate correlations were used for the heat transfer coefficients.

3. RESULTS, DISCUSSIONS

DELOCA code was used to simulate the fuel channel response at transient conditions that are described by heating rate of inside pressure tube surface. The temperature rate values used were: 1, 5, 10, 15, 20, 25, respective, 50°C/s. The failure criteria was pressure tube deformation rate, the critical value of 0.35 was used because time failure to exceed the contact time and dry out time.

Table 1

Predicted values of contact moments and onset of stable film boiling in dependence on temperature increasing rate of inner surface pressure tube

Temperature Rate [°C/s]	Contact Moment [s]	Dry-out Moment [s]	TP Temperature [°C]
1	305.37	305.81	637.4
5	73.97	74.38	679.9
10	38.95	39.34	699.5
15	26.75	27.14	711.3
20	20.49	20.87	719.8
25	16.66	17.04	726.5
50	8.74	9.10	746.6

The predicted contact and dry out times are presented in Table 1 and were plotted together (Fig. 3). The trendline function that describe the contact time in dependence of temperature increasing rate is a power function as follows:

$$t_c = 311.76\left(\frac{\partial T}{\partial t}\right)^{-0.9098} \qquad (8)$$

$$(R^2 = 0.9998)$$

where t_c is the contact moment and $\frac{\partial T}{\partial t}$ represents the temperature increasing rate.

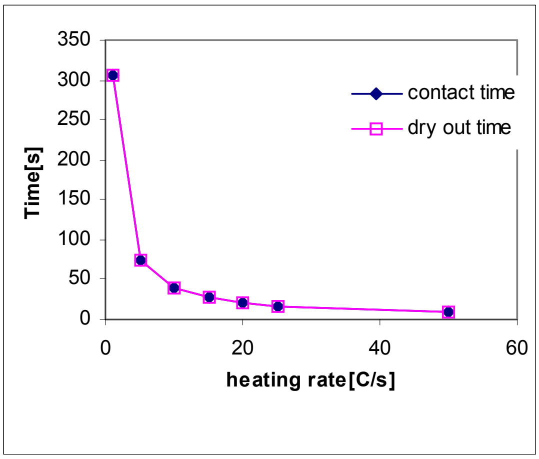

Fig. 3 – The dependency of contact time and dry out time on pressure tube heating rate.

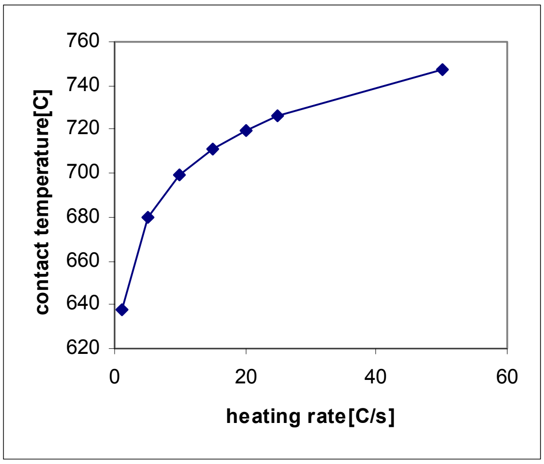

Fig. 4 – The dependency of pressure tube temperature at contact time on pressure tube heating rate.

In Fig. 4 is shown the contact temperature dependency on a heating rate, the dependency is a logarithmic form as follows:

$$\begin{aligned} T_c &= 27.997\ln\left(\frac{\partial T}{\partial t}\right) + 636.08 \\ R^2 &= 0.9991 \end{aligned} \tag{9}$$

where T_c is the pressure tube temperature at contact moment.

For a heating rate values about 1°C/s the pressure tube temperature at contact moment value is calculated a value of temperature about is 637.4°C, and for 50°C/s, calculated temperature value is about 746°C, with a difference about 100°C.

The DELOCA computer code has been used for a 3D simulation of fuel channel events during thermal transients similar to LOCA. The analysis considered the RIH 5% postulated accident.

The simulations predicted the strain and stress states in circumferential-axial elements. Also the contact instants of time between the pressure and calandria tubes and the transferred heat flux into moderator were calculated.

For each axial-circumferential element it was used the input data provided by CATHENA computer code, which is 1D thermo-hydraulic computer code for transient analysis of CANDU reactors. Analysis conditions for RIH 5% accident were:

- Unavailability of both shutdown systems.
- No emergency coolant injection.
- No isolation of broken loop from primary heat transport system.

Table 2

The contact instants (in seconds) corresponding to circumferential (C) - axial (A) elements of fuel channel

C\A	1	2	3	4	5	6	7	8	9	10	11	12
1	-	-	159.3	153	147.7	151.61	152.57	156.58	156.05	153.75	152.25	151.77
2	-	-	159.4	152.9	147.7	151.61	152.57	156.58	156.05	153.75	152.25	151.77
3	-	-	160.5	152.9	147.8	151.61	152.57	156.58	156.05	153.75	152.25	151.77
4	-	-	-	151.1	148.7	151.6	152.57	156.58	156.05	153.75	152.25	151.77
5	-	-	-	-	157.4	151.89	152.81	156.61	156.05	153.75	152.25	151.77
6	-	-	-	-	-	-	-	157.59	156.1	153.77	152.27	151.79

The contact time instants in different axial-circumferential segments, for the postulated accident RIH 5%, are displayed in Table 2. Actually, this is a map of contact time instants for circumferential-axial elements. The first contact is recorded after 147 seconds from the accident start up in central axial fuel bundles numbers 5 and 6. This is a region where the temperature has an increasing trend, but, in the same time, the contact acts to reduce the temperature by heat removal into moderator.

The simulation with DELOCA code shown the first full circumferential contact is recorded after 151.79 seconds. This result proves a good agreement with the validated code CATHENA used for thermo-hydraulic transient analysis of CANDU 6 NPP.

With CATHENA code was simulated the same accident RIH 5% and the code reported the first full circumferential contact at 12 fuel bundle after 155 seconds from the start of same postulated accident. The slight difference from the value calculated with the DELOCA code (151 seconds) could be attributed to the implementation in CATHENA code of a heat transfer by radiation between pressure and calandria tubes before contact.

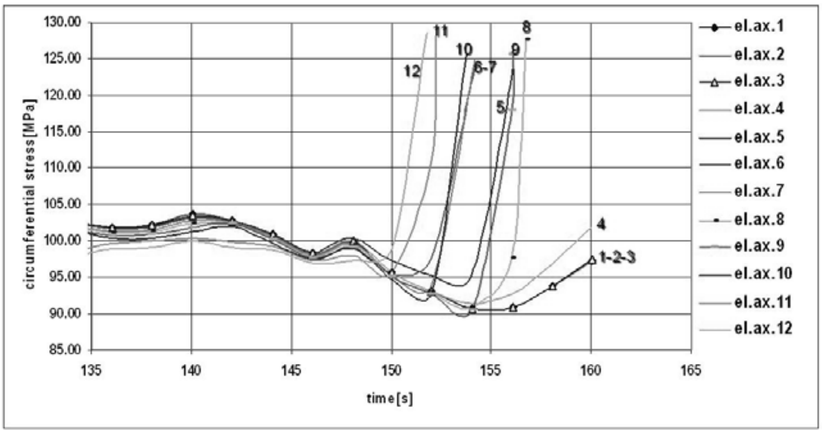

Fig. 5 – The transients of circumferential stress for the 12 axial segments.

For a range of axial segments from 1 to 7, the bottom circumferential segments were not in contact until the end of transient temperature data, while for the axial segment no.12 the contact is full circumferential. After 160 seconds, the tubes are in contact on a full circumferential area, from the axial segment no. 8 to no. 12.

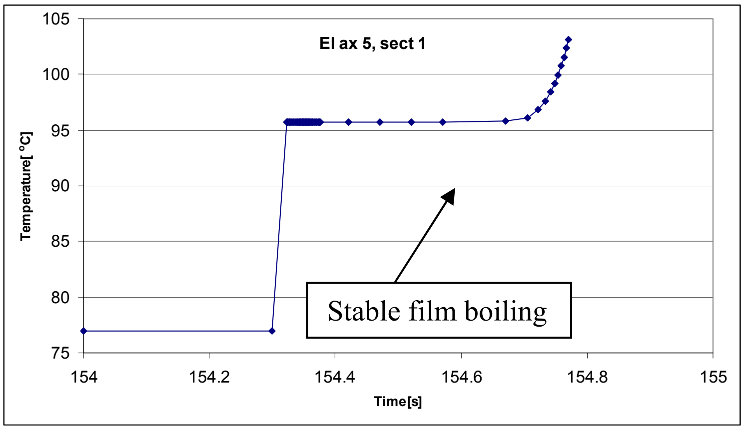

Fig. 6 – The variation of outer surface temperature for calandria tube at 5th element axial and 1st circumferential

A stress release occurs, as show Fig. 5, in the pressure tube due to the ballooning phenomenon in the first stage of the RIH5% transient. Even if the first contacts occurred at 5 and 6 fuel bundle, the fast increasing of the stress does not occur in these elements; the increasing of stress happened at fuel bundle number 12, where first full circumferential contact is occurred. The circumferential stress increase begins at the element number 12 followed by 11, 10, 6, 7, 5, 9 and 8 while in the elements 4, 1, 2 and 3 the stresses still release. In the analysis a failure does not happened, but is more than likely that it could appear at the channel outlet. This stress releasing is the result of tube ballooning under internal pressure transient.

In Fig. 6 is graphically represented the rapidly evolution in time of outer surface temperature for calandria tube until onset of stable film boiling regime.

4. CONCLUSIONS

It has been developed a computer code - DELOCA - which can perform the following analysis:

- Simulation of the thermal and mechanical behaviour for fuel channel components during thermal transient conditions similar to LOCA;
- Prediction the ballooning phenomenon; confident results have been obtained in simulation of RIH 5% accident;

The DELOCA simulation has shown an exponential increasing function of contact time *versus* temperature increasing rate.

The results of simulation of RIH 5% postulated accident shows:

– The temperature increasing and hoop stress relaxing for pressure tube before contact with calandria tube;

– The decreasing of pressure tube temperature after contact and speedily stresses increasing;

– The increasing of calandria tube temperature;

– Removal of a large heat amount to moderator before dry out of outer surface of calandria tube.

These results are in good agreement with those obtained with validated CATHENA computer code.

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