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Identification of constitutive parameters for high temperature deformation of pressure tube of Indian PHWR considering multi-axial state of stress

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ABSTRACT

In case of severe accidents like loss of coolant accident with failure of emergency core cooling system, the pressure tubes get heated quickly causing severe deformation. In this paper, an analytical solution technique has been used for calculating the radial deformation behaviour of pressure tubes. The analysis is carried out for different cases when the pressure tube is subjected to different values of internal pressure and heating rates. In the absence of specimen level creep test data of Indian pressure tube, data of Canadian pressure tube of similar material has been used. Due to observed differences between experimental and analytical values of radial deformation with time, the actual parameters have been calibrated from component level experiments using an optimization algorithm. Both uniaxial and bi-axial states of stress have been considered. Finite element method has also been used to calculate radial deformation of pressure tube and compared with experiment.

1. Introduction

Indian Pressurized heavy water reactors (PHWRs) are CANDU (CANadian Deuterium Uranium) type reactors with capacities of 220 MW_e and 500 MW_e. The 220 MW_e IPHWRs consists of a horizontal reactor core of 306 parallel reactor channels. All the reactor channels are submerged in a pool of heavy water called moderator maintained at around 65 °C. Each reactor channel consists of a pressure tube (PT) of 82.55 mm inner diameter and 3.32 mm wall thickness, which is concentrically placed in a calandria tube (CT) of 107.7 mm inner diameter and 1.5 mm wall thickness. The length of each channel is 6000 mm. The PT contains the fuel and hot pressurized coolant and under normal conditions, operates at about 300 °C with an internal pressure of about 10 MPa. Description of Indian PHWRs is discussed in Bajaj and Gore (2006). Four garter springs are located at the outer periphery of PT which also makes contact with the CT. The garter springs maintains an annular gas-filled insulation gap of around 8.9 mm between the PT and the CT. Schematic of Indian PHWRs coolant channel is shown in Fig. 1.

A study on Indian PHWR under prolonged deteriorated flow condition was discussed by Gupta et al. (1996) which states that under the severe accident like the loss of coolant accident (LOCA) with Emergency core cooling failure (ECCS) failure, coolant in the fuel channel may get boiled off or may get leaked out from the channel. Due to differences in heat generation in fuel and heat rejection to moderator, partial or complete voiding may occur. Complete voiding shall lead to symmetric deformation. If the rate of loss of coolant is low, then the coolant tube will be partially voided. Gillespie and Moyur (1985) and Yuen et al. (1988) conducted experiments for determination of circumferential temperature distributions developed in pressure tubes during slow coolant boil down at a constant internal pressure for CANDU PT material. The circumferential temperature gradient may lead to asymmetry in ballooning deformation and zone of contact with CT. Shewfelt (1986) had developed failure maps for internally pressurized pressure tube with circumferential temperature gradients. Maps were used to predict whether the pressure tube with circumferential temperature gradients would fail prior to contacting the CT. Mathew (2008) studied the severe core damage accident progression within a CANDU Calandria vessel. Both single channel and multiple channel tests were performed on the pressure tube to see how the pressure tube will deform and eventually get collapsed to form the debris.

The symmetric ballooning deformation is controlled predominantly by transverse properties and a model to predict the same accurately is essential. An experimental investigation of heat transfer from a reactor fuel channel to surrounding water is done by Gillespi (1981). They also predicted the heat transfer regime which will occur at the outer surface of the CT as a result of the contact between PT and CT. It had been concluded that cooling of the pressure tube was enhanced in the region of nucleate boiling.

A series of experiments was performed by So et al. (1987) to determine the thermo-mechanical behavior of a fuel channel by both

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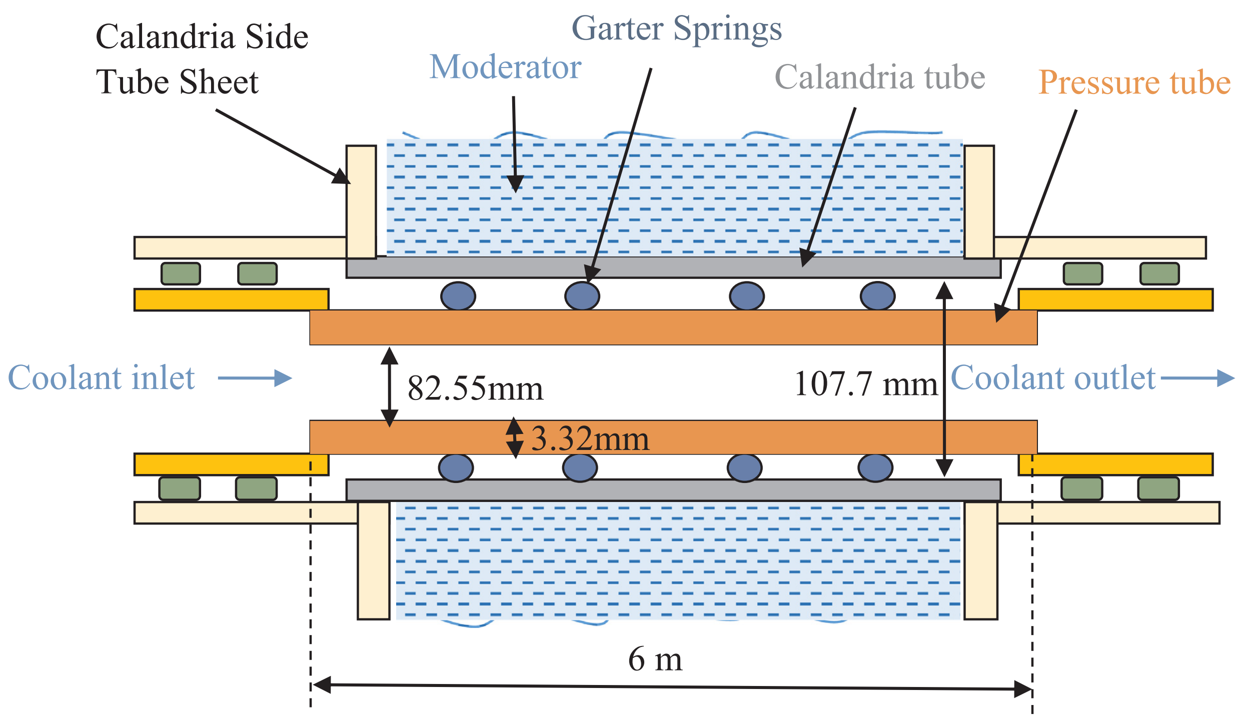

Fig. 1. Schematic of Indian PHWR coolant channels.

pressure and dead weight. Component level tests performed on Indian PHWRs were carried out by Yadav et al. (2013a), Yadav et al. (2012), Yadav et al. (2013b) and Yadav et al. (2013c) to investigate the variation of temperature along the circumference and axial directions of the pressure tube as a result of symmetric and asymmetric heating of the pressure tube. It had been found that circumferential temperature gradients during symmetric heating was quite low as compared to the asymmetric heat up conditions. Ballooning initiation temperature was found out to be inversely proportional to the internal pressure. Specimen level tests for Zr-2.5% Nb material were done by Shewfelt et al. (1984) and the transverse creep rate equations were given in Shewfelt et al., (1984a,b). Though the material is similar to that of Indian pressure tube, there are differences in chemical composition, processing route and microstructure.

Various models like CATHENA (Richards et al., 1985; Hanna, 1998), SMARTT (Locke et al., 1985; Locke et al., 1987) and AMPTRACT (Gulshani and So, 1986) are available for simulations of PT transients under accident conditions for CANDU reactors. Shewfelt and Godin (1985) were able to predict the non-uniform deformations of CANDU PT leading to PT-CT contact and failure of Zr-2.5 wt% Nb pressure tubes during a postulated LOCA through a computer program GRAD. To examine the mechanical deformation of the CANDU PTs during the pressure and temperature transients, a two dimensional computer code NUBALL (Non-Uniform Ballooning) was developed by Kundurpi (1986). Simulation of PT ballooning and sagging deformation was carried out by Majumdar et al. (2004) but the creep rate equations used for predicting the deformation were obtained from the CANDU PT tests and there is no experimental validation of the simulation results.

2. Description of experimental cases from literature used for evaluation of material parameters in this work

Experiments on ballooning of a completely voided pressure tube of Indian PHWR under heat up condition have been discussed in Nandan et al. (2012). Different experiments were performed by varying internal pressure and heat up conditions. Experiments were performed on the single channel consisting of PT and CT; the latter was submerged in a pool of water tank that acts as a moderator. Test was done on miniature PT with length of 1.5 m while CT length of 1 m. A DC rectifier was used for heating the PT. The temperature of moderator in the tank was raised to 60 °C using an external heater and the rectifier was switched on to heat the PT. Initial steady state temperature of 300 °C was achieved slowly after which ramp power is switched on. The deflection and the temperature of the PT were noted. Power supply to the PT was continued till PT–CT contact was established. It was assumed that PT–CT contact takes place when the deflection at any point is equal to PT–CT gap of 8.9 mm. Three experiments were performed at 2, 4 and 6 MPa internal pressure and the same will be used in validation of the results predicted in this paper. 2 MPa experimental data has been taken from Majumdar et al. (2011). LVDTs were placed at four locations i.e. 5 cm, 45 cm, 55 cm and 95 cm from the rectifier ends. Six thermocouples were placed along the circumference of the pressure tube. Schematic diagram is shown in Fig. 2.

3. Rationale for determination of creep parameters from component level data

Although extensive experimental creep studies were made with CANDU PT materials, it is required to assess the applicability of these creep models to Indian PT for two important reasons as mentioned below.

- Fabrication process of Indian pressure tube is very different from the Canadian process. The CANDU PT is nominally extruded at 815 °C, cold-worked 27% and stress relieved at 400 °C for 24 h. Indian PT is manufactured by two-stage hot extrusion of Quadruple Vacuum Arc-melted Zirconium–2.5% Niobium Ingots into mother blanks, which are annealed and pilgered in 2 stages to the final dimensions (NFC Hyderabad, 2012; Singh et al., 2000). The stress-relief treatment is done for tube.
- Creep stress-strain correlations are developed through experiments at constant stress and temperature conditions on standard specimen. Application of these creep correlations can be subjective depending on the boundary and transient conditions. Such correlations require