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EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER DURING LOCA WITH FAILURE OF EMERGENCY COOLING SYSTEM

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ABSTRACT

The pressure tubes (PT) in the Indian Pressurized Heavy Water Reactor (PHWR) are kept concentrically inside horizontal calandria tube (CT), which is submerged in a moderator pool. During postulated loss-of-coolant accident (LOCA) without emergency core cooling system, the temperature of PT could rise significantly. At elevated temperature, the weight of the PT with the weight of fuel pins could cause it to sag. Before sagging heat transfer from the PT to CT is mainly by convection. Once the PT sags and touches the CT, heat transfer mode changes to conduction. Direct contact between the PT and CT increases heat transfer and checks the temperature rise of the PT and limit the fuel heatup and subsequent degradation of the reactor core. An experimental set-up is designed and fabricated at Indian Institute of Technology Roorkee (IITR) to simulate the LOCA in the Indian PHWR. From the experimental investigation, it is found that the contact between the PT and CT occurred at around 300 seconds after the initiation of the simulation with corresponding temperature of the PT at around 680°C. The experiment was continued after the contact between the PT and CT and it is found that the temperature rise of the PT was within 800°C. This work demonstrates the inherent safety feature of Pressurised Heavy Water Reactor.

INTRODUCTION

The Indian PHWR is of 220MW capacity and consists of a horizontal reactor core of 306 parallel fuel channels [1]. The coolant flows through half of the channels in one direction and in the remaining 153 channels in the opposite direction. Each channel consists of a PT of 90 mm outside diameter, concentrically placed in a CT of 110 mm outside diameter. The PT is housed inside the CT supported along its length through four garter spring. The PT is made of Zirconium 2.5% Nb and CT is made of Zircaloy 2. A fuel pin bundle having 19 solid fuel pins of 12.5 mm diameter is placed inside the PT. The coolant flow in the PT is through the void of fuel pin bundles. The channels are surrounded by low temperature heavy water moderator maintained at around 70-80^{o}C. Heavy water behaves as a sink for heat generated in the fuel if other means of heat dissipation fails. The annulus space between the PT and CT is filled with CO_2 [2, 3]**.** During postulated LOCA the coolant flow through the PT is reduced resulting sharp rise in temperature of the PT. The heat flux incident on the surface of PT during LOCA is equivalent to that predicted for the decay power condition shortly after the shut down of a Nuclear Power Plant [4]. However, the temperature of the CT is not affected significantly as it is submerged in the low temperature moderator and there is a high rate of heat transfer from CT to bulk coolant. But, the rise in the temperature of PT may lead to deterioration in its thermo-physical properties and eventual meltdown of the reactor core.

In normal operating condition heat transfer from the PT to CT is by convection and radiation mode. The rate of heat transfer from the PT to CT is not uniform along the circumference, which results in a circumferential temperature gradient and has been reported by several researchers [5–8].

The behavior of the PT in LOCA depends on the internal pressure of the PT. The pressure inside the PT could be in the range of 0.1 to 9 MPa. If the internal pressure is lower than 1MPa, the PT deforms due to high temperature creep and sags due to its own weight and weight of the fuel pins. Ballooning deformation takes place when internal pressure is more than 1 MPa. The deformation of the PT leads to a physical contact between the PT and CT, thereby resulting in a high heat transfer to the moderator. Though the phenomenon leads to structural failure of the PT, is desirable as it checks the temperature rise of the PT, which prevents the meltdown of the reactor core.

Experimental investigations have been carried out by number of nuclear safety scientists to investigate the deformation of PT and resulting surface contact behaviour. Thompson et al.[4] concluded from their experiments that under non pressurized conditions, contact between the PT and CT is a small elliptical patch of approximately 5 cm major axis around the circumference at the bottom of the channel. They also concluded that the contact conductance between the PT and CT, which is a function of contact pressure, is less at low pressure in comparison to high pressure in the PT. Gillespie [9] has investigated the heat transfer from PT to surrounding water at high pressure inside the PT. He concluded that the contact conductance between the PT and CT is 11 kW/m^2 K.

In this work, an experimental set-up is designed and fabricated to simulate LOCA in the Indian PHWR. This work is carried out in collaboration with Bhaba Atomic Research Centre (BARC), Trombay, Mumbai, India; which is the premier research organisation for the design and development of nuclear power plants in India. These data will be used for the validation of computer codes developed in BARC and also will be used for the design and development of the advanced Indian PHWR.

EXPERIMENTAL SET UP AND PROCEDURE

The schematic diagram of experimental set up is shown in the Fig. 1. This consists of a mild steel water tank of 2m × 1m × 1m dimensions, which houses the PT and CT assembly. The length of the test section is 2000 mm. The CT is of 110 mm outside diameter with 1.6 mm wall thickness. The PT is of 90 mm outside diameter with 4 mm thickness. These are the actual PT and CT used in the Indian PHWR and are supplied by BARC. The extended ends of PT on both the sides of the tank are supported on vertical stands in such a way that one end of the PT acts as fixed and other end as free. This arrangement accommodates any lateral expansion of the PT during heating process. Ceramic end caps at the both 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 core, a DC rectifier of 42kW capacity (12VDC/3500A) is used. The rectifier can operate from 10 to 100% load with the option of varying the current or the voltage continuously. The test section is connected to the rectifier by electrolytic grade copper bus bars using specially designed copper clamps. The copper clamps are fixed very close to the outside of the tank wall on the PT. To simulate the weight of the fuel bundles inside PT, eight cast steel solid cylinders of 70 mm diameter and 250 mm length is used. The weight simulators are rapped with ceramic wool to minimize the heat gain from the PT. This arrangement helps to achieve higher rate of temperature rise of the PT. As the temperature of PT is expected to go up to 1000°C, the temperature of PT is measured with minerally insulated 0.5 mm K-type thermocouples while 1.0 mm J-type thermocouples are used for the CT. All the thermocouples were calibrated before use. The error in temperature measurement is less than 0.2%.

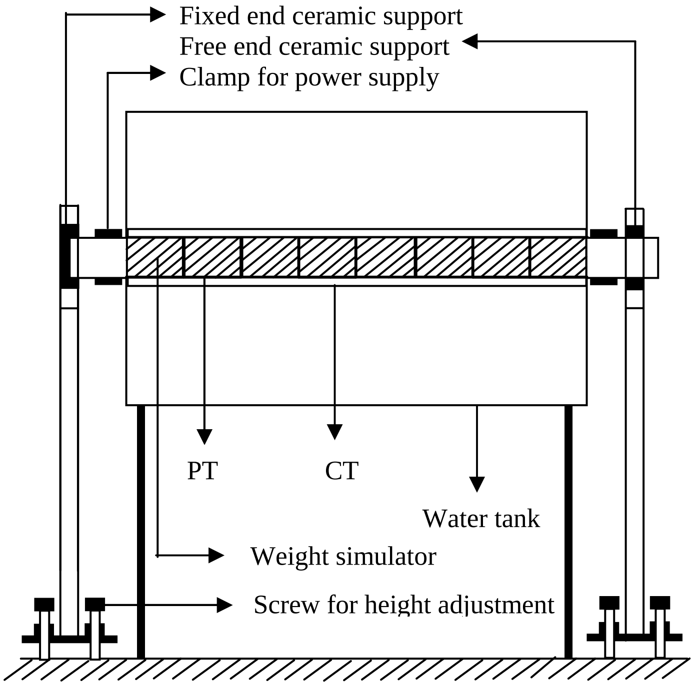

Figure 1 Schematic diagram of the test section

The thermocouples were mechanically fixed on the outer surface of the PT and CT with the help of 0.1mm thick Zr-alloy foils. A small groove is made on the surface of the PT and CT, the thermocouple is placed in the groove and 0.1 mm Zr-alloy foils are place on the top of the thermocouple and welded to the surface using spot welding. The location of thermocouple on test section is shown in Fig. 2. At any axial location six thermocouples are fixed at 60^o interval both on PT and CT. As contact between PT and CT is expected at the bottom of the PT, no thermocouple is placed at the bottom of the PT. The axial distance between two thermocouples is 30 cm and location C is at the centre of the test section.

The displacement measurement of the PT is carried out without any water in the tank. The CT is rapped with ceramic wools to minimize heat loss to the surroundings. The displacement of the PT is measured using potentiometers shown in Fig. 3. These potentiometers can measure displacement up to ± 25 mm, which is much higher the annular gap between the PT and CT (8 mm). The potentiometers are fixed at the bottom of the tank and are connected to the PT using a 1.0 mm ceramic extension rod, which passes through a hole at the bottom of the CT. The ceramic rods protect the potentiometer from direct contact with the PT, which attains very high temperature during the experimentation.

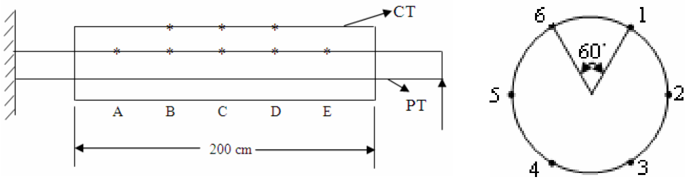

Figure 2 Axial location of thermocouples on PT and CT

Figure 3 Potentiometer for displacement measurement

RESULTS AND DISCUSSION

Initially the test section is heated slowly to attain temperature of 150°C. During this period, the reading of all the thermocouples and the potentiometers are checked. Then test section is heated with a constant power of 35.6 kW. The current through the PT was fixed at 3500A. The temperature rise of the PT and CT, and the deflection of the PT are recorded using a high precision National Instrument, USA, Data acquisition system.

The average temperature variation of the PT with time is shown in Fig. 4. From the graph it is clear that the initial temperature rise is identical at all axial locations. This is in the expected line as the temperature rise in the PT is due to Ohmic heating. The downward displacement of the PT with time is shown in Fig 5. From Fig. 5 it is clear that the sagging of the PT does not take place until 125 seconds. If coolant supply can be resumed before this time, the structural integrity of the reactor core can be maintained. The graph can be divided into three parts: Pre-sagging, sagging, and Post sagging periods. The initiation of sagging is observed at 125 seconds and is called pre sagging period. At the initiation of the sagging the average temperature of the PT is 515°C. The rate of temperature rise of the PT in the pre-sagging period is the highest and is 2.75°C/s.

The sagging phenomenon can further be divided in two parts based on the rate of sagging: (i) slow sagging and (ii) first sagging. In the slow sagging period the rate of temperature rise of the PT is observed to be around 2.40°C/s. From the Fig. 5 it is observed that the slow sagging continues for about 50 seconds. After about 175 seconds the sagging is faster. During this period the rate of temperature rise of the PT is of 0.85°C/s. The sagging of the PT completes when it touches the CT. It is clear from Fig. 5 that at 300 seconds PT touches the CT near the station D, where the down ward displacement is the maximum and is equal to 8mm. The corresponding average temperature of the PT was observed to be 680°C.

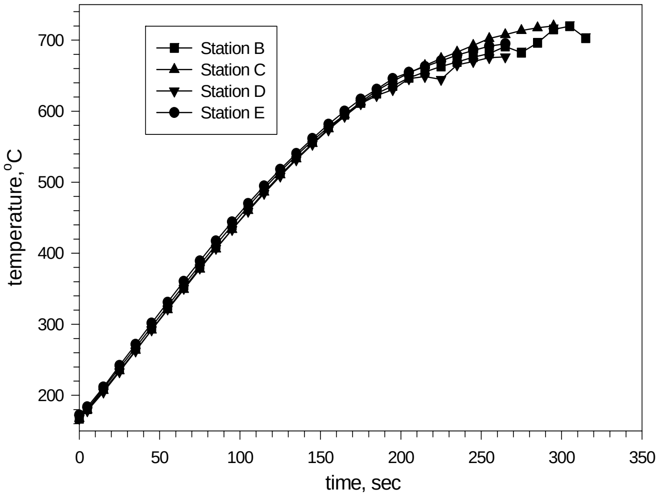

Figure 4 Average temperature rise of PT with time

The rate of temperature rise of the PT and CT, and the sagging of the PT with time are presented in Fig. 6. Table 1and 2 summarize the rate of temperature rise both in the PT and CT at different axial measuring locations. It is clear that the rate of temperature rise of PT is much higher than the CT in the pre-sagging period. Because, initially the temperature difference between the PT and CT is small and natural convection is the dominating mode of heat transfer. As the temperature of the PT increases, strong convective current increases heat transfer from PT to CT and radiation mode of heat transfer also becomes more dominant. This causes a sharp rise in the temperature of the CT. With the initiation of sagging, the gap between the PT and CT becomes smaller and smaller with time and the rate of heat transfer to the CT increases. This decreases the rate of temperature rise of the PT. When the PT touches the CT, the rate of heat transfer from the PT to CT is much higher due to conductive heat transfer. Because of higher rate of heat transfer from the PT to CT, the temperature rise of the PT further decelerates.

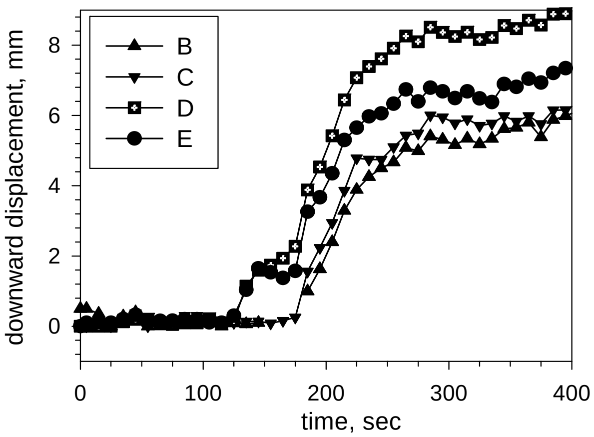

Figure 5 Vertical displacement of PT with time.

Table 1 The average rate of temperature rise of the PT

Location	Pre-sagging	Slow-sagging	Fast-sagging
B	2.73	2.03	0.73
C	2.74	2.05	0.89
D	2.78	1.93	0.83

Table 2 The average rate of temperature rise of the CT

Location	Pre-sagging	Slow-sagging	Fast-sagging
C	1.00	2.27	2.45
D	0.92	2.22	2.54

Heat transfer between concentric tubes at high temperature is complex and depends on convective and radiative heat transfer modes. The situation becomes further complicated when the tubes are not concentric; which is the case in the sagging period. The temperature along the circumference at any axial position is not uniform. Table 3 summarizes the temperature profile of the PT at the initiation of sagging. Figure 7 shows the circumferential temperature variation of the PT with time at axial location D. From the figure it can be observed that with time the temperature gradient along the circumference increases. The temperature is maximum at the top nodes (1, 6) and minimum at the bottom nodes (3, 4). After the contact between the PT and CT, no readings were obtained at nodes 2, 3, 4, and 5. During the dismantling process it was observed that either the thermocouples were damaged or the contact with PT was lost after the contact.

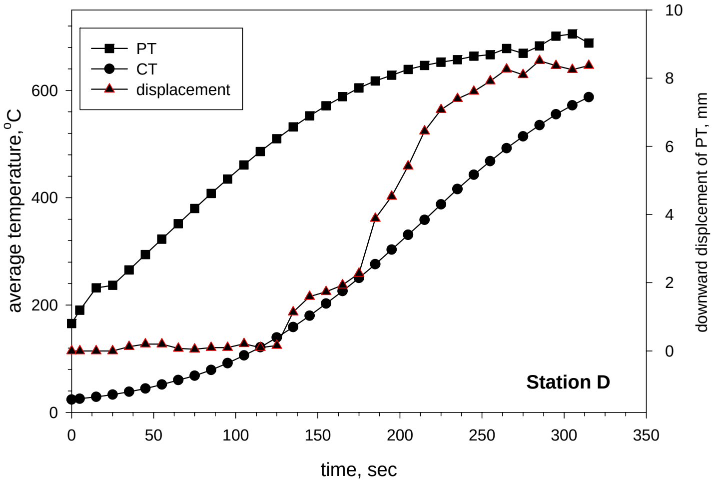

Figure 6 Average temperature rise of PT and CT at station D

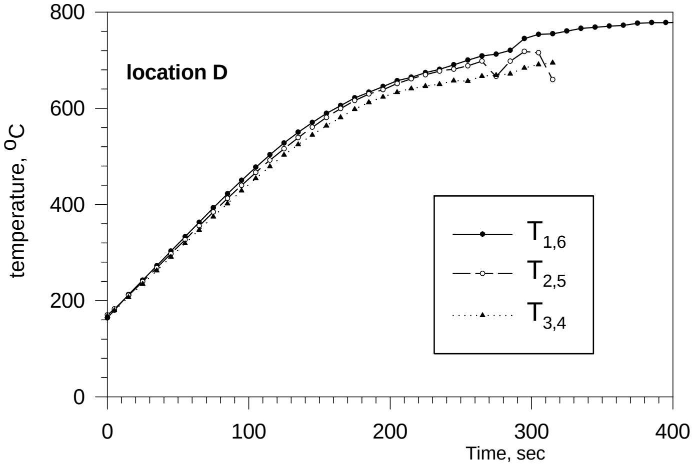

Figure 7 Variation of the surface temperature of PT with time

Table 3 Temperature of the PT at different nodes at the time of sagging initiation (125 seconds)

	T at B (°C)	T at C (°C)	T at D (°C)	T at E (°C)
Node 1 & 6	527.3	524.9	528.5	527.1
Node 2 & 5	515.3	510.0	499.3	510.5
Node 3 & 4	502.7	495.9	497.8	506.7
Average	515.0	510.3	508.6	508.1

CONCLUSION

The LOCA in Indian PHWR is simulated at IIT Roorkee. The investigation was carried out without water in the tank to measure the deflection of the PT during heat up process. From the preliminary investigation, the following salient points are observed:

- In case of LOCA, the temperature rise of the pressure tube will be checked because of direct contact between the PT and CT.
- The maximum temperature attended was less that 800(°C), which is well below the melting point of Zircaloy. Hence, the sagging deformation can prevent the meltdown of the reactor core. Such a deformation, however, renders the fuel channel unusable. As a result, this will lead to substantial period of break down of the plant.
- The sagging of PT starts at around 2 minutes after the start of heating and takes about 3 minutes to complete.
- To protect the physical structure of the PT from permanent deformation, the emergency coolant supply should be resumed within two minutes of coolant loss.

Further experiments will be conducted with water in the tank to calculate the contact conductance between the PT and CT. Also the ballooning of the PT will be carried out at different pressure inside the PT.

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