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Experimental investigation of symmetric and asymmetric heating of pressure tube under accident conditions for Indian PHWR

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HIGHLIGHTS

- Circumferential temperature gradient for asymmetric heat-up was 400 °C.
- At same pressure ballooning initiates at lower temperature in asymmetrical heat-up.
- At 1 MPa ballooning initiated at 408 °C and with expansion rate of 0.005 mm/s.
- At 2 MPa ballooning initiation at 330 °C and with expansion rate of 0.0056 mm/s.
- For symmetrical heat-up strain rate was 10 times faster than asymmetric heat-up.

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ABSTRACT

In pressurized heavy water reactor (PHWR), under postulated scenario of small break Loss of Coolant Accident (LOCA) coincident with the failure of Emergency Core Cooling System (ECCS), a situation may arise under which reduction in mass flow rate of coolant through individual reactor channel can lead to stratified flow. Such stratified flow condition creates partial uncover of fuel bundle, which creates a circumferential temperature gradient over PT. The present investigation has been carried out to study thermo-mechanical behaviour of PT under asymmetric heating conditions for a 220 MWe PHWR. A 19-pin fuel simulator has been developed in which preferential heating of elements could be done by supplying power to the selected pins. The asymmetric heating of PT has been carried out at pressure 2 MPa and 1 MPa, respectively, by supplying power to upper region heating elements thus creating an half filled stratified flow conditions. The temperature difference up to 425 °C has been observed along top to bottom periphery of PT. A comparison is made between thermo-mechanical behaviour of PT under asymmetrical and symmetrical heat-up, expected from a large break LOCA condition. The radial expansion rate during symmetrical heating is found to be much faster as compared to that for asymmetric ballooning of PT at the same internal pressure. Integrity of PT is found to be maintained under both loading conditions. Heat sink around of test section, simulating moderator is found to be helpful in arresting the rise in temperature for both fuel pins and PT, thus establishing moderator as an effective heat sink under accident conditions.

1. Introduction

In 220 MWe, PHWR heavy water is used as coolant and flows through 306 horizontal channels housed in calandria vessel and submerged in heavy water. The coolant flows through half of the channels in one direction and in remaining 153 channels in opposite direction. The nuclear heat is removed from fuel bundles by heavy water coolant in primary circuit and is transferred to secondary circuit of steam generators.

During normal operation, creep sagging of pressure tube is a common problem for horizontal tube type reactors. Under a very low probability event (10^{-6} per reactor year), postulated LOCA along with failure of ECCS may lead to slow fuel heat-up which eventually heat the PT. Based on the internal pressure conditions

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PT may either balloon or sag. Circumferential heat-up of PT is again dependent on the break size causing LOCA. For a small break the depressurisation rate is slower and the flow rate through the channel is low. This situation leads to flow stagnation and stratification causing partial exposure of fuel bundle. Under this situation a circumferential heating is imposed on PT. The upper side of PT gets heated up more from the exposed channel as compared to lower side where fuel bundle is still submerged. For a large LOCA as the flow rate is high such condition does not arise, a circumferential symmetrical PT heat-up is expected. Brown et al. (1984) analyzed the PT deformation in CANDU reactors for a large LOCA combined with a loss of emergency core coolant injection system. Kohn et al. (1985) made an analysis for a case when pressure is still high enough in an early heated channel, PT can balloon uniformly and contact the calandria tube, establishing an effective heat transfer path to the moderator. The pressure tube integrity was assessed by Gulshani (1987) for a CANDU reactor channel experiencing a small LOCA coincident with total loss of ECCS. During the study of PT ballooning by creep, Shewfelt et al. (1984) observed that a rise in temperature above 450 °C would produce rapid creep deformation in the pressure tube and internal pressure generates large hoop stresses deforming it plastically outwards. Shewfelt and Lyall (1985) experimentally studied the longitudinal creep behaviour of Zircaloy at relatively high temperature of 650–950 °C. At this high temperature, the strain caused by the fuel bundle weight and self-weight of the pressure tube is enough to cause sagging at the unsupported region. A series of experiments were carried out on pressure tubes by Shewfelt et al. (1984) and Gillespie et al. (1987) to estimate the ballooning and sagging behaviour separately. Yuen et al. (1988) experimentally analyzed the structural integrity of PT and assessment of moderator as a heat sink has been carried out for CANDU reactor for circumferentially symmetric and asymmetric heating heat-up conditions. Gupta et al. (1996) observed that during postulated low frequency events like LOCA along with the failure of ECCS, the cooling environment for the bundles degrade and this results the heat-up of the fuel bundles which in turn heats up the PT through radiation heat transfer. The prediction of creep deformation of PT used in Indian PHWR under simultaneous internal pressure and weight has been reported by Majumdar et al. (2004). The sagging and ballooning of PT under LOCA at different heat-up rates was carried out by Nandan et al. (2010).

It has been found that the thermal behaviour of fuel channel under asymmetric heat-up for Indian PHWR has been not discussed in open literature. Hence for understanding the behaviour of PT of Indian PHWR under LOCA, a series of experiments has been carried out using 19-pin fuel element simulator of capacity 17.5 kW (approx. 5% of nominal power). The temperature profiles and radial expansion rate of pressure tube under simulated full and partially voided conditions at different internal pressure conditions have been studied experimentally and discussed in the paper.

2. Experimental set up and procedure

The schematic diagram of experimental set-up is shown Fig. 1. The set-up consists of a mild steel tank of 1000 mm × 500 mm × 500 mm size with 5 mm sheet thickness. The calandria tube (CT) having 1000 mm length was fixed in the tank and the joint with the tank wall was made leak proof of water. The PT length was 1150 mm, out of that middle 1000 mm length was inside the CT and remaining 150 mm length was outside of the CT (75 mm on each side). A 19-pin fuel simulator of IPHWR with assembly in pressure tube is shown in Fig. 2. The total input power was distributed in the outer, middle and centre heating rod of simulator in ratio of 1.4:1.1:1, respectively. All the heating rods were connected in parallel arrangement and the above ratio of power distribution was attained by controlling the diameter of heating rod. The clad tubes were insulated from heater rod by compacted castable alumina (Al_2O_3). The technical details of test section are shown in Table 1.

PT has been pressurized up to 5.0 MPa pneumatic pressure to check any leakage from end flanges and pipe fittings. Two pressure switches were fixed in the pipe line to maintain the pressure inside the PT within of ±0.2 MPa through a feedback control system. During testing the pressure switches contained the pressure under the prescribed range and during experiments the excess gas was purged to maintain the pressure within the set range.

The temperature of PT was measured with mineral insulated ungrounded K-type thermocouples of 0.5 mm diameter while J-type thermocouples of 1 mm diameter were used for the temperature measurement of CT. All the thermocouples were calibrated before installation on the test section. To trace the temperature profile, thermocouples were located at five axial positions (Fig. 2) on PT and six axial locations on CT. For the installation of thermocouples a small grove of 8 mm × 4 mm × 0.1 mm was made on particular locations. The tip of thermocouples was inserted in small groves on tubes and was covered by zircalloy foils and subsequently the foils were spot welded over the surface.

In order to measure the radial expansion of PT during ballooning, contact type displacement transducers were used at three stations and at each station displacement was measured at top, two sides and at bottom positions. The radial displacement of the hot PT surface was transmitted to the potentiometer through a 1 mm diameter and 30 cm long ceramic rod. The holes were made at specific locations over CT to insert ceramic rod for radial displacement measurement during ballooning of PT. One side of this rod was rested on tube surface and another side was fixed with displacement transducer. To isolate the holes over CT from surrounding water, sleeves were placed on CT aligning with CT holes. Water sealant was injected between the junction of CT and sleeve to make it leak proof.

The heating of PT was carried out using a thyristor controlled 42KW (12 V/3500 A) rectifier. The power was transmitted to fuel simulator by mechanically clamping the bus bar with copper rod of fuel simulator. The output of all the thermocouples and potentiometers were recorded at every 0.1 second with the help of a data acquisition system.

First of all, the tap water was filled in the tank up to 400 mm height from the base of the tank submerging the CT. The water in the tank was heated to a temperature of 60 °C (normal operating temperature of moderator for 220 MW PHWR) using immersion heater, followed by the heating of PT with the rectifier. The moderator was periodically stirred manually while heating up-to 60 °C and moderator temperature was monitored using ungrounded T-type thermocouples located at three different locations. While pressurized heating of PT the moderator was not stirred. Initially PT was slowly heated to operating temperature and then a ramp of power was injected to simulate LOCA scenario. The pressure was maintained at desired value in PT by fine tuning of pressure switches and solenoid valves. The step input power was given to the test-section by injecting DC in the fuel bundle. The experiment was continued until complete contact of PT with CT was established. The corresponding temperature and displacement were recorded during the process at a time interval of 0.1 s.

3. Results and discussions

The results of the investigation for symmetric and asymmetric heating of PT have been discussed below. As the pressure tube and calandria tube circumferential temperature along the test section were quite similar and hence temperature distribution measured at

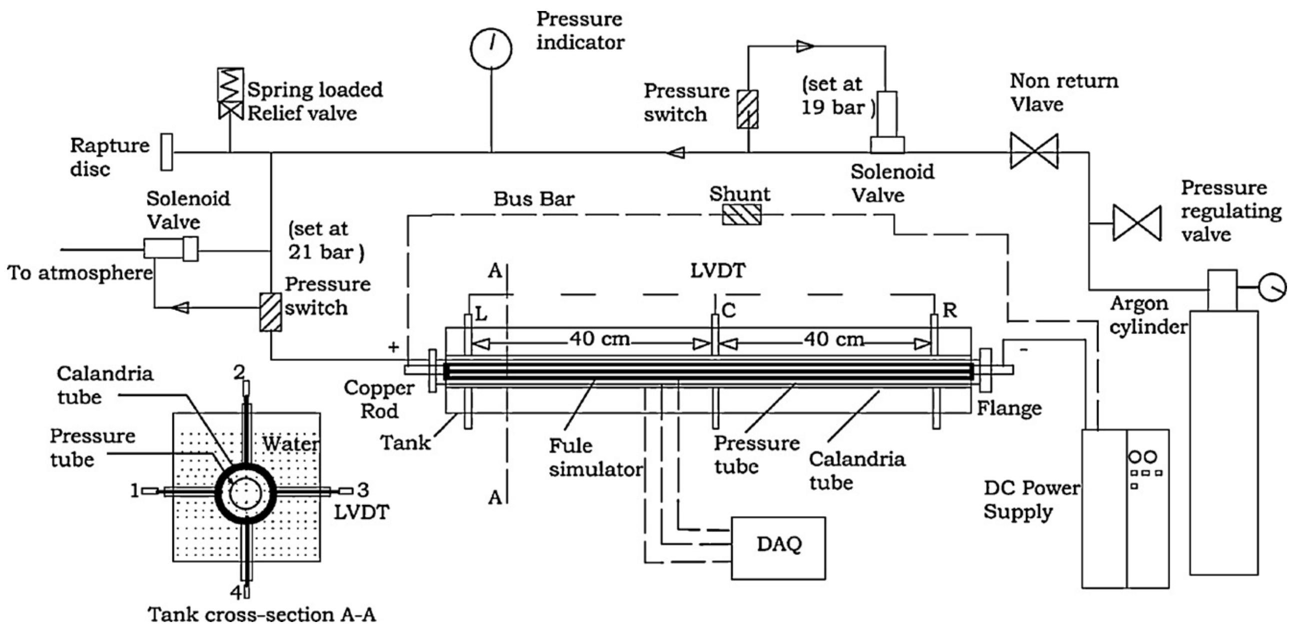


Fig. 1. Schematic diagram of experimental set up.

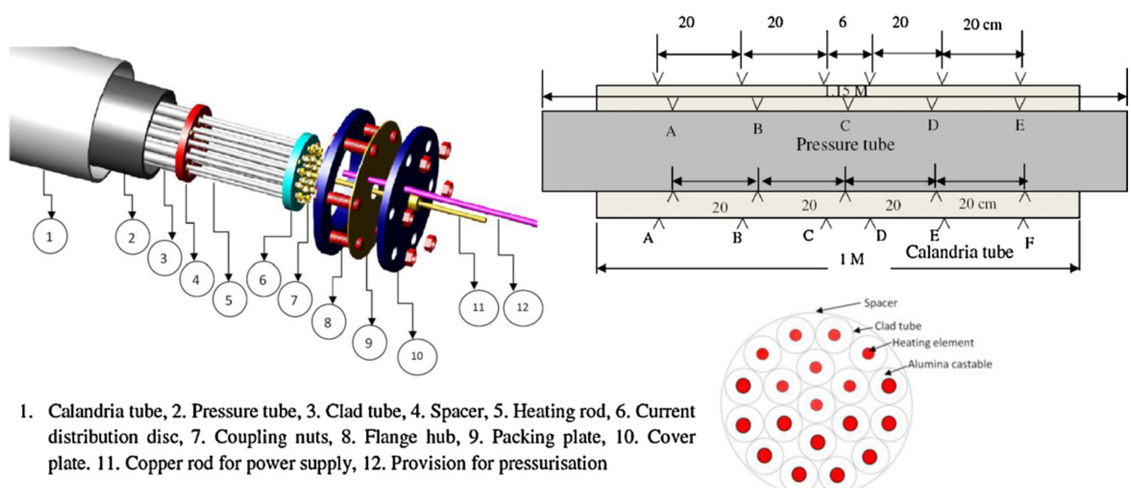


Fig. 2. Details of fuel simulator and location of thermocouples.

one of the section is described here. The range of operating parameters is given in Table 2. An investigation summary is furnished in Table 3.

The test-1 was carried out at 2.0 MPa pressure inside the PT to analyze thermal behaviour of pressure tube under fully voided condition by injecting a total ramp power of 17.5 kW to all the 19 pins of fuel simulator. The power transient is shown in Fig. 3. The ramp power of 17.5 kW was given after passage of 710 s of heating when average temperature at section-C was 300 °C. The Power input to PT was maintained approximately at 17.5 kW for the duration of 500 s of heating till beyond the complete contact of PT with CT was established.

The variation of temperature over periphery of PT and CT at centre location is shown in Fig. 4. After passage of 210 s of ramp, the temperature at upper periphery of PT was 590 °C while temperature at bottom was 500 °C. According to Kuehn and Goldstein (1976) this is due to increase in local equivalent thermal conductivity from top to bottom of PT. The average temperature rise rate after the ramp input was 1.08 °C/s and initiation of ballooning occurred at 638 °C temperature. The temperature rise rate for PT

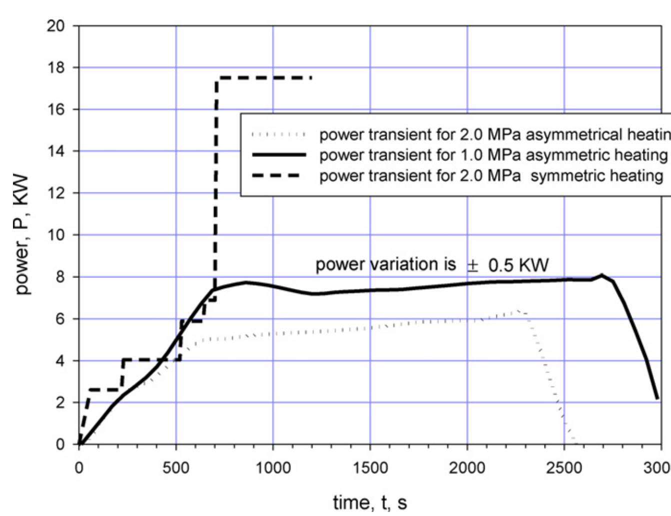


Fig. 3. Power transient during the experiments.

Table 1
Technical detail of various components.

Description	Diameter (d) mm	Thickness (t) mm	Length (L) M	Material composition	Emissivity (∈)	Density (ρ) kg/m^3	Thermal conductivity (K) W/m °C	Specific heat (C_P) kJ/kg K
Clad tube	15.7	0.75	0.9	SS-316	0.79	7850	21.4	0.5
Heating rod					0.79	7850	21.4	0.5
Outer rods	5	–	1	SS-316				
Middle rods	4.5		1	SS-316				
Centre rod	4		1	SS-316				
Pressure tube	90	4.03	1.15	Zirconium 2.5 wt% Nb	0.7 (outer surface) 0.4 (inner surface)	8570	19.54	0.328
Calandria tube	110	1.25	1	Zircaloy-2	0.4 (inner surface)	8583	15.42	0.3376
Alumina (castable)	5 mm (max)	–	–	Al_2O_3–90% SiO_2–2.3% Fe_2O_3–0.75% TiO_2–1.3%	–	2200	1.2	0.83
Spacer	81.2	10	–	Mild steel	–	–	–	–
Current distribution disc	70	10	–	Copper	–	–	–	–
Flange	145	10	–	Mild steel	–	–	–	–

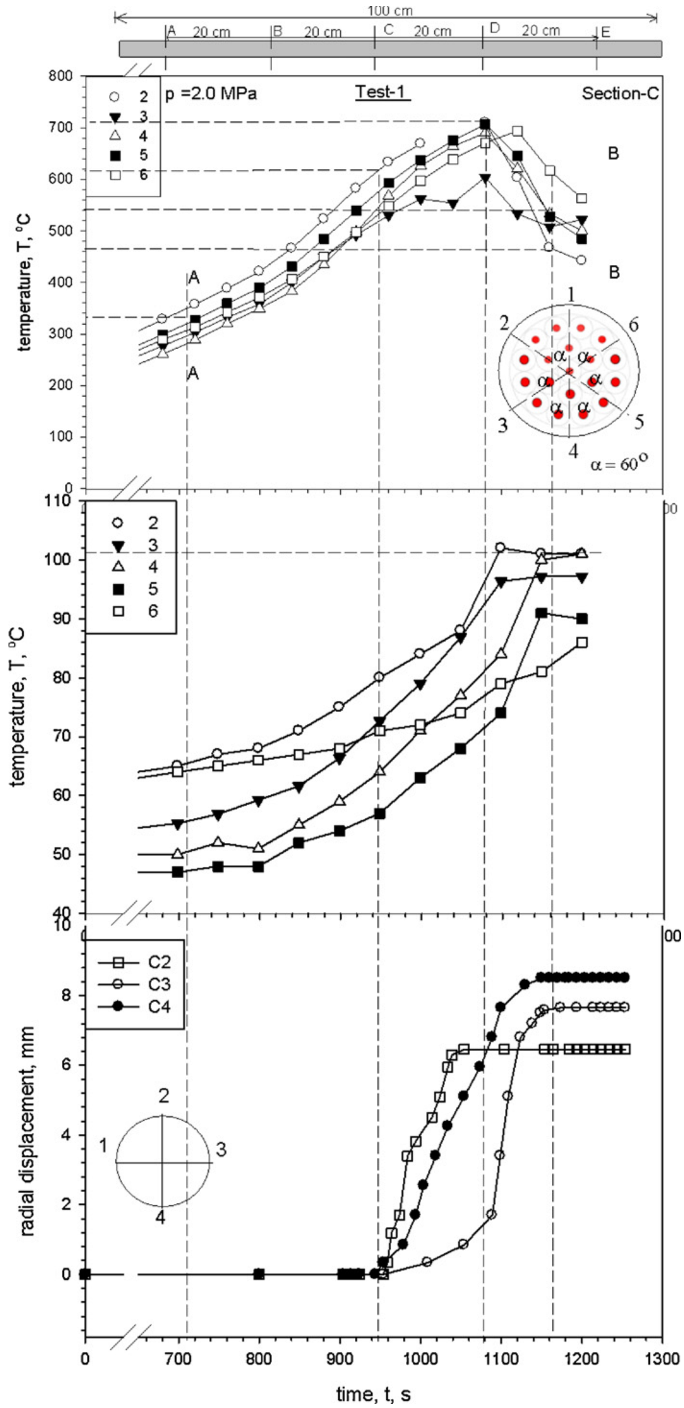


Fig. 4. Transient temperature and radial displacement under symmetrical heating at 2.0 MPa.

starts declining after passage of 245 s of ramp. The highest temperature attained by PT is 710 °C and then steep decrement in temperature has been observed. The reason for this behaviour is the reduction in gap between PT and CT which leads to an enhancement in radiative and convective heat transfer. After passage of 450 s of ramp, the temperature of PT declined to 467 °C at location 2 because of contact of PT was established with CT. Then the temperature of PT was stabilized due to balance between the heat generation and the dissipation of that to moderator in the tank. The temperatures at upper periphery of PT are still higher as compared to that at bottom because firm contact of PT with CT is not occurred at top. The firm contact of PT with CT at bottom was due to combined ballooning

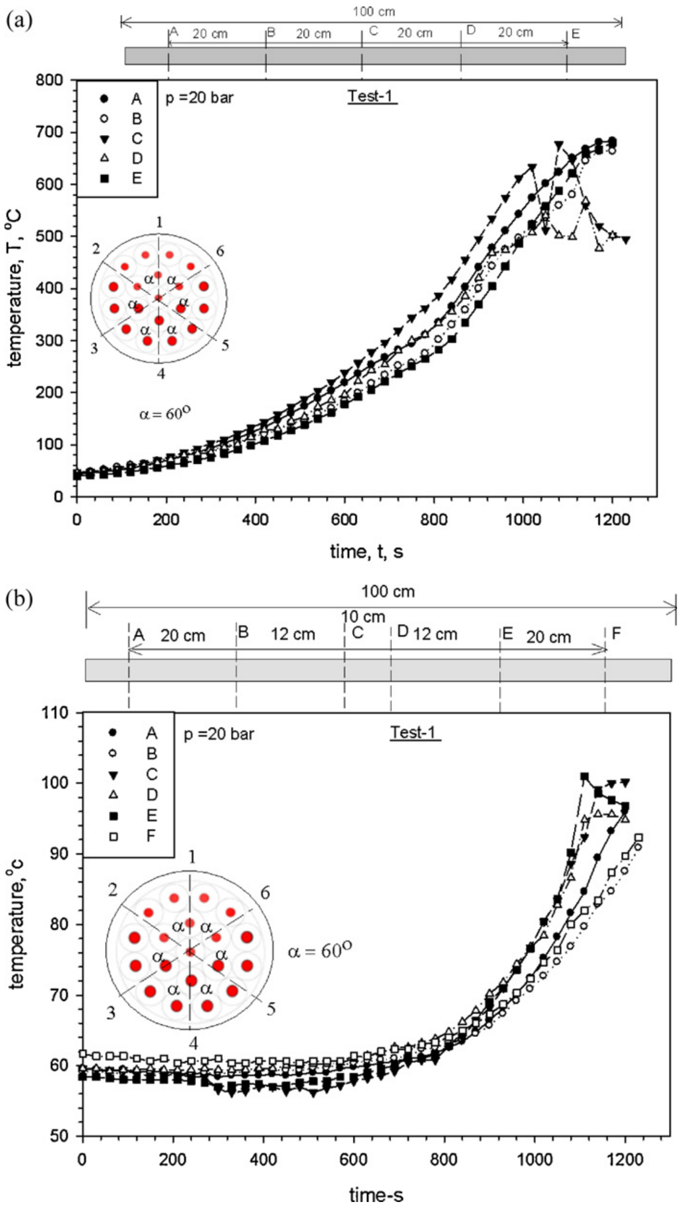


Fig. 5. Average temperature variations at each section of PT and CT.

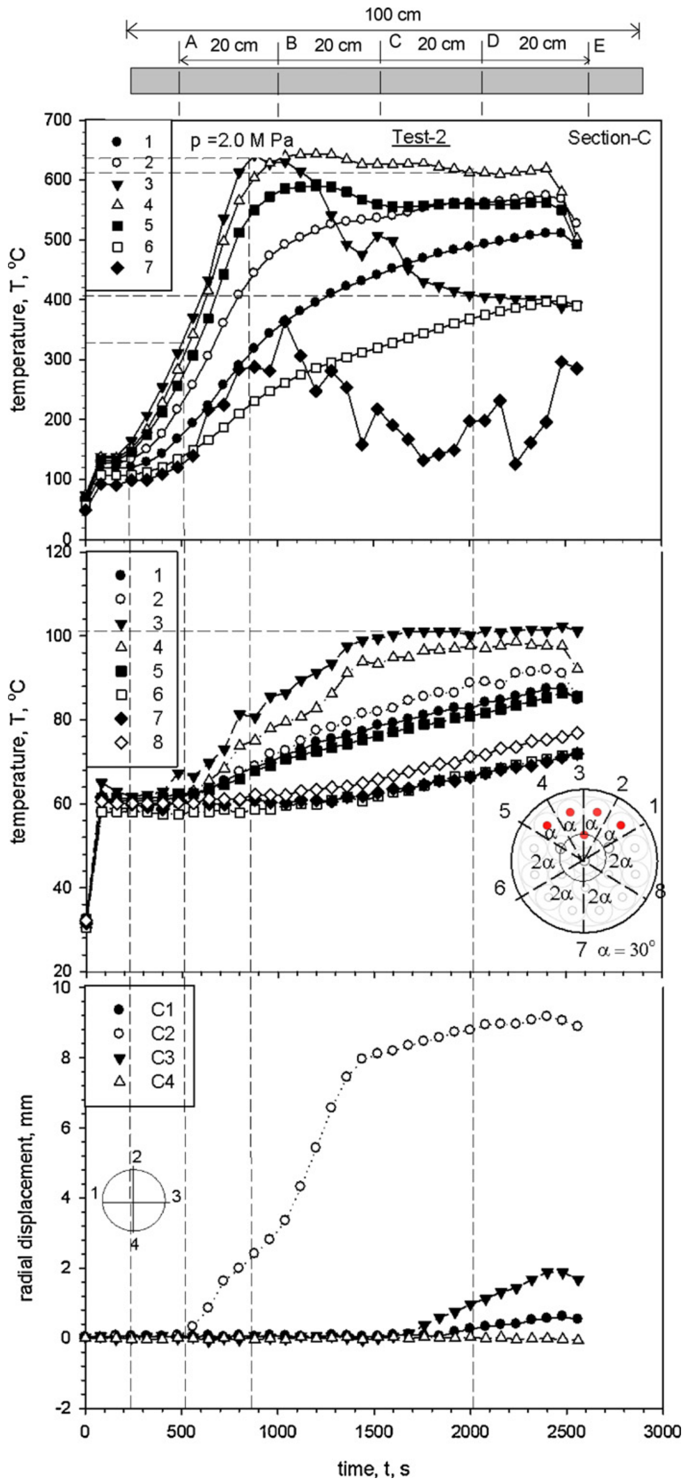


Fig. 6. Transient temperature and radial displacement under asymmetrical heating at 2.0 MPa.

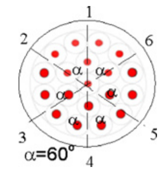
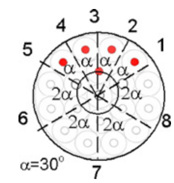
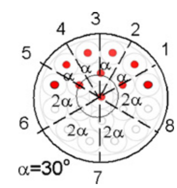
and sagging of PT under weight of fuel simulator. As shown in Fig. 4, the highest temperature attained by CT was 101 °C at location 2 and 4.

The response of displacement transducers shows that radial expansion at bottom and side of PT is around 8.5 mm but expansion at top is around 6.5 mm. The average rate of displacement by LVDTs is used as ballooning rate of PT. The ballooning rate was calculated in following way:

Ballooning rate = (final LVDT reading − initial LVDT reading)/time during ballooning. The ballooning rate at top of PT was at faster rate of 0.065 mm/s because of higher temperatures at upper periphery as compared to bottom and sides. The variation of average temperature at each section of PT is shown in Fig. 5(a). A steep decrement in temperatures at sections C and D has been observed after passage of 320 s of ramp and it stabilizes at around 490 °C due to firm contact of PT with CT. Similarly, Fig. 5(b) shows higher temperatures at sections C and D over CT as compared to other sections due to firm contact with PT and stabilized at around 100° C.

The test-2 was carried out at 2.0 MPa to analyze thermal behaviour of pressure tube under asymmetric heat-up condition by injecting ramp power of 5.5 kW to upper 5 pins of fuel simulator. The PT was heated symmetrically to 129° C and after passage of 208 s ramp power of 5.5 kW was injected in pins. The power transient during experiment is shown in Fig. 3. The PT ballooned from top and firm contact occurred with CT at location 3. Fig. 6 shows temperature variation along the circumference of PT at centre location. It can be observed that temperature at upper periphery of PT is significantly higher as compared to bottom. The temperature rise rate after ramp was 0.646° C/s and the highest temperature

Table 2
Experimental parameters.

	Activated pins	Power (kW)	Position of activated pins
Pressure (2.0 MPa)			
Test-1	19 (all)	17.5	
Test-2	5	5.5	
Pressure (1.0 MPa)			
Test-3	10	7.6	

difference of 400° C has been observed between top and bottom periphery of PT. The highest temperature attained was 640° C at locations 3 and 4 after passage of 652 s of ramp and then steep decrement in temperature has been observed. The reason was the enhancement in heat dissipation from PT to CT by combined radiation and convection due to reduction in gap between them. The temperature at location 3 declines to 410° C and then stabilized due to firm contact of PT with CT. On the other hand temperature at locations 4 and 5 are still 610° C and 560° C, respectively, because contact of PT with CT not yet occurred at these locations. Such situation of uneven strain and sharp temperature gradient from top to bottom of PT creates issues over integrity of pressure tube under high pressure. Due to firm contact of PT with CT, the temperature at locations 3 was significantly higher as compared to other locations over CT and stabilized at 100 °C. The response of displacement transducer shows that ballooning initiated at top of PT after passage of 302 s of ramp at 330° C and complete contact with CT occurred after 1802 s. The transducers located on sides of PT shown a radial displacement of 2 mm and 1 mm, respectively, and hence support no physical contact between PT and CT at these locations. After firm contact of PT with CT the temperature at location 3 has been stabilized because of heat balance between heat generation from fuel simulator to heat dissipation to moderator in tank.

The test-3 at 1.0 MPa was carried out to analyze thermal behaviour of pressure tube under asymmetric heat-up condition by injecting ramp power of 7.6 kW to upper 10 pins of fuel simulator. The PT was heated symmetrically to 180.5° C and after passage of 305 s ramp power of 7.6 kW was injected. The power transient during commencement of experiment is shown in Fig. 3. The PT ballooned from top and firm contact occurred with CT at locations 1 and 2. Fig. 7 shows temperature variation along the circumference of PT at location C. It can be observed that temperature at upper periphery of PT is significantly higher as compared to bottom. The temperature rise rate after ramp was 0.63° C/s and highest temperature difference of 425° C has been observed between top and bottom periphery of PT. The highest temperature attained was 701° C at location 1 after passage of 795 s of ramp and then steep decrement in temperature has been observed. The reason was enhancement in heat dissipation from PT to CT by combined radiation and convection due to reduction in gap between them. Due to firm contact of PT with CT the temperature at locations 1 and 2 decline to 447° C and 520° C, respectively. After contact of PT with CT the temperature at locations 1 and 2 has been stabilized because of heat balance between heat generation from fuel simulator to its dissipation to moderator in tank. On the other hand temperature at locations 3–5 are still in range of 600 °C because contact of PT with CT not yet occurred at these locations. Such situation creates a circumferential temperature gradient over PT and may lead to rapture under high pressure. Due to firm contact of PT with CT, the temperature at location 1 was significantly higher as compared to other locations over CT and then stabilized at 102° C.

Table 3
Summary of experimental results under symmetric and asymmetric heat-up.

Test No.	Activated pins	Power (kW)	Ballooning initiation temperature and time (after Ramp)	Max circumferential temperature gradient and ballooning rate mm/s at top of PT	Max temperature before contact and time (after Ramp) of contact
20 bar					
Test-1	19	17.5	638 °C 245 s	80 °C 0.065 mm/s	710 °C 450 s
Test-2	5	5.5	330 °C 332 s	400 °C 0.0056 mm/s	640 °C 1802 s
10 bar					
Test-1	10	7.6	408 °C 235 s	425 °C 0.005 mm/s	701 °C 1925 s

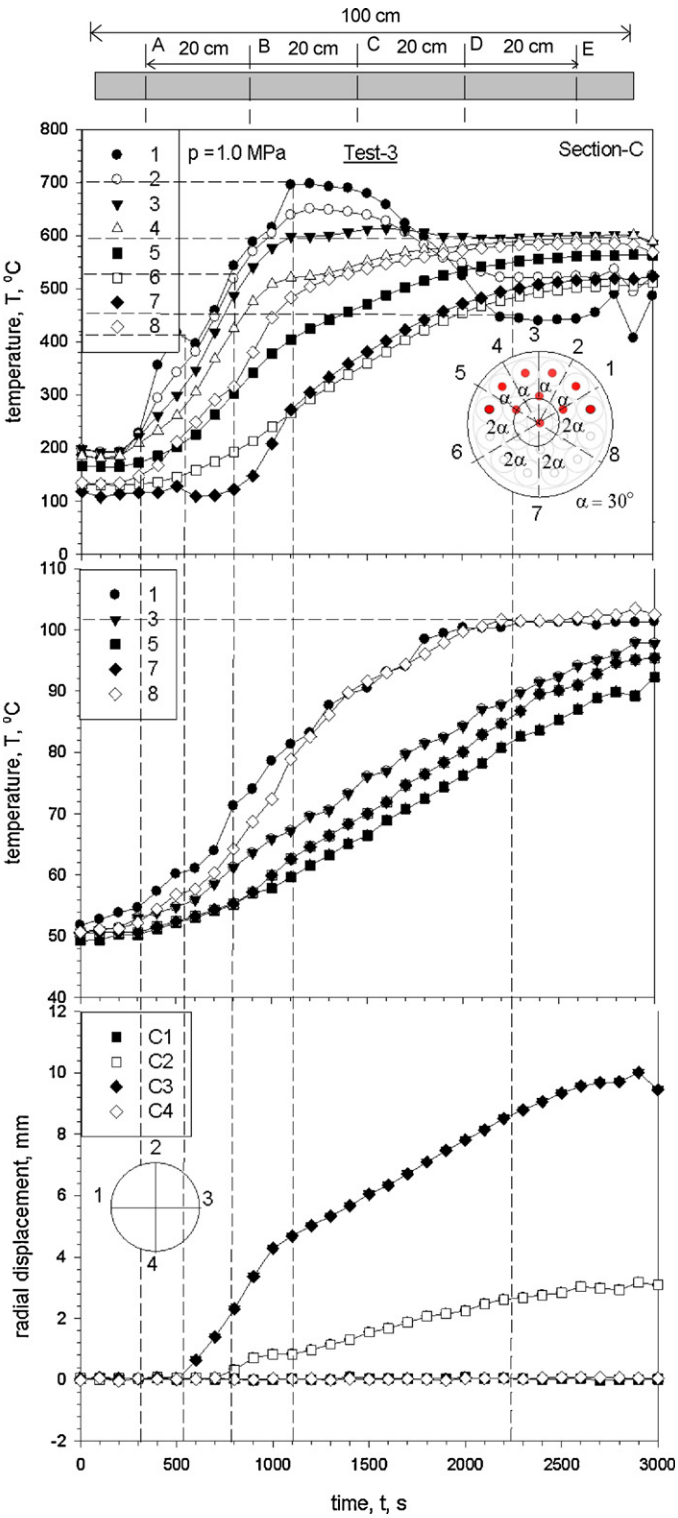


Fig. 7. Transient temperature and radial displacement under asymmetrical heating at 1.0 MPa.

The response of displacement transducer shows that ballooning initiated from side of PT periphery at location 3 after passage of 253 s of ramp at 408° C and complete contact with CT occurred after 1925 s of ramp. The transducers located on top of PT shown displacement after passage of 585 s of ramp at temperature 525° C. Initiation of ballooning from side releases stress over periphery of PT and hence ballooning from top delayed. It has been observed during asymmetrical heating that the un-heated bottom portion along periphery of PT delayed the creep deformation of heated top portion. Further the power input during asymmetric heating was 5.5 kW however for the symmetrical heat-up of PT the power input was 17.5 kW for the same internal pressure. These factors may have prompted high ballooning rate during symmetrical heating as compared to asymmetrical heat-up of PT.

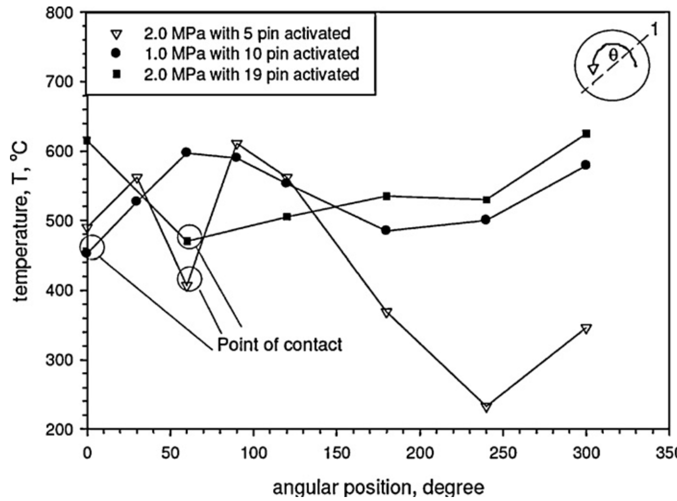


Fig. 8. Circumferential temperature over PT after contact with CT.

Fig. 8 shows circumferential temperature distribution over PT after contact with CT for symmetric and asymmetric heating. The angular positions are measured in anticlockwise direction with location 1 as reference. For symmetrical heat-up at 20 bar pressure, the temperature difference between point of contact and its adjacent locations was 150° C and temperature difference from top to bottom periphery of PT was 80° C. On the other hand for asymmetric heat up at 20 bar pressure with 8 pin activated, the temperature difference between point of contact and its adjacent locations was 215° C and the temperature difference from top to bottom periphery of PT was 380° C. Similarly for asymmetrical heating at 10 bar and 10-pin activation, the temperature difference between point of contact and its adjacent locations was 150° C and the temperature difference from top to bottom periphery of PT was 100° C. It can be analyzed that circumferential temperature over PT for 10 bar was quite higher as compared to 20 bar. The reason behind it was slower ballooning rate under 10 bar which leads to delayed heat transfer from PT to CT in radial direction. Further the contact conductance is proportional to internal pressure and hence at 20 bar the temperature at point of contact was lesser as compared to 10 bar. Due to abrupt change in temperature at adjacent locations over PT, the magnitude of thermal stress was quite higher in case of asymmetric heating at 20 bar pressure with 8-pin activation. Such scenario of combined thermal stresses and high pressure could leads to breaching of PT and responsible for contamination in open atmosphere.

4. Conclusion

To understand the thermo-mechanical behaviour and overall integrity of PT under different simulated voided conditions of the reactor channel, a series of experiments were conducted. Following conclusions are made from the study:

1. Circumferential temperature gradient during symmetric heating was quite low as compared to asymmetric heat up of pressure tube.
2. At same pressure, initiation of ballooning occurred at higher temperature for symmetrical heating as compared to asymmetric heat-up conditions.

3. Under asymmetric heat up, the temperature at which ballooning initiates depends on internal pressure. At lower pressures ballooning initiation temperature is higher and ballooning rate is slow.
4. Under symmetric as well as asymmetric heating, ballooning initiates from centre and then propagates towards the end. In symmetrical heating ballooning case PT strain rate is found to be higher as compared with asymmetric heat up conditions for the same internal pressure. This shows influence of un-heated portion plays an important role of creep deformation of heated portion.
5. The integrity of pressure tube was observed during all experiments. Inherent safety feature of moderator, which acts as a heat sink is able to limit the rise in temperature of fuel pins as well as PT.

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