Experimental Investigation of Sagging and Ballooning in LOCA for Indian PHWR

Gopal Nandan, P. K. Sahoo, Ravi Kumar, B Chatterjee, D. Mukhopadhyay, H. G. Lele [*]

Abstract—**In a nuclear reactor Loss of Coolant accident (LOCA) considers wide range of postulated damage or rupture of pipe in the heat transport piping system. In the case of LOCA with/without failure of emergency core cooling system in a Pressurised Heavy Water Reactor (PHWR), the Pressure Tube (PT) temperature could rise significantly due to fuel heat up and gross mismatch of the heat generation and heat removal in the affected channel. The extent and nature of deformation is important from reactor safety point of view. Experimental set-ups have been designed and fabricated to simulate sagging (downward deformation) and ballooning (radial deformation) of PT for 220 MWe Indian PHWRs. It is observed that sagging initiates at a temperature around 450°C. Contact between PT and Calandria Tube (CT) occurs at around 585°C. At 60 bar internal pressure and initial heat up rate of 2.37°C/sec, ballooning of PT initiates at a temperature around 520°C. The PT-CT contact is found to take place at 640°C temperature. The structural integrity of PT is retained (no breach) for all the experiments. The PT heatup is found to be arrested after the contact between PT and CT, thus establishing moderator acting as an efficient heat sink for IPHWRs.**

Keywords: Pressure Tube, Calandria Tube, Thermo-mechanical deformation, Boiling heat transfer, Reactor safety

1 Introduction

Indian PHWRs are of 220 MWe and 500 MWe capacity. The 220 MWe 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. The channels are housed in the Calandria Vessel. Each reactor channel consists of a PT of 90 mm outside diameter, which is concentrically placed in a CT of 110 mm outside diameter. Short fuel bundles are housed in PT. The gap between PT and CT is 8.95 mm and is filled with CO_2 for thermal insulation. The PT is supported along its length through tight garter springs as shown in Fig. 1. PT and CT are made of Zirconium 2.5 wt% Nb and Zircaloy-2 material respectively. Nuclear heat is removed from fuel bundles by heavy water coolant and transferred to the Steam Generators secondary side, where the secondary side water boil-off generate steam at 40 bar pressure for turbine. The coolant after releasing the heat in Steam Generator returns back to other half of the reactor channels through centrifugal pumps.

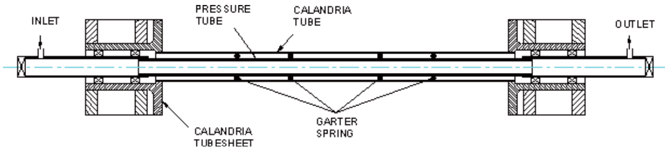

Figure 1: Schematic of Indian PHWR Reactor Channel

During postulated low frequency events like LOCA along with the failure of the Emergency Core Cooling System (ECCS), the cooling environment for the bundles degrades that results heatup of the fuel bundles [3], and in turn heatup the PT through radiation heat transfer. The heat flux incident on the surface of PT during such event is equivalent to that of decay power (2% - 1% of nominal power) as the reactor will undergo shutdown during such situation. However, the temperature of the CT is not affected significantly as it is submerged in the low temperature moderator. In such event, CT will experience a high rate of heat transfer from its surface to bulk moderator by various mode of pool boiling heat transfer. The rise in temperature of the PT will lead to deterioration in its thermo-mechanical properties. The pressure inside the PT could be in the range of 0.1 to 9 MPa. If the internal pressure is lower than 1.0 MPa, the PT deforms (sags) due to high temperature creep and due to its own weight and weight of the fuel bundles. Ballooning deformation takes place when internal pressure is more than 1.0 MPa. The deformation of the PT leads to a physical contact between the PT and CT, thereby resulting in high heat transfer to the moderator. Enhanced heat transfer from PT to CT arrests the rise in temperature of the fuel bundles and PT. It is an important aspect in reactor safety to study the behaviour of

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Gopal Nandan (email:gopalnandan@gmail.com), Pradeep K Sahoo (e-mail: sahoofme@iitr.ernet.in), and Ravi Kumar (e-mail: ravikfme@iitr.ernet.in) are at Mechanical and Industrial Engineering Department, Indian Institute of Technology, Roorkee, India
Barun Chatterjee (e-mail:barun@barc.gov.in), D. Mukhopadhyay (e-mail: dmukho@barc.gov.in), and H. G. Lele (e-mail: hglele@barc.gov.in) are at the Reactor Safety Division, Bhabha Atomic Research Centre, India

PT to assess the structural integrity during this process as well as establishing moderator as an efficient heat sink during LOCA. The structural integrity of PT and assessment of moderator as a heat sink has been investigated for CANadian Deuterium Uranium (CANDU) reactor for circumferentially symmetric and asymmetric heating heatup conditions [2, 5, 6, 7, 8, 9]. The structural integrity has been found to be maintained for all cases having symmetric heating and in some cases of asymmetric heating has caused breach of PT. The mechanism for transverse strain between 450°C and 850°C is found to be due to power law creep in α-phase and grain boundary sliding between 850°C and 1200°C. Power law creep of α-phase and grain boundary sliding are major contributor to the creep strain. Correlations for transverse strain rate as a function of applied stress and temperature ramp has been developed for CANDU-PT material [6].

In this work, a study has been carried out to assess the behavior of Indian PT material which is having different fabrication history, under a typical heatup condition expected from LOCA with complete Loss of ECCS scenario. A scaled down experimental set-up is designed and fabricated at the Mechanical and Industrial Engineering Department, Indian Institute of Technology, Roorkee, India to simulate such scenario. The paper describes the experimental setup and the findings of the experimentation.

2 Experimental Set up and Procedure

2.1 Sagging deformation set up

The schematic diagram of experimental set up is shown in Fig. 2. A CT of length 2000 mm and 110 mm outer diameter is fixed horizontally to the tank such that its centre is 500 mm about the tank base. The ends are sealed with the help of specially designed flanges and silicon rubber packing that can withstand temperature upto 300°C. PT having 90 mm outer diameter is concentrically placed inside the CT. The length of PT is 2.5 meter, out of which middle 2.0 meter is inside the CT and 250 mm is outside of CT at both ends. Both ends of PT were supported by a vertical metallic stand, in such a way that one end acts as fixed and the other end as free. Ceramic end caps at both the ends of the PT are used to minimize heat loss from the PT to the metallic stand. To simulate the heat generation in the reactor channel, a DC rectifier of 42kW capacity (12V/3500A) was used. The rectifier can operate from 10 to 100 percent load variation with the option of varying current or power continuously. Both the ends of PT are connected to the rectifier with the help of copper clamps and bus bars. The copper clamps were fixed on the PT very close to the outside of the tank wall. The flange was connected to the rectifier by four 99% electrolytic grade copper bus bars having cross sectional area of 10mm 6mm. Water was filled in the tank upto 80 cm height from the base of the tank, so that CT was submerged in the water. The temperatures were recorded at an interval of 100 ms using a Data Acquisition System (DAS) made by National Instruments, USA until the PT-CT contact was established. Initially, the water in the tank was heated to a temperature of 60°C. The PT was heated slowly and waited until the tube attained steady state temperature of around 300°C. This was done to obtain the normal operating temperature of a nuclear reactor. In the preliminary heating period, the readings of all the thermocouples were checked. After obtaining the steady state temperature close to 300°C, the power supply was ramped to the desired value. As the temperature of PT is expected to reach 800°C, the temperature of PT was measured with minerally insulated ungrounded K-type thermocouples of 0.5 mm outer diameter while J-type thermocouples of 1.0 mm outer diameter were used for CT. The temperature of the PT and CT are recorded at different axial locations. At each axial location, six thermocouples were used at 60° apart, as shown in Fig. 3. The experiment continued till PT-CT contact was fully established. The experiment further continued for more than 10 minutes to check the heat transfer behavior of the PT-CT.

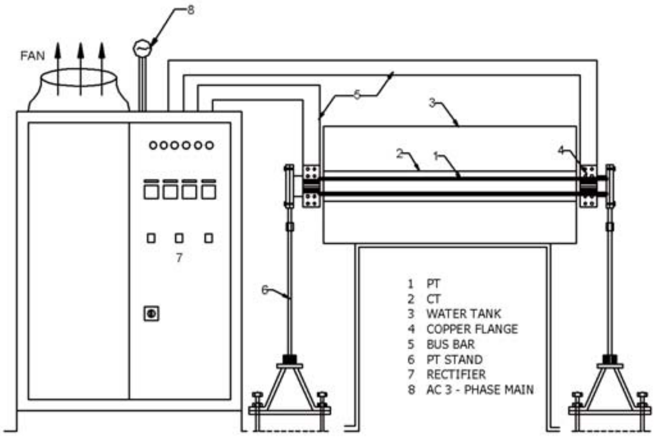


Figure 2: Schematic of the Test Setup for sagging experiment.

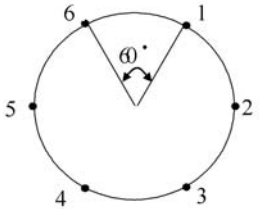


Figure 3: Circumferential thermocouples positions at any axial location

2.2 Ballooning Deformation Setup

The experimental set up, shown in Fig. 4, consists of a mild steel water tank having 1000 mm 500 mm 500 mm dimensions. The CT was fixed to the tank, similar to the sagging experiment, at a height of 250 from the tank base. The PT is concentrically placed inside the CT. The length of PT is 1.5 meter, out of which middle 1.0 meter is inside the CT and 250 mm is outside of the CT at both ends. The rectifier, and copper bus bar and clamps used in sagging experiment were also used in this experiment. In order to put the PT under high pressure both the ends of the PT were sealed with the help of specially designed high carbon steel flanges. One end of the PT was connected to an Argon gas cylinder, with the help of SS 316L pipe (schedule 8) having outer diameter of 12 mm and wall thickness of 2.88 mm. In the pressurizing circuit a rapture disk, pressure relieve valve (spring type) and feed back control valve were provided. Apart from relieve valve, pressure gauge of dial type, pressure sensor, manual control valve and non return valve were provided. Necessary arrangement is made to release the high pressure and temperature gas at a height of 4.5 meter from the ground level, which minimizes chance of injury to people at work in case of failure. Different types of controls and the safety devices are also shown in the Fig. 4. The whole experimental set up was kept inside a high tensile strength micro alloy steel tanks which covers the experimental setup from all sides. At any axial location, six thermocouples were fixed at 60° interval both on PT and CT. In this experiment the PT temperature was measured at axial locations 5, 35, 45, 55, 65 and 95 cm. For the radial expansion measurement potentiometers were used at three axial locations, i.e. 10, 50 and 90 cm from the rectifier end. At each axial location displacement was measured at four directions, i.e. two in vertical plane and rest two is in the horizontal plane as shown in Fig. 4. A special arrangement, shown in Fig 4, was made to measure the displacement of the PT while the test section is submerged in water. A ceramic rod of 2 mm diameter passed through the tube and sleeve hole in such a way that one end is in contact with the PT and the other end was attached to the potentiometer tip. The potentiometers were fixed on a platform outside of the tank in all four directions.

3 Results and Discussion

The experimental findings of the sagging deformation and ballooning deformation are presented in the following sections.

3.1 Sagging Deformation Experiment

In this experiment, the PT was heated slowly and waited until it attained steady state temperature of around 300°C. In the preliminary heating period, the reading of all the thermocouples and the potentiometers were checked. A ramp power of 26.7 kW was applied to heat up the test section and was maintained thought the experiment. The CT temperature at the beginning was 58°C and bulk temperature of water was 51°C. PT and CT temperatures were measured at three axial locations 70, 100, and 130 from rectifier end. The circumferential temperature variations of PT at all axial locations are shown in Figs. 5(a)-(c). From these figures it is observed that the rate of temperature rise in PT is almost linear in the first 100 seconds. However, circumferential temperature gradient exists at all locations. After 100 seconds, the rate of temperature rise decreases. The temperature of the PT reaches a maximum at all locations and thereafter remains almost constant or decreases. The variation of temperature rise in the PT may be due to following reasons: Heat transfer between PT and CT annulus gas takes place due to conduction, convection and radiation. However, in practice only two mode of heat transfer is dominant in any heat transfer problem. Convection and conduction are dominant at the beginning. As the temperature of PT increases, radiative heat transfer becomes more dominant. As a result, rate of heat transfer from PT to CT increases. This causes slowing down of the temperature rise of PT.

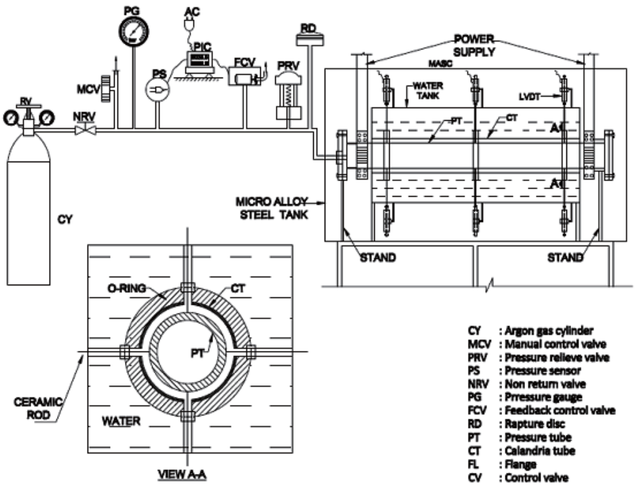
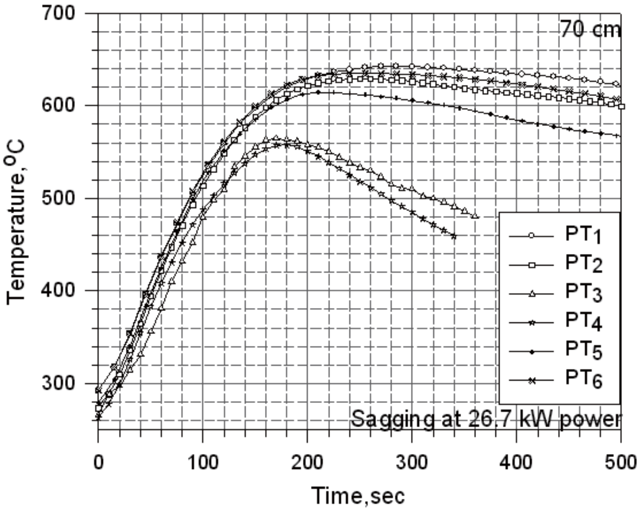
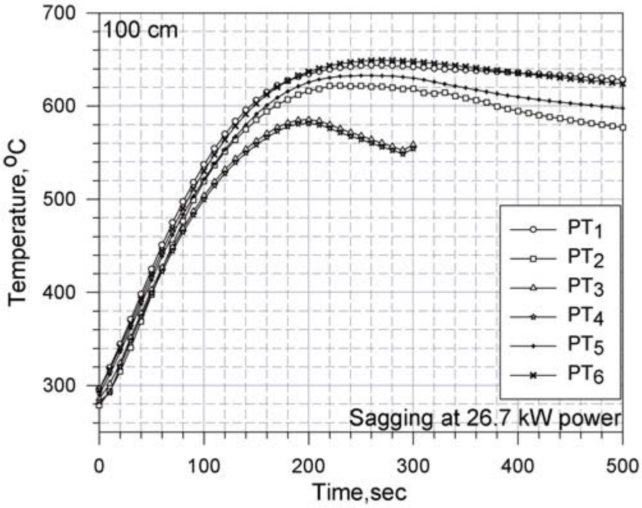


Figure 4: Schematic of the Test Setup for ballooning experiment.

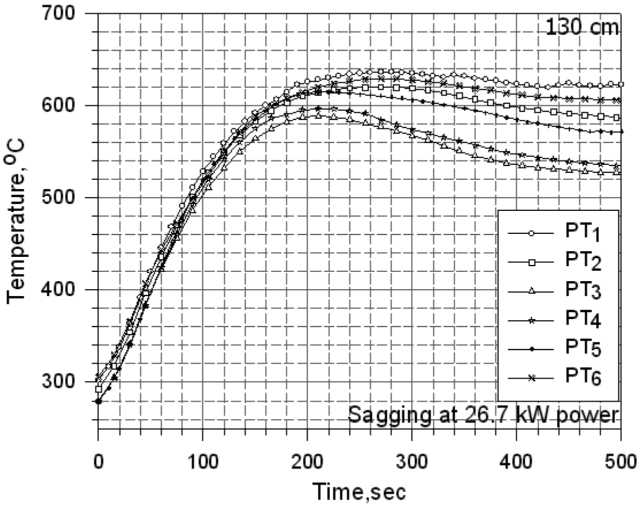
It is important to note that at any given location, the rate of temperature rise along the circumference is not the same. At all axial locations, the temperature rise of the bottom two nodes (PT_3 and PT_4) are relatively lower than the other nodal points and the top two nodes are invariably at higher temperature. This matches with the finding of Date [1], and Kuehn and Goldstein [4]. At all axial location PT_3 attains a maximum and then decreases. However, the variation of PT temperature is sharper at axial locations 70 cm and 100 cm, which indicates possible PT-CT contact nearer to these locations. The peak temperature is reached at about 200 seconds at 100 cm after initiation of heating. Beyond 300 seconds, no data could be recorded at PT_3 and PT_4, which could be due to loss of contact at these two locations due to deformation. The circumferential temperature variations of CT at all axial locations are shown in Figs 6(a)-(c). From



(a) Axial location 70 cm



(b) Axial location 100 cm



(c) Axial location 130 cm

Figure 5: Variation of circumferential temperature of PT with time for 26.7 kW heating power

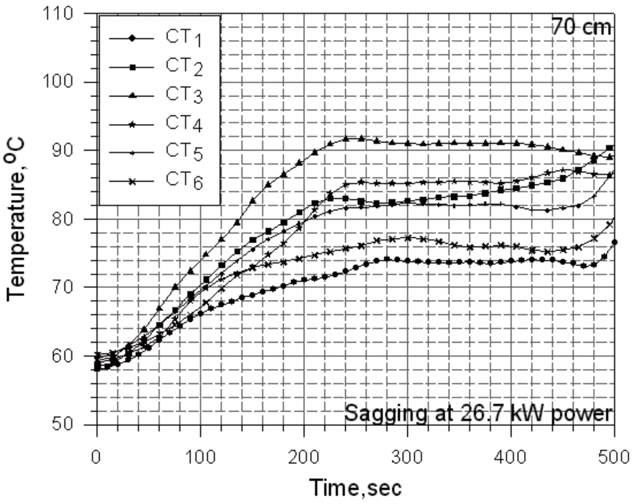
these figures it is observed that the rate of temperature rise in CT is also linear in the first 100 seconds. After 100 seconds, the rate of temperature rise along the circumference is different for each of the nodes. One can observe that CT_3 at axial location 100 cm reached the maximum temperature among all CT temperature readings. At axial location of 100 cm, the temperature at CT_3 shoots up suddenly and reaches a maximum at around 240 seconds and remains constant thereafter. This indicates that contact point must be nearer to this location. The temperature of CT_4 also shows similar trend of temperature rise. The difference in CT_3 and CT_4 is less than 3°C. From Fig. 5(c), one can observe that PT_3 and PT_4 reach the maximum temperature simultaneously. This clearly indicates that the contact is exactly between circumferential location 3 and 4. During the disassembly of the test set up, it was observed that the PT-CT contact was at 98 cm from the rectifier end and the contact area was elliptic with axes of 5.2 cm and 4.1 cm. The major axis of the area was along the circumference.

At the time of contact, average temperature of PT at the centre of the test section was 600°C. After the contact, the temperature at PT_3 and PT_4 dropped sharply, and most of heat energy passes through CT to moderator water. However, the temperature of PT1 and PT6 continued to increase for the next 60 seconds. This indicates that contact at the bottom of the tube does not immediately affect the temperature profile at the top of the tube. The maximum temperature difference observed between PT_1 and PT_3 were at location 100 cm. CT_3 and CT_4 temperatures reaches a maximum and then it decreases. As the PT-CT contact is achieved, there is sudden shoots of CT temperature near the contact area. This leads to nucleate boiling at the outer surface of the CT, which increases heat transfer significantly from CT to water. However, the heating rate is constant and most of the heat passes through CT to water at the contact area. Thus, both the temperature of PT and CT decreases. The variation in temperature decreases with time and attains a steady state.

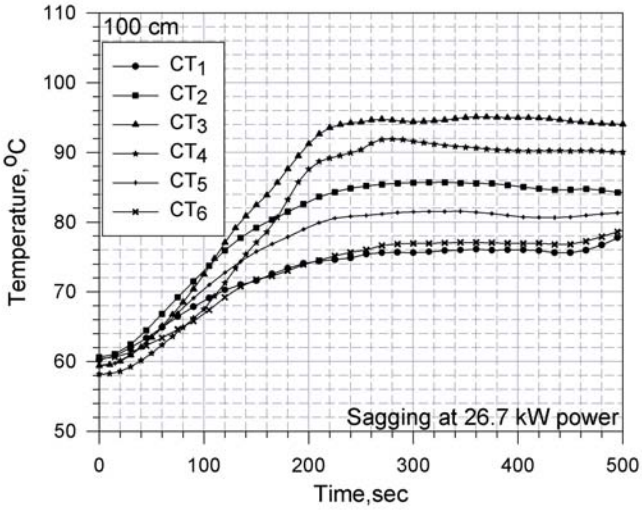
3.2 Ballooning deformation experiment

Initially the water in the tank was heated to a temperature of 55°C. The PT was heated slowly and waited until it attained steady state temperature of around 270°C. Then the PT was pressurized to 60 bar pressure and the power supply was increased to the 14 kW. The experiment was continued till PT-CT contact was fully established and the corresponding temperature and displacement were recorded.

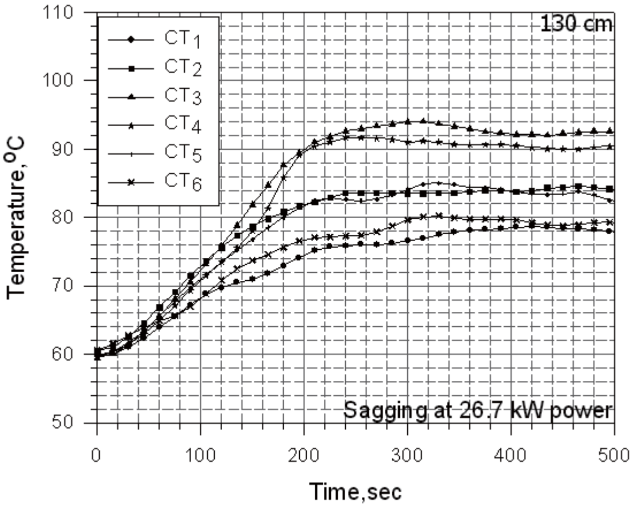
The radial deformation of the PT is shown in Fig.7. One can observe that maximum deformation is at the second node (bottom of the test section) and is about 9 mm. It may be noted that the top node shows negative displacement at around 100 second and continues upto 200 sec-



(a) Axial location 70 cm



(b) Axial location 100 cm



(c) Axial location 130 cm

Figure 6: Variation of circumferential temperature of CT with time for 26.7 kW heating power

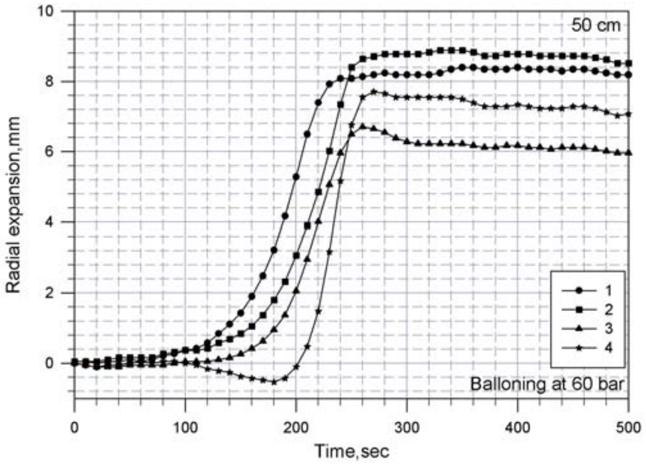


Figure 7: Pressure Tube Circumferential Deflection variation with time at centre of the test section.

onds. This could be attributed to initial sagging of PT. It changes as ballooning initiates. Ballooning initiated at about 105 seconds when the PT temperature was about 520°C. PT-CT contact is expected to take place around 230 seconds when the temperature of PT was 640°C. After PT-CT contact took place, nucleate boiling was observed at the outer surface in almost 80 percent length of CT. The bubble density was higher in the central location compare to the ends of CT, which confirms that the contact was near the centre of the test section.

The temperature profile of all thermocouples of the CT and PT, at axial location 55 cm, near which a possible PT-CT contact had taken place, are shown in Figs. 8 and 9, respectively. Figure 8 reveals that the initial temperature rise of the CT is almost linear up to 185 seconds at all locations. However, there exists a circumferential temperature gradient due to the variation of the convective heat transfer coefficient along the circumference. It is important to note that the rate of temperature rise of the thermocouples CT_3 and CT_4 after 185 seconds is higher than other thermocouples and reaches a temperature of about 102°C, which is slightly higher than the boiling temperature of the water at ambient pressure. The temperature rise of water temperature above boiling point could be due to formation of bubbles at the thermocouple tip. This clearly indicates that PT-CT contact could be near to these nodes. Similar temperature variation is also observed for PT in Fig. 9. At all circumferential measuring points, PT temperature decreases after PT-CT contact. One can observe that after PT-CT contact there is a drop in temperature at all circumferential nodes of the PT. This is due to high heat transfer rate from PT to CT.

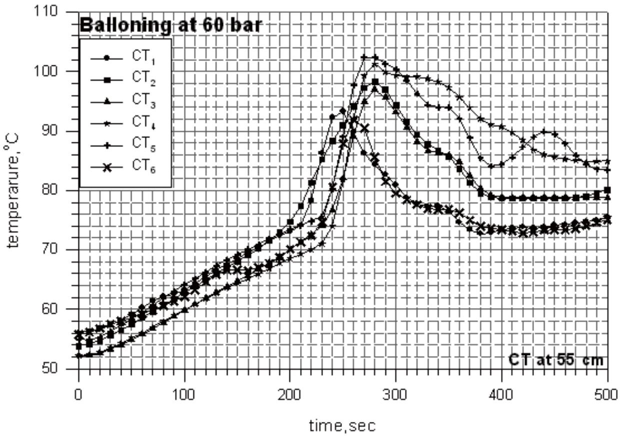


Figure 8: Calandria Tube Circumferential Temperature variation with time at 55 cm from rectifier

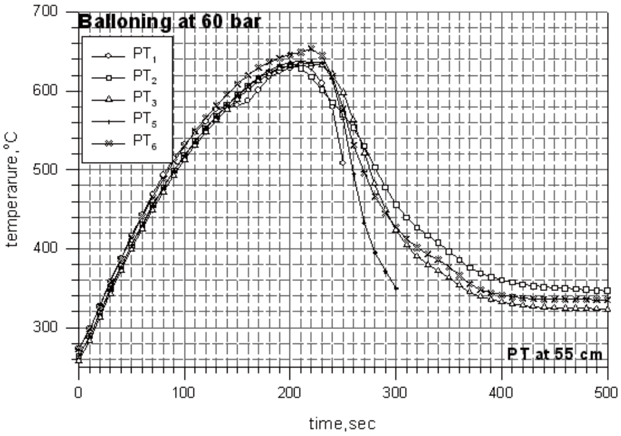


Figure 9: Pressure Tube Circumferential Temperature with time at 55 cm from rectifier

4 Conclusions

The postulated loss of coolant accident in Indian PHWR has been simulated. Experiments were conducted for sagging and ballooning deformation at heat up rate 2.4°C/sec and 2.4°C/sec respectively using same pressure tube used in the Indian nuclear reactor channel.

- Sagging of the PT initiates at around 450°C.
- Complete PT-CT contact takes place at PT temperature of 585°C in sagging deformation.
- At 60 bar internal pressure and initial heat up rate of 2.37°C/sec, the PT ballooning is found to take place at 640°C temperature with the initiation at 520°C.

The arrest of temperature rise of PT, mechanical integrity of PT (no breach) and non occurrence of Critical Heat Flux on CT show the channel integrity under efficient cooling of the simulated moderator. This demonstrates that the functioning of ”moderator as a heat sink” as an inherent safety feature of IPHWR design for a very low frequency even.

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