Thermo-mechanical Behavior of Pressure Tube of Indian PHWR at 20 bar Pressure

Gopal Nandan[a], P. K. Sahoo[a,*], Ravi Kumar[a],
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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, 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 ballooning (radial deformation) of PT for 220 MWe IPHWRs. Experiments have been conducted by covering the CT by ceramic fibers and then by submerging CT in water of voided PTs. In both the experiments, it is observed that ballooning initiates at a temperature around 665°C and complete contact between PT and Caldaria Tube (CT) occurs at around 700°C approximately. The strain rate is found to be 0.116% per second. 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

I. 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. The coolant flows through half of the channels in one direction and in the remaining 153 channels in the opposite direction. 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.

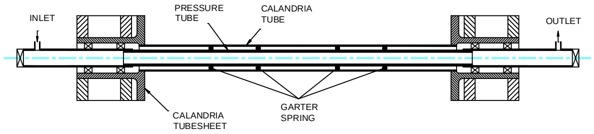

Fig. 1 Schematic of Indian PHWR Reactor Channel

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. The schematic of Primary Heat Transport System is shown in Fig. 2. 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 [1], 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

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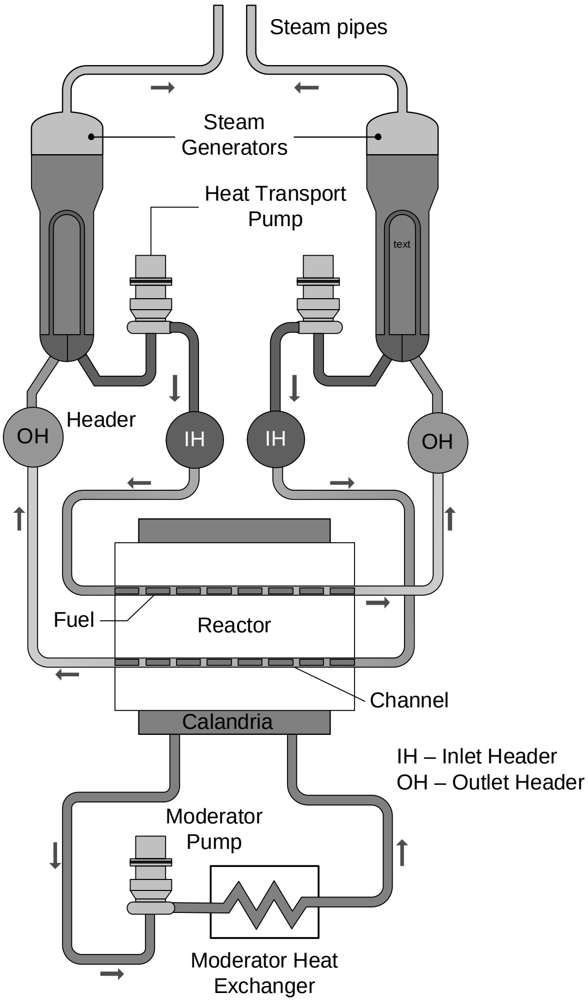

Fig. 2 Schematic of Indian PHWR

aspect in reactor safety to study the behaviour of 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 [2-7]. 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^{o}C and 850^{o}C is found to be due to power law creep in α-phase and grain boundary sliding between 850^{o}C and 1200^{o}C. Power law creep of 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 [8]. 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 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.

II. EXPERIMENTAL SET UP AND PROCEDURE

The details of experimental set ups are discussed one by one.

A. Ballooning deformation set up while CT is wrapped by ceramic fiber

The experimental set up is shown in Figure 3, consists of a mild steel water tank having 1m × 1 m × 1 m dimensions. Holes of 110 mm diameter have been made on the opposite faces of the tank at a height of 0.5 m from the base of the tank. CT, which is of 1 m length and 110 mm outer diameter, is fixed in the tank aligned with the side holes. The ends of CT are fixed on the water tank wall with the help of specially designed angles and silicon rubber packing. The PT having 90 mm outer diameter 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. Both ends of PT is supported by a vertical metallic stand, in such a way that one end acts as fixed joint and the other end is free one, which accommodates its longitudinal expansion during the heating process. Ceramic end caps at both the ends of the PT are used to minimize heat loss from the PT to the metallic stand. There is a provision for vertical adjustment of the PT within the CT to fix the PT concentric to CT. The metallic stands have been electrically insulated from tank as well as ground.

To simulate the heat generation in the reactor channel, a DC rectifier of 42kW capacity (12V/3500A) is used. The rectifier can operate from 10 to 100 percent load variation with the option of varying current or voltage continuously. Both the ends of PT are connected to the rectifier with the help of copper clamps and bus bars. The copper clamps are fixed on the PT very close to the outside of the tank wall. The copper clamps are made by casting in two parts (half circles). In the casting of copper clamp adequate amount of pure silver has been added to avoid any cavity in casting. The two half circles have been machined internally. It is fixed over the PT with the help of allan bolts. Internal machined surface is created in the clams so that minimum clearance is there between copper clamp and tube, which reduces the electrical resistance as well as local heating of PT. The width of angle is 100 mm and it is of 12 mm thick. The flange is connected to the rectifier by four 99% electrolytic grade copper bus bars having cross sectional area of 10 mm × 6 mm × 4 nos.

In order to put the PT under high pressure both the ends of the PT are sealed with the help of specially designed high carbon steel flangles. One end of the PT was connected to an Argon gas cylinder (Figure1), with the help of SS 316L pipe (schedule 8) having outer diameter of 12 mm and wall thickness of 2.88 mm. In the pressurising circuit a rapture disk, pressure relieve valve (spring type) and feed back control valve is provided. Feed back control valve operated by an electronic device which has 2 seconds operation time for the operation of pressure relieve valve. Apart from relieve valve, pressure gauge of dial type, pressure sensor, manual control valve and non return valve are 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 minimises chance of injury to people at work in case of failure. Different types of controls and the safety devices are also shown in the Figure 3. The whole experimental set up was kept inside a high tensile strength micro alloy steel tanks which covers the experimental setup from all sides. In order to prevent damage under any accident, 6 mm thick MS sheet barricades were provided around the experimental set up.

As the temperature of PT is expected to reach 1000°C, the temperature of PT is measured with mineral insulated ungrounded K-type thermocouples of 0.5 mm outer diameter while J-type thermocouples of 1 mm outer diameter are used for CT. All the thermocouples were calibrated before the use. The thermocouples were mechanically fixed on the outer surface of the PT and CT with the help of 8 mm × 4 mm × 0.1 mm thick Zircalloy foils. A thin groove of 0.1 mm depth and 10 mm length was made longitudinally on the outer surface of tube. The thermocouple tip is placed in the groove. It is covered by 8 mm by 3 mm zirconium foil, which is spot welded to the tube. The material of tube as well as of foils, being the same one, the weld surfaces remain intact at all temperature. At any axial location of tube six thermocouples are fixed at an angular interval of 60° both on PT and CT. The location of thermocouple and potentiometer for displacement measurement are shown in Figure 4. For the radial expansion measurement contact type potentiometers are used in the four directions, i.e. two in vertical plane and rest two is in the horizontal plane as shown in Figure 4(b). The potentiometers were not in direct contact with the PT as the temperature of PT is expected to reach up to 800°C. Direct contact of potentiometer probe and PT surface may lead destroy electronic circuit of potentiometer. So the Ceramic rods were used between the potentiometer tip and PT. At the measuring location a hole of 2 mm diameter is drilled in the CT to pass ceramic rods of 1 mm diameter (Figure 4(a)). A ceramic rod is passed through the hole in such a way that one end is in contact with the PT and the other end was attached to the potentiometer. This protects the electronic circuit of potentiometers from high temperature. The potentiometers are fixed on a platform outside of the tank in all four directions. This type of arrangements were provided at the three axial stations at 100 mm, 500 mm and 900 mm from rectifier ends of the test section as shown in Figure 4. The PT is fixed with the help of two vertical stands. The concentricity of PT and CT is checked with the help of vernier scale. CT is completely wrapped by ceramic fibers to minimize heat loss from it. The thermocouples and potentiometers were connected to the Data Acquisition System (DAS). The temperature and potentiometer data is recorded at an interval of 100 mS using a DAS made by National Instruments, USA.

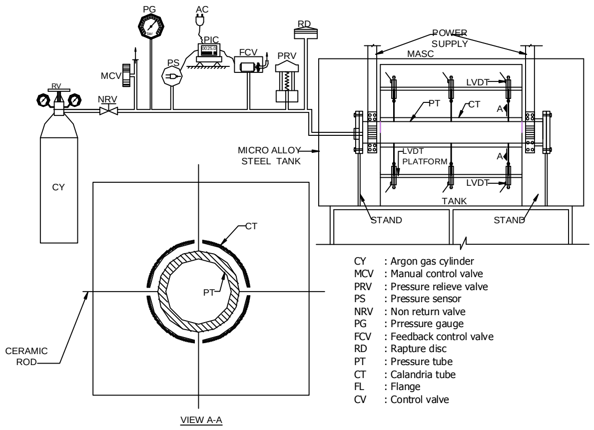

Fig. 3 Schematic of the Test Setup for ballooning while CT is wrapped by ceramic fiber

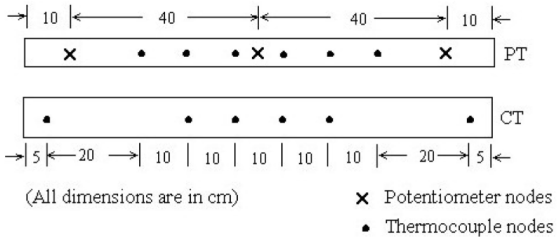

Fig. 4(a) Axial stations of thermocouples and potentiometers

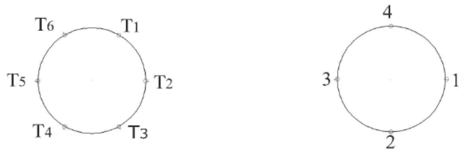

Fig. 4(b) Thermocouple nodes and LVDT Positions on tube circumference

B. B Ballooning deformation set upwhile CT is submerged in water

Later on the experimental set-up was modified to conduct experiments while CT is submerged in water. The experimental set up is shown in Figure 5. The instrumentation and control for this experiment was same as the previous one. In this experiment, additional measures were taken to measure the deformation while the PT was submerged in water. For the radial expansion measurement potentiometers are used in the four directions, i.e. two in vertical plane and rest two is in the horizontal plane as shown in Figure 4. A hole of 2 mm diameter is drilled on CT for the insertion of ceramic rod for displacement measurement. A specially designed sleeve having rectangular cross sectional area was fixed over the CT. In the sleeve radial hole of 6 mm diameter was made in four perpendicular directions namely top, bottom and the two sides, which matches with the potentiometer positions as shown in Figure 4(b). A stainless steel pipe of 6 mm outer diameter is fixed in the hole of sleeve and to the tank surface. A ceramic rod of 2 mm diameter is passed through the tube and sleeve hole in such a way that one end is in contact with the PT and the other end is attached to the potentiometer tips (Figure 5). The potentiometers are fixed on a platform outside of the tank in all four directions. This type of arrangement was provided at the three axial stations at 10, 50 and 90 cm (from rectifier end) of the test section as shown in Figure 4. First the CT, with the sleeve attachment, is fixed in the tank aligning with the side wall holes. The concentricity of PT and CT is checked with the help of vernier scale. Water is filled in the tank upto 0.4 m height from the base of the tank, thus CT is submerged in the water.

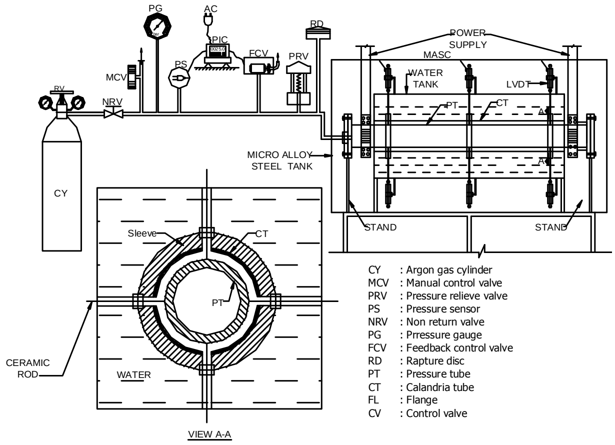

Fig. 5 Schematic of the Test Setup of ballooning experiment

III. RESULT AND DISCUSSION

Two sets of experiments were carried out for the ballooning of PT at 20 bar pressure. The experiment was conducted in two steps. The first experiment was carried out by covering the CT by ceramic fibers. The objective of this experiment was to measure PT ballooning (radial deformation) behaviour of the PT. the Objective of second experiment, CT submerged in water was to study dissipation of heat from PT to water moderator and boiling phenomena at the outer surface of CT. The experimental observations of both the experiments are presented in the following sections.

A. Ballooning of PT at 20 bar while CT wrapped by ceramic fiber

This was the first experiment on ballooning of PT. The objective of this experiment was to measure pressure tube deformation during ballooning. The PT is heated slowly and waited until the tube attained steady state temperature of about 300°C. This is done to obtain the normal operating temperature of nuclear reactor. In the preliminary heating period, the reading of all the thermocouples and the potentiometers are checked. The PT is pressurized to 20 bar. The ramp power supply was increased to 17 kW. The temperature of PT and CT recorded at four and eight axial locations respectively. The experiment was continued till the PT touched the CT. After this point, the power supply was continued for some more time and rectifier was switched off at 450 seconds and pressure was released. The radial displacement along four perpendicular directions at all three axial stations at 10, 50 and 90 cm from rectifier ends are shown in Figure 6(a) to 6(c). The potentiometers were fixed in such a way that it can record both inward and outward radial displacement. The initial displacement was set to zero at the beginning of the experiment when the PT was free from deformation. In all three figures it can be observed that there is no appreciable displacement up to 60 seconds. After 60 seconds one can observe a negative displacement of the potentiometer placed at the top (node position '4') of the PT at all axial locations. This displacement is relatively higher at the centre (location 50 cm) than those placed at the sides. The negative displacement can be attributed to initial sagging of the PT due to temperature, which takes place around 500°C [9]. This causes the inward movement of the PT which shows a negative displacement. The temperature rise of PT and CT at 35 cm and 65 cm are presented in Figures 7 and 8. Figure 6 also infers that ballooning initiates after 100 second at all three stations. The temperature of PT at the time of ballooning initiation is about 665°C. After ballooning initiation rate of deformation is very fast. It can be observed that the maximum displacement occurs at the centre of the test section. It is important to note that the first contact takes place at around 160 seconds at the locations 50 cm. After the PT-CT contact, there is further deformation of the PT at the central location, which is attributed to the combined deformation of the PT-CT after the contact. The combined PT-CT deformation after PT-CT contact is very small in comparison to the initial deformation. From Figure 6, it is clear that initial contact takes place near to the centre and gradually expands to the sides. The deformation at locations at 10 cm and 90 cm (i.e. near both ends) continues to about 300 seconds. The PT-CT contact takes place at 10 cm in 230 seconds and at 90 cm location in 190 seconds. From Figure 6, it was clear that the maximum ballooning takes place in central portion of the test section. The temperature rise of PT and CT is shown in Figure 7(a)-7(c). The temperature rise rate of PT is around 3.0°C/s i.e. almost constant up to 100 seconds. After 100 seconds the rate of temperature rise decreases in the PT. The temperature of the PT reaches a maximum at all locations and thereafter sudden drop is observed and finally remains almost constant. 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. As the temperature of the PT increases, the radiation heat loss to the CT increases. Initially up to 60 seconds the rate of temperature rise of CT is very slow (Figure 7(b)) after that it increases steadily up to 150 seconds due. The maximum PT temperature at location 35 cm is observed at 150 sec when PT CT contact takes place after that sudden drop in the PT temperature at PT_1 and PT_6 is observed and sudden temperature drop at PT_3 and PT_4 is not observed This means complete contact is at the top portion of PT is first observed. The circumferential

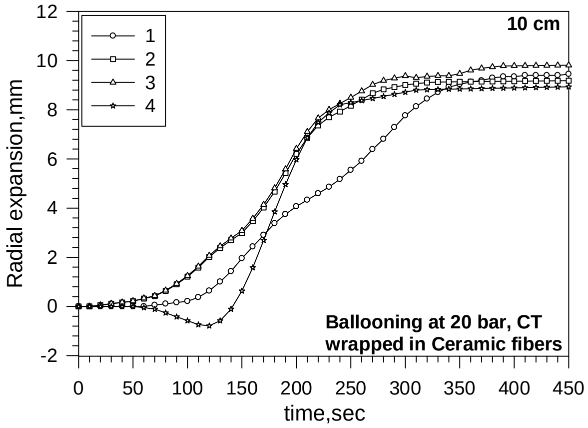

Fig. 6(a) Radial expansion of PT at axial stations at 10 cm

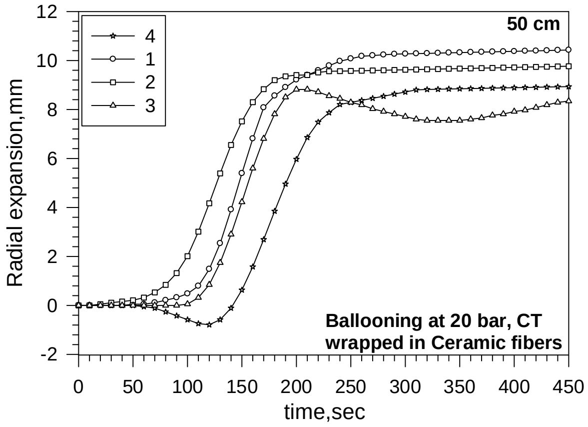

Fig. 6(b) Radial expansion of PT at axial stations at 50 cm

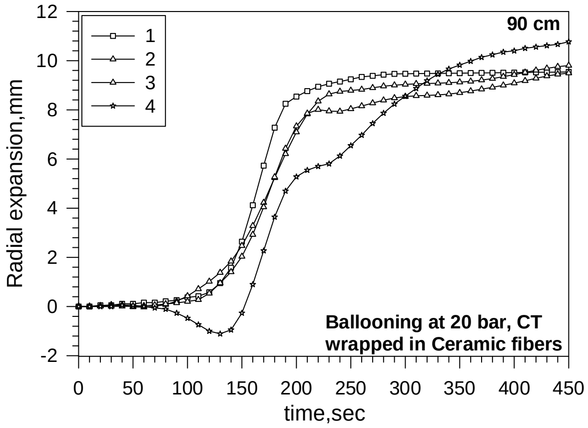

Fig. 6(c) Radial expansion of PT at axial stations at 90 cm

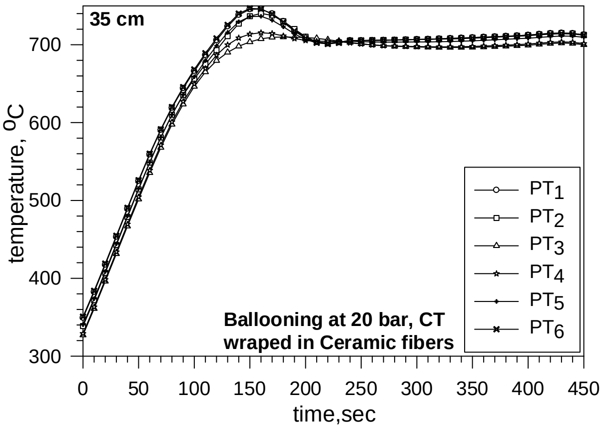

Fig. 7 Temperature variation of the PT with time at 35 cm from rectifier end

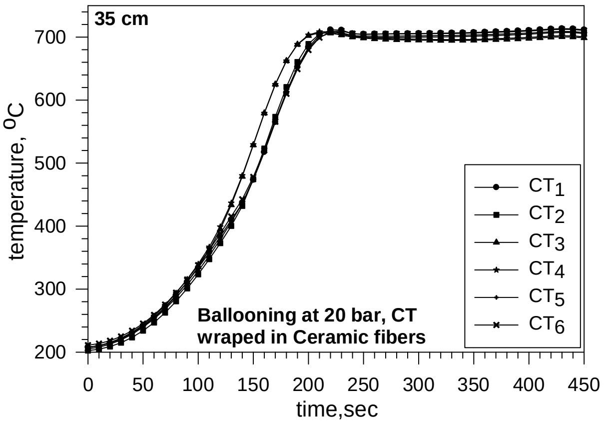

Fig. 7(b) Temperature variation of the CT with time at 35 cm from rectifier end

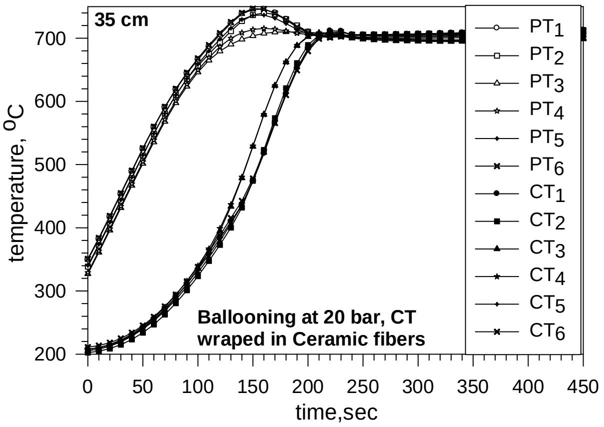

Fig. 7(c) Temperature variation of the PT-CT with time at 35 cm from rectifier end

temperature variation of PT and CT at location of 35 cm are shown in Figures 8(a)-8(c). Similar sudden temperature drop of PT (PT_1 and PT_6) is also observed at the location 65 cm at 160 seconds. As soon as PT contacts the CT, the temperature of CT also shoots up and ultimately temperature drops and finally PT and CT temperature becomes same and steady state

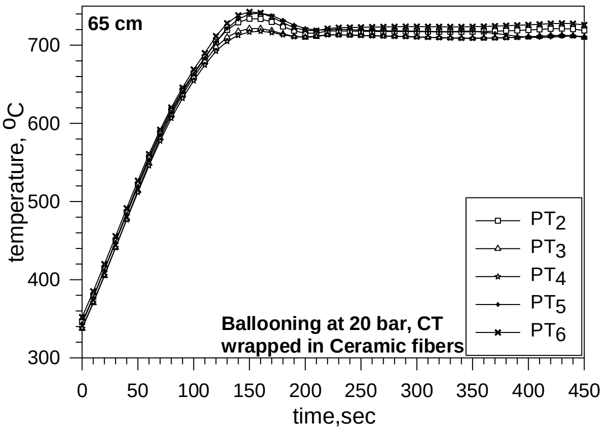

Fig. 8(a) Temperature variation of the PT with time at 65 cm from rectifier end

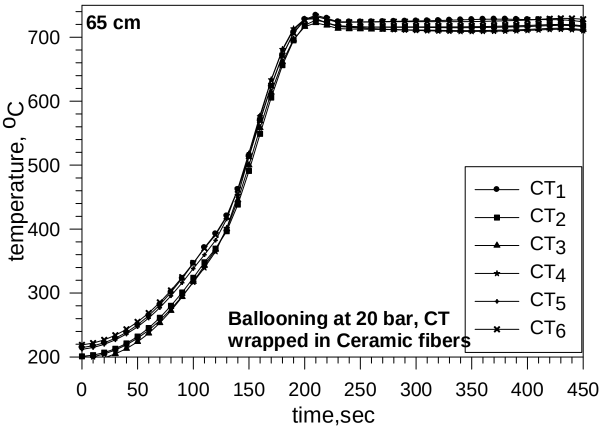

Fig. 8(b) Temperature variation of the CT with time at 65 cm from rectifier end

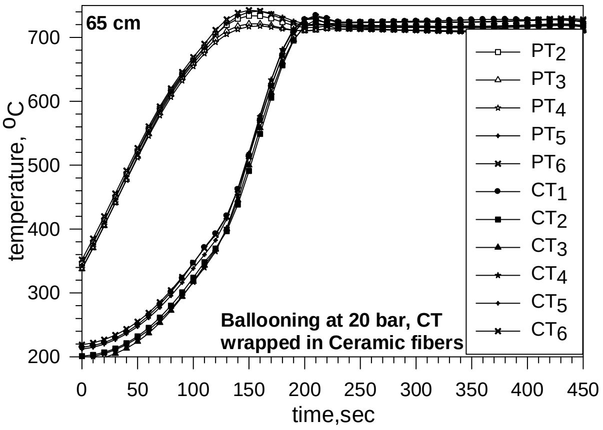

Fig. 8(c) Temperature variation of the PT-CT with time at 65 cm from rectifier end

is achieved between PT and CT. Once ballooning starts, the annular gap between PT and CT decreases, which causes higher rate of heat transfer from PT to CT and causes the temperature rise of the CT. This is clearly demonstrated in Figure 7(b). The PT temperature attends a maximum of 750°C and then deceases to about 700°C after the PT-CT contact, which takes place at 180 seconds. From Figure 6(a) it is clear that the PT temperature remains constant at 700°C as long as the power supply is on. A closer look at CT temperature profile in Figure 6(b) also indicates that the CT temperature also remains constant at 700°C after 240s. Figure 6(c) shows the temperature rise of PT and CT on same figure. From this figure it could be concluded that the PT-CT contact is complete after 240 seconds at the axial location at 35 cm from the rectifier end. A similar temperature variation of PT and CT is observed at axial location 65 cm from rectifier end. However, it can be observed that the temperature rise of CT faster than that at location 35 cm. The CT attains 700° C at around 180 seconds and remains constant. Moreover the PT and CT temperature remains constant at 700°C from 180 seconds still the power supply was there. After the completion of the experimental investigation, the PT-CT assembly was dismantled. It was observed that PT and CT were fused to each other and there was difficulty in distinguishing the PT and CT. The photograph of CT pre-experiment is shown in the Fig. 9.

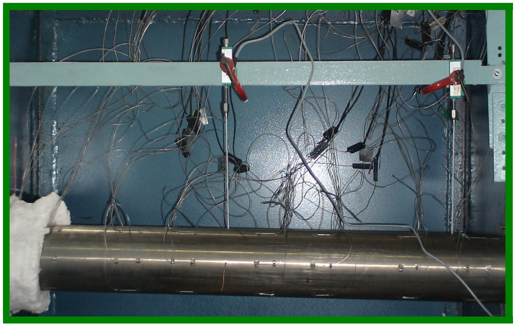

Fig. 9 Photograph of the state of CT before ballooning experiment

B. Ballooning deformation of PT at 20 bar while CT is submerged in Water

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 300°C. This is done to obtain the normal operating temperature of a nuclear reactor. In the preliminary heating period, the reading of all the thermocouples and the potentiometers were checked. The PT was pressurized to 20 bar with Argon gas and maintained at this pressure throughout the experiment. After obtaining the steady state temperature close to 300°C, the ramp power of 17 kW applied to heat up the test section. The experiment was continued till PT-CT contact was fully established and the corresponding temperature and displacement were recorded.

The radial expansion of PT at same three locations measured in experiment no. 1, are shown in Figure 10. In all three figures appreciable deformation was observed after 140 seconds. The temperature of PT at the time of ballooning initiation is 685°C, which is same as in the case of experiment set 1. As compare to the previous experiment, negative displacement of the potentiometer were observed at the top (node position ‘4’) of the PT at all axial locations. But the magnitude of negative deformation is very less. These figures clearly show that the maximum radial expansion of PT was not at the same position at three axial location test section. The maximum deformation of PT is 7.4 mm at position ‘3’, 8.3 mm at position ‘2’ and 8 mm at position ‘1’ at locations 10 cm, 50 cm and 90 cm respectively. But it is clear that the whole tube has ballooned and at the centre maximum ballooning is observed. First PT-CT contact is at 260 second when the expansion of tube is more than 8.22 mm at position ‘2’ which is at the side of the tube.

The average temperature rise of PT and CT at all axial locations are shown in Figs. 11 and 12 respectively. In this experiment the PT temperatures were measured at five axial locations namely at 25, 35, 45, 55 and 75 cm from rectifier end. One can observe that at the beginning the rate of temperature rise of PT and CT are linear. After about 185 seconds, the average rate of temperature rise of CT at axial location 55 cm is faster than other axial locations. It is important to note that CT attains a maximum temperature of around 100°C and then remains constant. This indicates that the contact is near about this location. From Fig. 11 one can observe that the rate of temperature rise of PT was very fast (about 2.9°C/sec) up to 185 seconds and after that gradually the rate of temperature rise decreases and reaches a maximum and then starts to decrease. When the PT and CT are relatively low temperature, convective heat transfer is the dominant mode of energy transfer from PT to CT. The temperature difference between the PT and CT is low; hence heat transfer from the PT to CT is low. As a result most of the heat generated in the PT contributes for temperature rise. As the PT temperature increases, gradually radiative heat transfer from PT to CT increases, which causes the decrease in temperature rise of the PT. When the PT touches the CT, the heat transfer is by conduction, which is much higher than the other modes of heat transfer. This causes a temperature drop of the PT. Examining the average temperature rise of CT (Fig. 12), one can see that the rate of temperature rise is not the same at all axial locations. The temperature rise is higher at the centre than the end locations. This could be attributed to end losses at both the ends of the test section. The temperature profile of all thermocouples of the PT and CT, at axial location 55 cm, near which a possible PT-CT contact had taken place, are shown in Figs. 13 and 14 respectively. Figure 14 reveals that the initial temperature rise of the CT is almost linear up to 185 seconds at all axial 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 3 and 4 (bottom two thermocouples) after 185 seconds is higher than other thermocouples and reaches a temperature of about 100C, which is the boiling temperature of the water at ambient pressure. This clearly indicates that PT-CT contact location is at the bottom of the PT. One can observe that after PT-CT contact there is a temperature drop at all circumferential nodes of the PT. This is due to high heat transfer rate from PT to CT. CT temperature profile at 55 cm location also confirms (Fig. 14) that maximum CT temperature

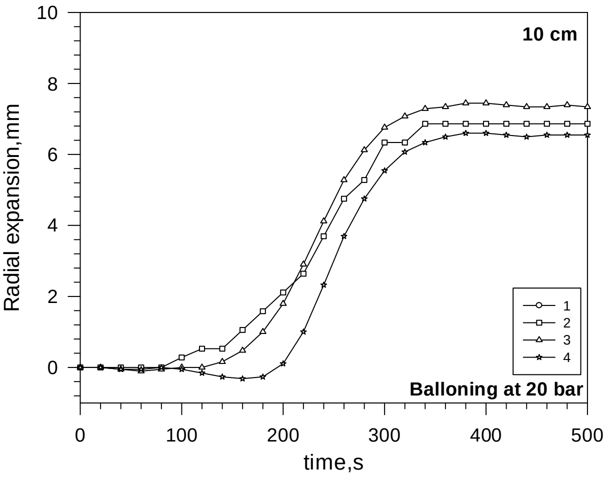

Fig. 11(a) PT circumferential deflection at 10 cm from rectifier end

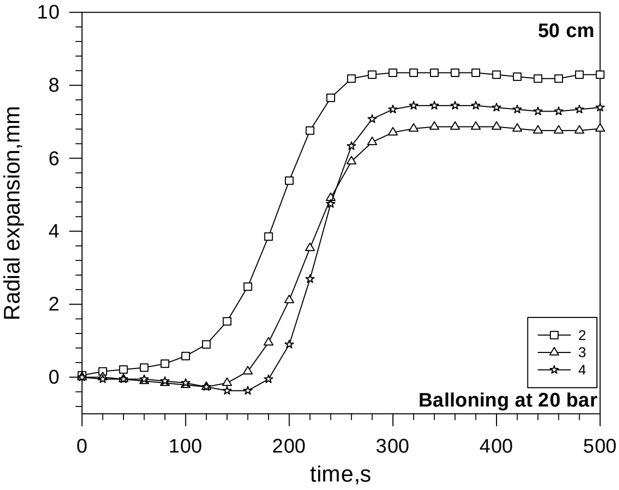

Fig. 11(b) PT circumferential deflection at 50 cm from rectifier end

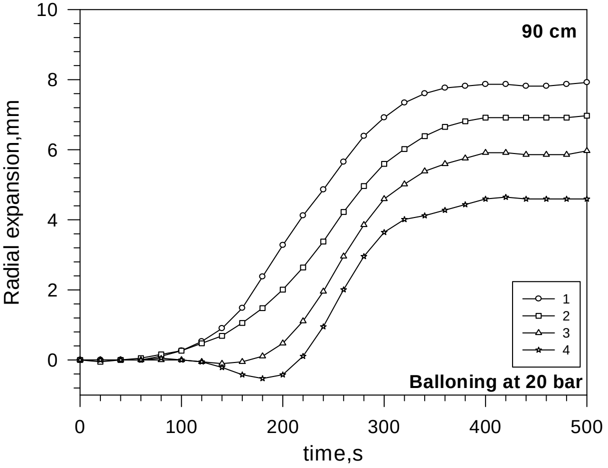

Fig. 11(c). PT circumferential deflection at 90 cm from rectifier end is observed at 165 seconds. PT-CT contact took place around 265 seconds when the PT temperature was 677°C. Once the PT touches the CT, there was no further deformation at the bottom location. The finding of the experimental investigation is summarized in table 1.

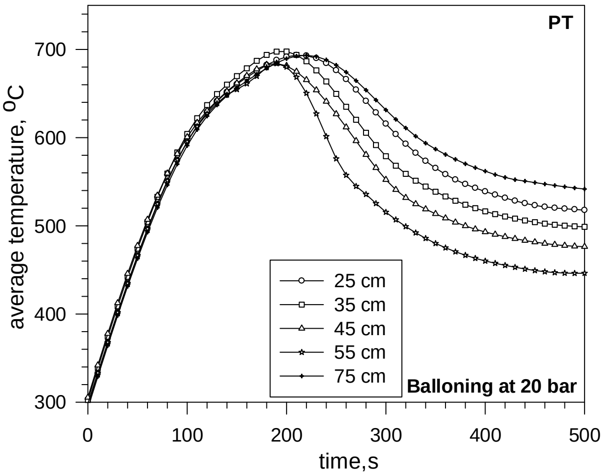

Fig. 12 Average PT temperature of at 20 bar pressure

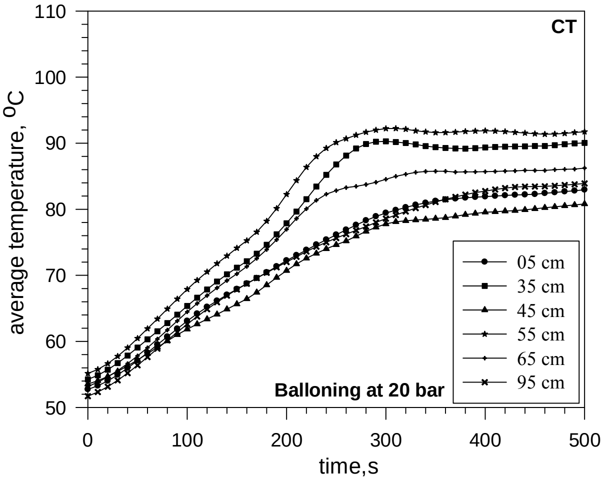

Fig. 13 Average CT temperature at 20 bar pressure

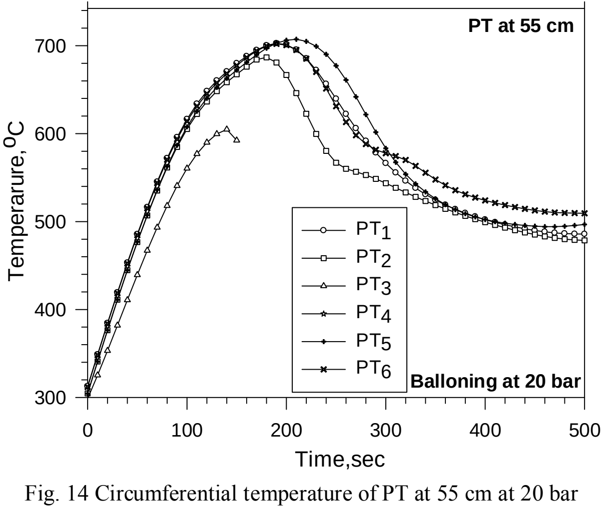

Fig. 14 Circumferential temperature of PT at 55 cm at 20 bar

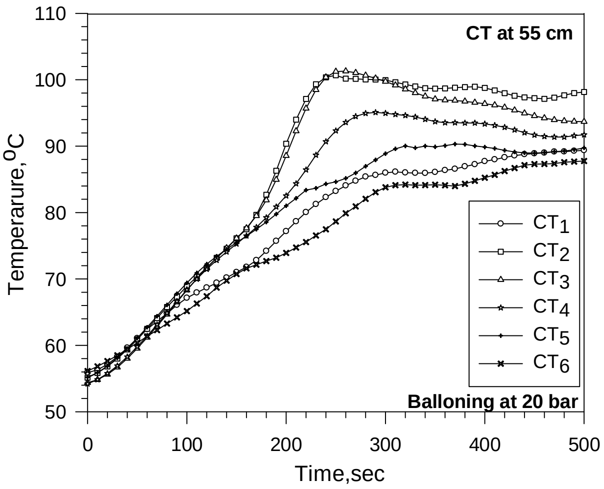

Fig. 15 Circumferential temperature of CT at 55 cm at 20 bar

TABLE I TEST SUMMARY OF EXPERIMENT

Condition of exp.	Power (kW)	Initial PT Temp. (°C)	initial average heating rate of PT (°C/sec)	Ballooning Initiation temp (°C) and time	Contact temp. (°C) and time
CT wrapped by ceramic fiber	26.7	290	2.4	450°C at 60 sec	585°C At 200 sec
CT submerged in water	17	300	2.85	600°C at 80 sec	710°C At 265 sec

IV. CONCLUSION

The postulated loss of coolant accident in Indian PHWR has been simulated at IIT Roorkee to investigate the ballooning of PT in case of LOCA using same pressure tube used in the Indian nuclear reactor channel. From the investigation the following salient features could be concluded:

- Ballooning starts at a temperature around 665°C. In the present experiment it started at around 150 seconds after the commencement of the heating. The time could be different if the heating rate is altered.
- The total duration of the ballooning was about 30 second.

- It is observed that once PT touches the CT, there is no further rise in PT temperature.
- The maximum PT temperature was below 750°C.
- At 20 bar internal pressure while CT was submerged in water and initial heat up rate of 2.85°C/sec, the PT ballooning contact is found to take place at 710°C temperature with the initiation at 665°C.
- The average of strain rates is found to be 0.116% per second in ballooning deformation at 20 bar pressure.

From the above findings one could conclude that the ballooning effect can protect the nuclear reactor from meltdown in case LOCA. 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 event.

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