EXPERIMENTAL STUDY ON LOCA SCENARIO IN INDIAN HEAVY WATER NUCLEAR REACTORS

Ph.D. Synopsis

Submitted in partial fulfilment of the

Requirement for the award of the degree

of

DOCTOR OF PHILOSOPHY

In

MECHANICAL ENGINEERING

by

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July 2019

1. INTRODUCTION

The understanding of operating and emergency thermal hydraulic conditions of the Indian nuclear power plant play significant role for safety of power plant. The fleet of nuclear plant consists of 22 commercial operating units, which are managed (design, construction, commissioning and operation) by Nuclear Power Corporation of Indian Ltd (NPCIL). The total installed capacity of 18 PHWRs, 2 BWRs and 2 VVER (2 units of Kudankulam nuclear plant) produce 6780 MW power which is approximately 2.3 % of the total consumed power in India. The PHWR is based on the CANDU (Canadian Deuterium Uranium), which burns natural uranium as fuel. The availability of the natural uranium in India is limited but the abundant amount of thorium can fulfill the demand of energy in coming decays. The AHWR (burns thorium as a fuel) design and development phase include greatly the safety of the plants during emergency scenario. The LOCA scenario in PHWR and AHWR change the thermal condition and mode of heat transfer, which are being understand with the understanding of components of core, Primary Heat Transport System (PHTS), Moderator system and ECCS of PHWR and AHWR. The LOCA scenario of PHWR and AHWR reactors are discussed greatly along with the rewetting process of AHWR.

The nuclear power plant operating cycle is based on the Rankine cycle and similar to the operation cycle of the conventional coal thermal power plant. The conventional thermal power plant burns coal as a fuel whereas, uranium used in nuclear power plant. The 220MWe and 540MWe rating PHWRs are operating in India whereas, the 700 MWe IPHWR is in design and development stage. The heat is supplied to the boiler from the nuclear power. The produced power in 200MWe PHWR is supplied to Rankine cycle with the help of primary heat transport system.

The 54 pin fuel cluster having height of 3.5 m is concentrically housed inside a Zr-2.5 wt% Nb pressure tube (PT). The 54 pins of fuel bundle are arranged in three concentric ring inner ring, middle ring and outer rings. These rings consist of 12, 18 and 24 pins in inner, middle and outer rings respectively. The fuel bundle center has a water rode, which is used to provide water supply during the LOCA of the channel. The holes provided on the water rod produce jet effect and able to break the vapor film formed on the surface of the clad tube and promote the nucleate boiling heat transfer so that more decay heat can be removed from clad surface.

2. RESEARCH GAP

After the comprehensive study of past published research work, following gaps were identified. The literature review can be concluded that the most of research work was restricted to CANDU reactor and limited research is available related to the thermal behavior of the 220 MWe IPHWR under LOCA condition. The boil-off condition is very limited at higher temperature with 19 pins fuel bundle. Our present work will be focused on thermal behavior with temperature profiles in channel (fuel bundle, PT and CT) of IPHWR undergoing different eccentric conditions (vertically) of PT at different temperature of fuel bundle.

The literature reviews on rewetting scenario of AHWR are very much limited to types of rewetting phenomena and mechanism of the rewetting phenomena. The research work on jet impingement cooling for 54 pins AHWR and pins rewetting time are very few. The AHWR rewetting experiment result is focus on the effect of surface temperature and axial as well as radial location of the pin on the rewetting phenomena.

3. OBJECTIVES

The experimental facility for IPHWR was developed to investigate the thermal behavior of the nuclear channel, which includes: fuel bundle, CT and PT under different heat up conditions and eccentric position of PT w.r.t. CT with following objectives:

- Experimental investigations using simulated 19 pins fuel bundle under boil off condition at different elevated temperature (600°C, 900°C and 1100°C).
- Experimental investigations with the three different eccentric position of PT w.r.t. CT (i.e. effect of sagging)

The second experimental facility was developed to investigate the rewetting time of 54 pins fuel bundle at different axial and radial location with following objective:

- Experimental investigation on rewetting using simulated 54 pins fuel bundle of AHWR under four different temperatures (450ºC, 500ºC, 550°C, 600ºC) at 90 LPM coolant flow using jet impingement method.

4. EXPERIMENTAL SET-UP

The experimental set-up is shown below in Figure 4.1, which have test section as a major component. The test section of the experimental set-up consist a calandria tube, pressure tube and 19 pins simulated fuel bundle, which was symmetrically fixed in the mild steel tank of size 1000 mm x 500 mm x 500 mm and sheet thickness was 5 mm. The both end of 19 pins simulated fuel bundle of test section were connected with connecting bus bar followed by the terminals of the 490 kW DC rectifier.. The calandria tube, made of Zircaloy-2 and one meter of length was fixed in the mild steel tank with the help of gasket and flanges to insure leak proof. The pressure tube which was made of material Zr-2.5% Nb and length of 1.25 m was concentrically assembled inside the Calandria tube. The simulated 19 pins fuel bundle had length of 500 mm and clad tube was made of Zircaloy-4 having 15.2 mm external diameter and 0.4 mm wall thickness. The stainless steel rods of diameter 5.0 mm, 4.5 mm and 4.0 mm for center, middle and outer pins of fuel bundle respectively were concentrically fixed inside the clad tube with the help of alumina (an electrical insulator but has a high thermal conductivity) as shown in Figure 4.2. All 19 pins were assembled with the help of high speed stainless steel spacer to maintain the exact positions of the pins as it remain in 220 kW Indian nuclear power plant's fuel bundle. The K type thermocouples had 0.5 mm outer diameter and made of Chromel/Alumel were spot welded with the help of zircaloy-2 foil, over all nodes of pressure tube, fuel bundle and at the location where temperature may exceed 600°C. The J type thermocouple had 1.0 mm outer diameter and made of Iron/Constantan were spot welded on calandria tube and in moderator. All the thermocouples were connected to the DAQ of control room for recording and storing of data. Assembled simulated fuel bundle were fixed concentrically inside and in middle of the pressure tube and then the Copper bus bar was used to connect the experimental test section and the 490 kW DC water cooled rectifier.

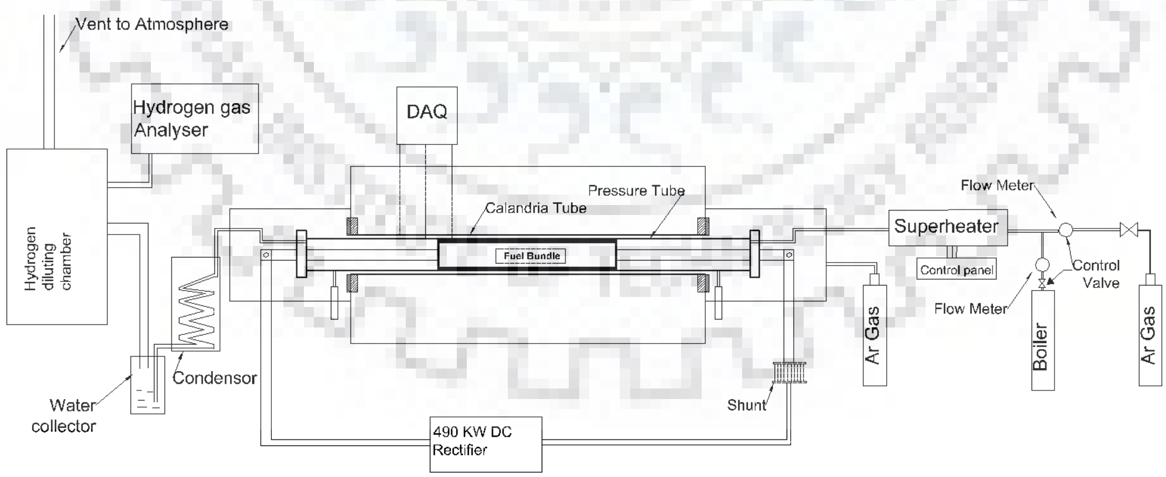

Figure 4.1: Schematic Auto-Cad drawing of Experimental Set-up.

Figure 4.2. The 19 pins simulated fuel bundle and spacer.

Further, the experimental set-up for AHWR rewetting was develop and its schematic diagram of experimental set-up is shown in Figure 4.3. The experimental set-up consists of experimental test section, 490 kW DC rectifier, boiler, coolant supply system, control room, DAQ system and power analyzer.

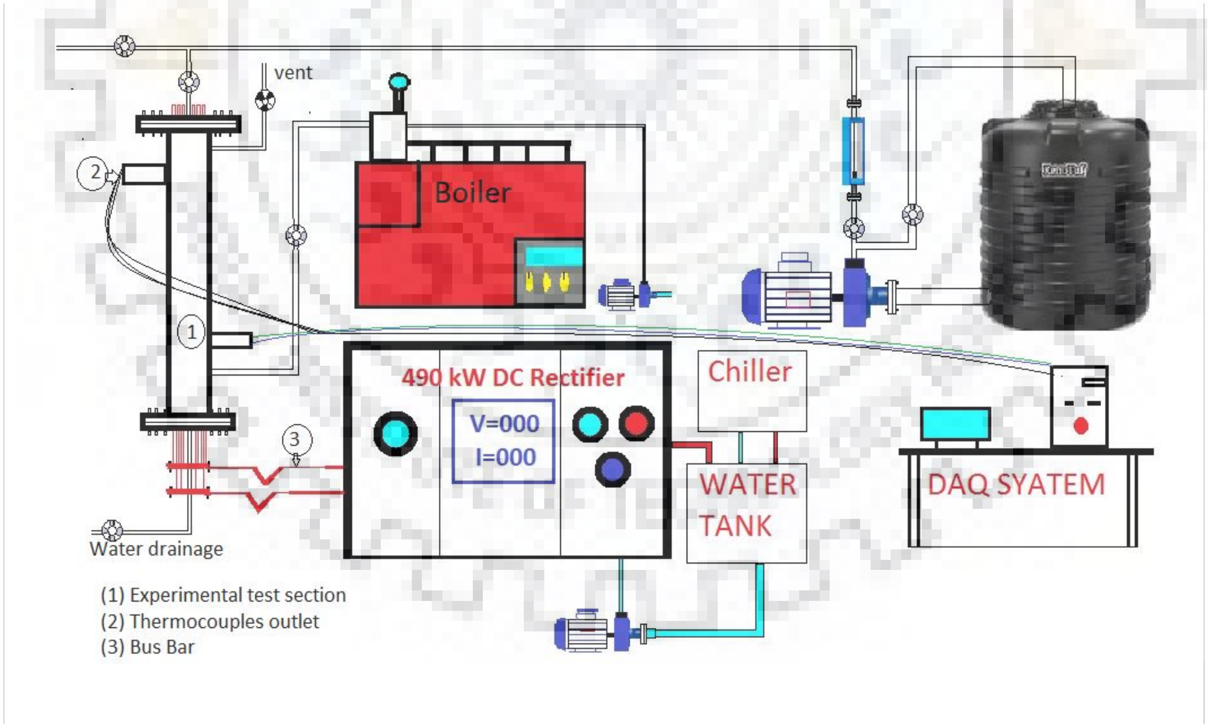

Figure 4.3: The schematic diagram of experimental set-up for AHWR.

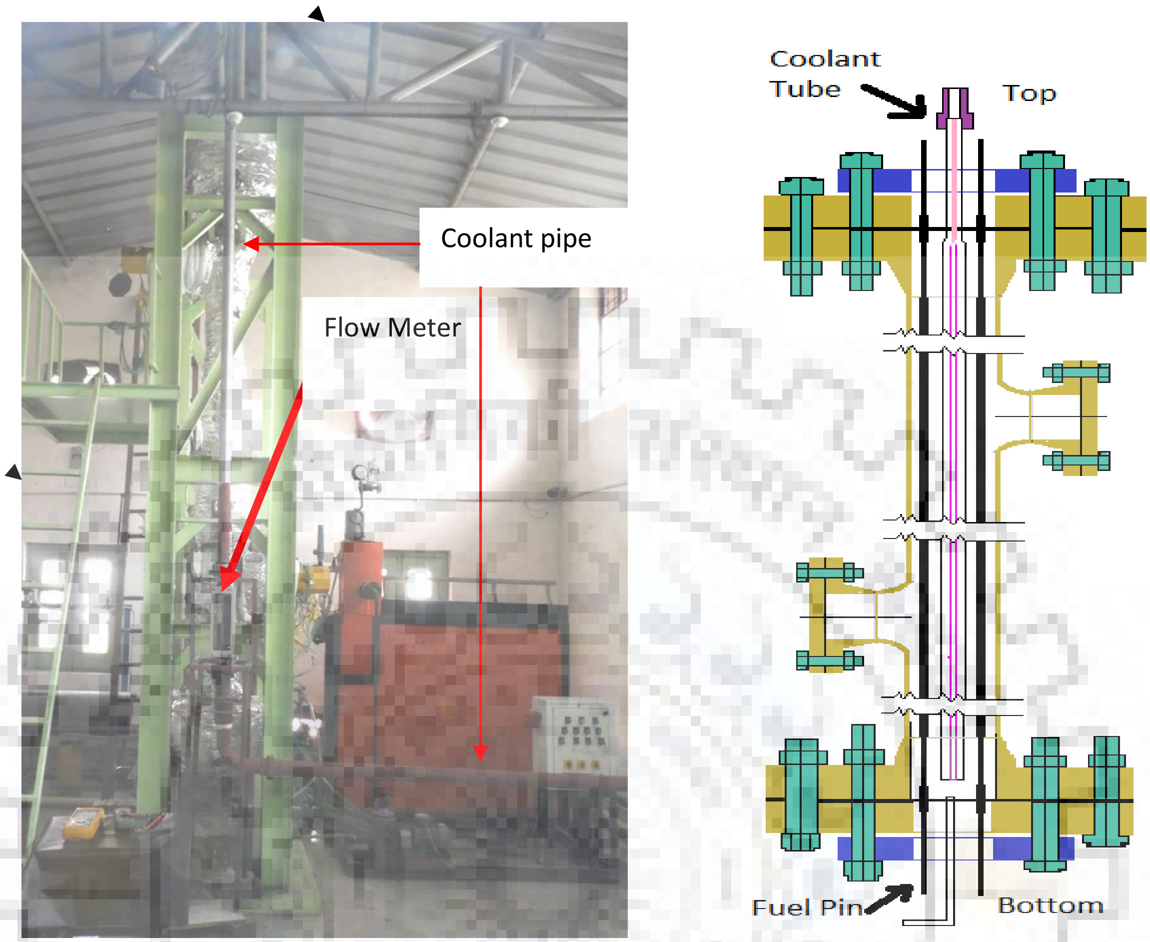

Figure 4.4: Experimental test section in lab and drawing

Figure 4.5. Experimental test section during fabrication.

Figure 4.6. The experimental test section during installation in laboratory at IIT Roorkee**.**

A single channel of 54 pins, Advance heavy water reactor was fabricated in BARC Mumbai (Figure 4.5) and installed in IIT Roorkee for experiment as it can be seen in Figure 4.6. The test section consists of Calandria tube (CT), Pressure tube (PT), 54 fuel pins of fuel bundle and central cooling supply tube. Outer surface of the experimental set-up has been insulated to resist heat transfer using glass wool and aluminium foil as it can be seen in Error! Reference source not found.

5. RESULTS AND DISCUSSION

5.1. The temperature distribution across PHWR channel

The set-up was prepared and brought to the thermal steady state of a LOCA condition with ECCS failure of nuclear power plant. A gradual DC power input was given to the fuel bundle and the power input was increased to 2.5 kW ± 1 kW. The fluctuation of power supply to the rectifier causes the variation of power input to the fuel bundle. Power supply was manually adjusted by regulating the current output of the 490 kW rectifier.

The moderator temperature was maintained at 60°C throughout the experiment and considering average temperature of middle pin at section-C as a hottest section (Tavg) of fuel bundle, the average temperature of middle pin at section-C was maintained at 600°C by regulating the rectifier output power to the fuel bundle. The mixture of argon and steam at 150°C were supplied with flow rate 2.0 g/sec and 1.0 g/sec respectively inside the pressure tube which acts as a coolant to simulate postulated LOCA in 220 MWe IPHWRs. Once, all nodes attained thermal steady state, temperatures of all nodes of CT, PT and fuel bundle recorded in three sets (for 15 minutes in each set). The net power supplied to the fuel bundle was 2486 W, which got distributed in ratio of 1.4: 1.1:1 to the outer, middle and center pins of the 19 pins simulated fuel bundle pins respectively. The highest temperature (Tmax) 631 °C was recorded at C01a of center pin whereas minimum temperature was 542°C (16 % less than Tavg) at node O16c of section-C among all nodes of section-C. The temperature distribution was observed in similar way as section-C. The minimum and maximum temperature 443°C &519°C occurred at nodes O16c and C01a respectively. The outer pins of fuel bundle were recorded lowest temperature among center, middle and outer pin at both section-B & C.

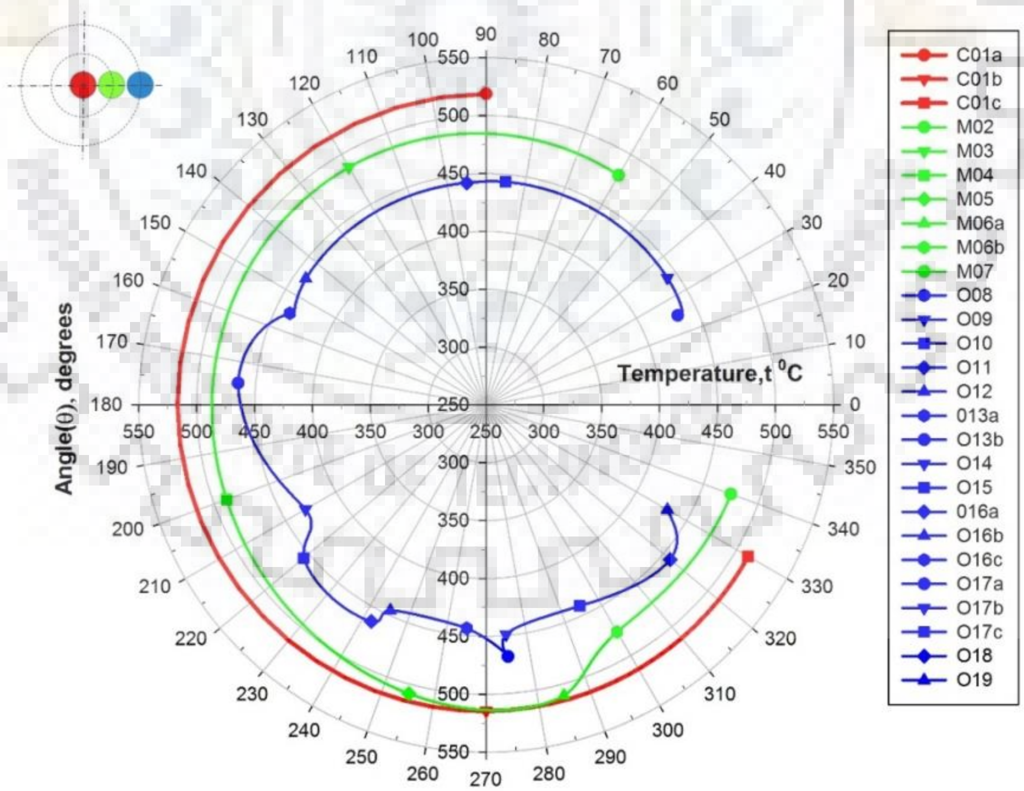

Figure 5.1: Circumferential temperature distribution in bundle at 600°C at section-B

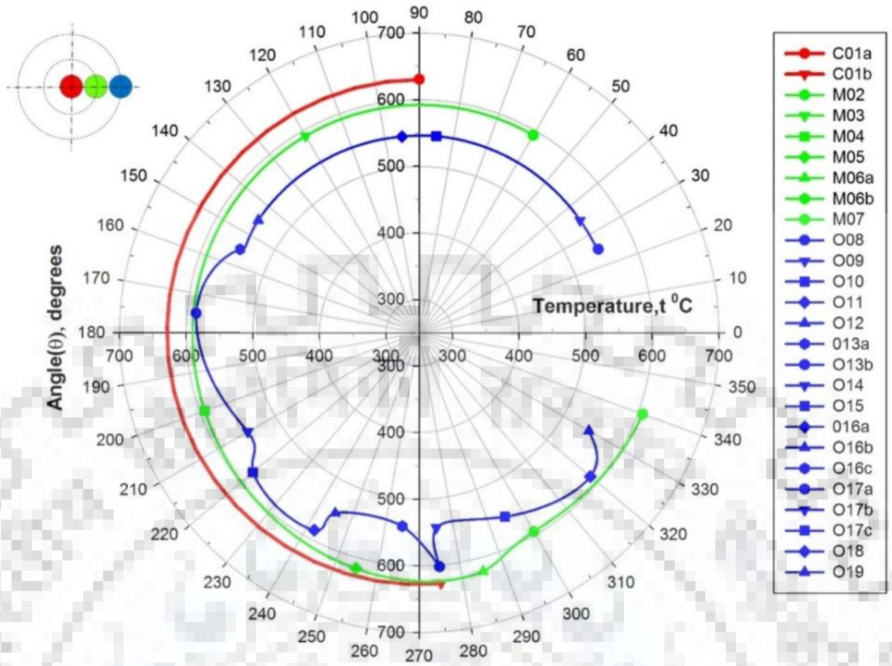

Figure 5.2: Circumferential temperature distribution in bundle at 600°C at section-C

The overall average temperature of nodes at section-C were higher than average temperature of section-B of fuel bundle because the coolant heat removal capacity retards with rise of coolant temperature along downstream side. The marginal temperature increments observed at top nodes O10, O11 with respect to bottom nodes 16c and 16b at both sections-B & C respectively as shows in Figure 5.1 and Figure 5.2. The axial rise of temperature at section-C observed 24% rises with respect to average temperature of section-B of fuel bundle. The axial variation of temperature is 17 to 21 percent across the section and highest temperature variation was nearly 21% over sides of the outer pin whereas, temperature variation over top and bottom section observed 17 to 18%. The inner pin and outer pins shows lowest temperature deviation compare to outer pins.

The pressure tube which acts as a shield to protect from the leakage of the radioactive material and maintaining the integrity of the channel is most significant challenge for thermal hydraulic point of view. The section-C was recorded at highest whereas, section-A at lowest temperature than other sections as shown in Figure 5.4. The circumferential temperature gradients exist in all four sections of PT and maximum temperature gradient recorded at section C with highest temperature 443°C (30% less than T_{avg} of middle pin at section C) at node P2 of section-C due to its location near the fuel bundle and downstream side of the flow. The area between sections-B & C of PT were observed at elevated temperature than other parts of PT because it lies just around the fuel bundle. The minimum and maximum temperature observed, diametrically opposite to each in PT, CT as well as in fuel bundle. The calandria tube which act as a separator between the channel and moderator had no significant rise in temperature and was near about the moderator temperature with marginal difference which ensures the moderator excellent heat sink capacity to maintain the integrity of channel.

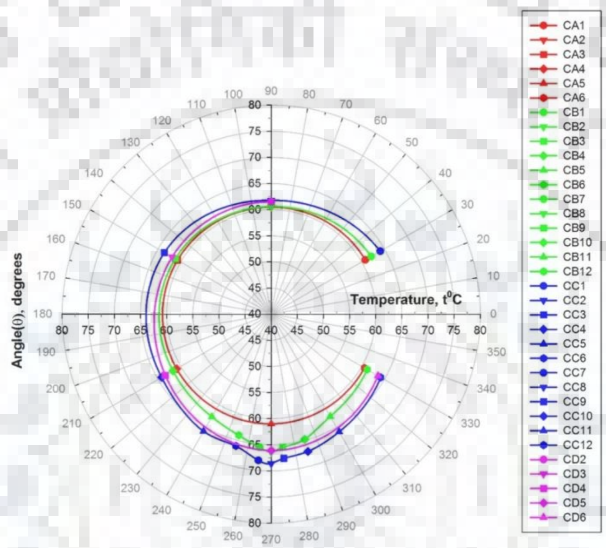

Figure 5.3. Circumferential temperature distribution over CT at 600°C

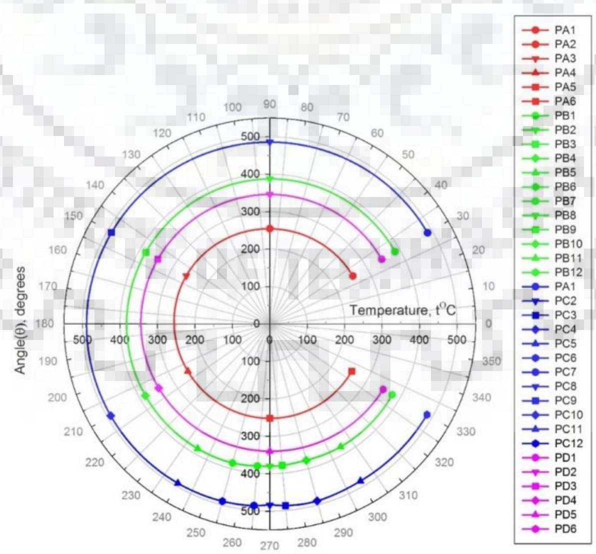

Figure 5.4. Circumferential temperature distribution over PT at 600°C

The power 2486 W DC supplied to bundle and the heat balance was done. 34.8% heat was reached to moderator, which indicates the heat sink capacity of the moderator to maintain the integrity of the fuel channel.

Table 5.1. Heat balance in watt (W) when fuel channel was at 600°C at e = 0 mm

Power input (**P**)	2486.0
Heat carried out by argon and steam	616.0
Heat conducted by Copper rod	691.0
Heat supplied to PT	1179.0
Heat loss by PT	264.8
Heat supplied to CT	914.2
Axial heat loss by CT	0.151
Heat supplied to modeartor	867.3
Heat unaccounted	46.9
% unaccounted heat	1.9

Further, experiments were conducted at 800°C and 1100°C by raising the power supply to the fuel bundle. The circumferential and axial temperature distributions were analyzed. The effect of eccentric position of the PT with respect to CT over temperature distribution was also analyzed.

5.2. The rewetting of 54 pins fuel bundle of AHWR

The result and discussion chapter consists of the observations and analysis of results obtained from experiments, conducted on single channel of an Indian AHWR. The investigation of rewetting phenomena of AHWR conducted at 450ºC, 500ºC, 550°C and 600ºC with 90 LPM coolant flow. The coolant at 90 LPM was supplied from the pump to the central water rod, which spray the water at all the rods to quench it.

The inner pin undergoes drastic temperature drop within fraction of second with the initiation of water supply. The temperature of the inner pin has two faces, one is in direction of jet and other is in opposite side (OS) of the jet direction. The opposite side of the inner pin (opposite to jet direction) takes little more quenching time compare to face in jet direction. The inner pin node-A2 temperature fall from 428°C to 185°C in just 0.49 second thereafter, 30°C rise of temperature was observed and again temperature drop recorded from 216°C to 140°C in 0.58 seconds, further, rise in temperature recorded by 50°C and thereafter, continuous drop in temperature recorded with time except little fluctuation at some points. The nodes at opposite side of inner pin i.e. node-A2(OS) temperature drop from 425°C to 244°C in 0.46 seconds and further drastic decrease of temperature from 390°C to 146°C recorded in just 12 seconds there onward, rise and drop of temperature continue with insignificant amplitude. It was observed that the pin-2 is directly enter into the rewetting heat transfer regime and due to direct contact of water with the clad tube surface, drastic rate of heat discharge was recorded. The absent of film boiling during quenching of pin-2 enhance nucleate boiling heat transfer. The node-A2 and A2(OS) take 73 seconds and 79 seconds to attain surface temperature 100°C from initial wall temperature respectively.

The middle pin and outer pin shows little different trends than the inner pin quenching. The middle and outer pins takes more time to get its surface wet because pin-2 receives water jet directly whereas, the middle and outer rings pins receives mostly reflected water jet. The temperature drop in middle and outer pins were recorded 0.19 seconds later than inner pin. The node-A15 shows temperature drop by 67°C in 2.88 seconds, again rise in temperature recorded and it attain temperature 372°C in 39.0 seconds. The node-A15 temperature matches with temperature of node A15(OS) at 372°C, which is continuously undergoing fall in temperature but not able to get its surface wet for 48.0 seconds. The longer film boiling time of node-15(OS) shows that the water jet is not significantly approaching at this node. Thereafter, sharp declination of temperature at both the nodes of pin-15 by 208°C and 194°C recorded at node-A15 and A15(OS) in 2.33 and 2.88 seconds respectively and then the continuous declination of temperature were recorded in nodes A15 and A15(OS).

In case of outer pin, node-A34 and A34(OS) temperature time trends nearly similar to middle nodes A15 and A15(OS). It can be easily explained from the temperature time graph that the outer pins takes more time in quenching than middle and inner pin. The longer period of film boiling regime on the pin-35 surface shows that the water is not able to carry out heat from the surface for longer time. The film boiling regime of heat transfer continue for 54 seconds and 57 seconds and temperature drop by 88°C and 72°C at node-35 & 35(OS) respectively. The ends of film boiling heat transfer leads to initiation of rewetting which last for short period. The longer rewetting period of the outer ring nodes shows that the integrity of the nuclear core only can be maintained if the outer ring pins wet its surface within the predefined safety time. The rewetting time for node-34 & 34(OS) were 3.66 seconds and 0.66 seconds and temperature droped by 223°C and 242°C respectively. Thereafter the continuous drop of temperature with time was observed. The time taken by middle pin to initiate rewetting is 48 seconds (maximum) whereas, the outer pin takes 54 seconds (minimum) to starts rewetting.

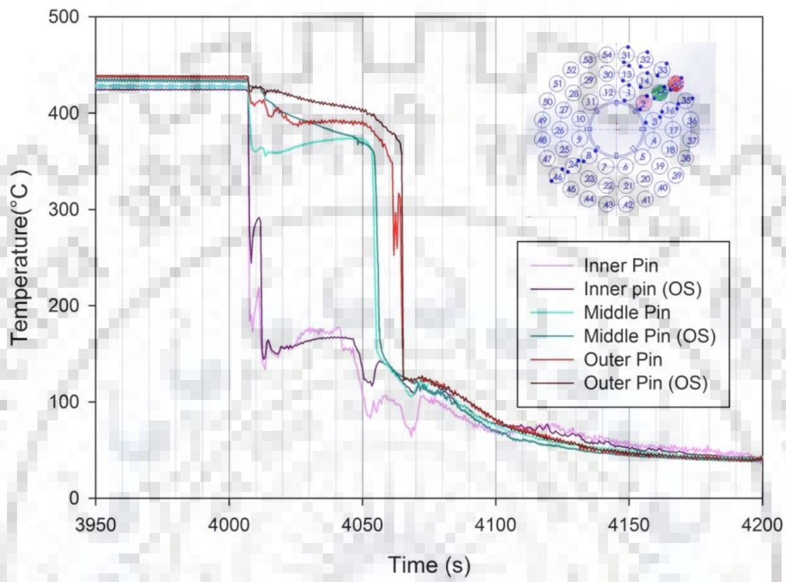

Figure 5.5. Temperature-time graph for section-A at 450°C.

The temperature time graph of rewetting at section-B (542 cm down from section-A) is shown in Figure 5.6. The graph of temperature time transient shows three distinct phases: first one is gradual decrease in temperature almost remain constant which is known as film boiling regime of heat transfer, then drastic fall in temperature approximately within fraction of seconds attributes to rewetting and heat transfer takes place by nucleate boiling and third one where onset of single phase cooling occur and temperature decrease gradually and takes large time compare to other two stage. If we focus on the inner ring node it can be easily observed that the sudden fall in temperature occur just immediately with the start of coolant flow. The node-B2 temperature drop (4°C in 0.07 second) observed with small curve in quenching graph thereafter, rewetting starts and node-B2 sudden temperature drop was recorded as it can be seen from the Figure 5.6 that, 258°C fall in temperature recorded in just 1.17 seconds. The similar trends like node-B2 was followed by nodes B2(OS), because both nodes B2 and B2(OS) are fixed on same fuel pin. After rewetting, the quenching of the fuel rod-2 occurs in gradual manner except few rises in temperature were observed at few points. The temperature time profile was observed different in inner pin than middle and outer pin nodes. The nodes B15 gets its surface wet earlier than node B15(OS) due to its location in jet direction which enable it to receive water earlier than opposite side node. The temperature difference in middle pin jet direction side and opposite to jet direction side is recorded highest in middle pin than inner and outer pins in early stage of cooling which shows that the chances of thermal shock and thermal stress are more in the middle pin compare to inner and outer ring pins due to large circumferential temperature gradient. The temperature drop in node B15 occurs mainly in two steps, once immediately after the coolant flow start and its temperature drop drastically by 234°C in just 1.07 seconds and thereafter, the rise of temperature recorded and it attain the temperature equal to opposite side of rod temperature (i.e. equal to node B15(OS) temperature). The node B15(OS) also shows fall in temperature but comparatively less than node B15. Once both the nodes of middle pin attain approximately same temperature thereafter, sudden fall in temperature occur and during this period rewetting occurs which takes less than second to drop by 249°C at both the nodes. It can be easy analyzed from the Figure 5.6 that the nodes in direction of jet always get rewetted earlier than the node opposite to the jet direction.

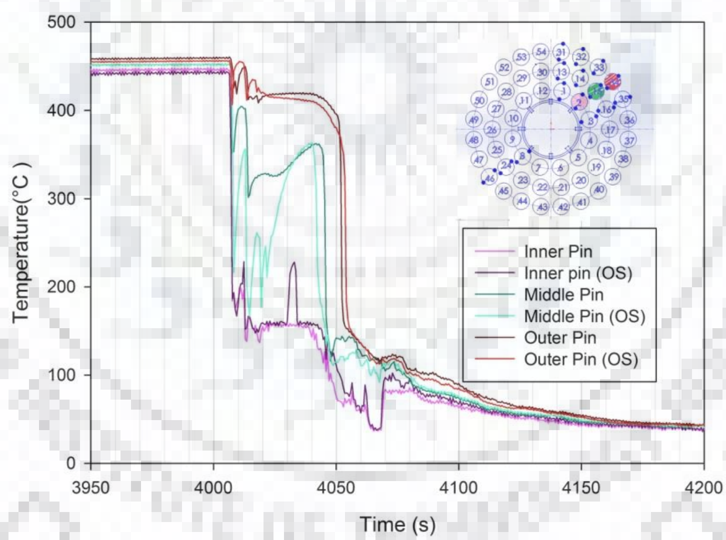

Figure 5.6.: Temperature-time graph for section-B at 450°C.

The outer pins which is away from the central cooling rod, takes more time to receive water because, water has to travel long to reach, so the circumferential location of outer pin enable it to quench after inner and middle pins. The outer pins nodes at section-B do not receives coolant directly by jet, but it receive either splashed water by middle pin or the pressure tube, so it is obvious that the time taken by the coolant will be comparatively high than inner and outer pins. The coolant is also not getting directly so the cooling and rewetting time is higher. The inner pins shows sudden drop in temperature with start of coolant supply whereas, the middle pin shows high fluctuation and temperature drop takes more time than the inner pin. The outer pin node-B34 and B34(OS) approximately shows similar trend in temperature time graph. It takes almost 45 seconds before initiation of rewetting and during this period the temperature of both nodes on outer pin declined gradually as it can been seen as a cure in Figure 5.6 thereafter, the rewetting occurs and the rewetting time for the nodes B34 and B34(OS) was recorded 3.5 seconds and 1.78 seconds and during this period the temperature drop was recorded 215°C and 225°C in respective nodes respectively. It was observed the node-35(OS) enters into rewetting earlier than the node-35 implies that the reflected water from the pressure tube reaching to the outer clad tube first than radially outward water.

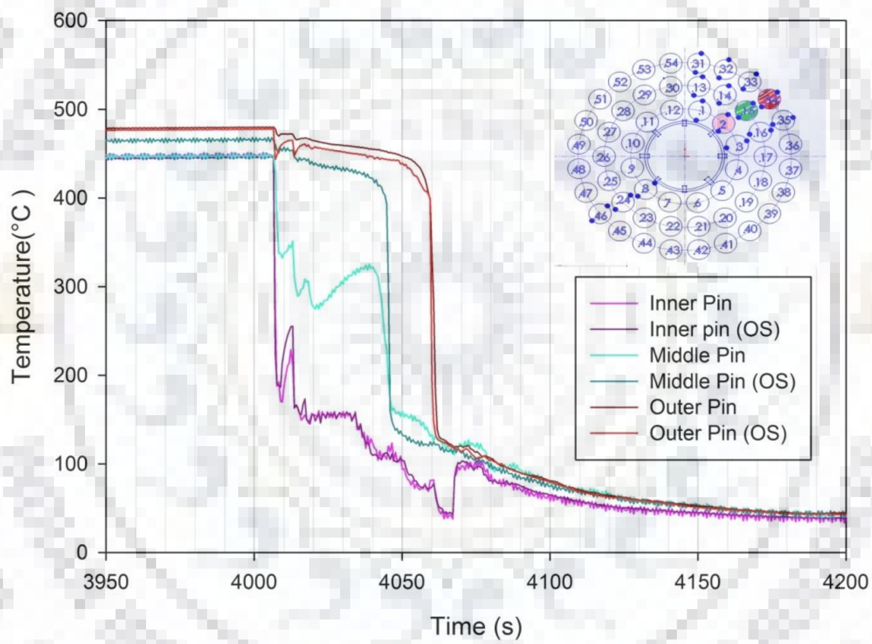

Figure 5.7.: Temperature-time graph for section-C at 450°C.

The temperature time graph for section-C at 450°C and 90 LPM have shown in Figure 5.7. The quenching at both nodes of inner pin-2 at section-C of fuel bundle occurs simultaneously. The node-C2 and C2(OS) approximately follow the same trends. It was seen that the node C01 takes 0.5 seconds whereas C01(OS) takes 0.8 seconds before large temperature drop and during this period the temperature decreases by 12°C and 3°C respectively. The rewetting time recorded in the inner pin nodes are 1.60 and 1.63 seconds and temperature reduced by 255°C and 257°C in node C2 and C2(OS) respectively. The decrease in temperature during rewetting was observed minimum in inner pin compare to middle and outer pins as it can be also seen in the Figure 5.7.

The node C15 and C15(OS) are located on middle pin of fuel bundle. The trends of temperature time graph of these two do not match with each other like inner and outer rings pin of fuel bundle. The temperature difference between the node-15 & 15(OS) was recorded highest during quenching inner and outer pins. The fluctuation of temperature with time was more at node C15 compare to all others nodes of section-C. The temperature of node C15 drop by 100°C in just 3.06 seconds and thereafter, fluctuation start and temperature rise and fall continue till it attain the temperature 321°C in 30 seconds. The node-15 temperature 321°C onward, continuous drop in temperature recorded and it can be seen from the graph that there is curve like declination of temperature and thereafter, rewetting start and high rate of temperature drop was recorded. The node-C15 temperature dropped by 160°C in 6.55 seconds, which is highest rate of temperature drop for node-C15. The node-C15(OS) temperature time trends was different and in its early stage of cooling, the rate of change of temperature was recorded minimum and declination of temperature continue till rewetting starts. The temperature declined by 70°C in 38 seconds in film boiling regime of quenching and thereafter, highest rate of change of temperature recorded which is known as rewetting. The temperature reduced by 236°C in 1.01 seconds during rewetting, when water establish contact with clad tube surface. There onward, continuously temperature fall was recoded till it attains the water temperature.

The nodes of outer ring (C34 and C34(OS)) shows similar trends as node-C15. The film boiling heat transfer regime has low rate of temperature drop and it continued till the rewetting starts and during this period the coolant try to wet the hot surface of the clad tube. The formation of vapour on the clad surface resist the heat transfer significantly and due to that, the rate of heat transfer remain low throughout the film boiling regime. The node-C34 remains at low temperature compare to node C34(OS) temperature but the rewetting starting time and end time was observed same as it can be seen from theFigure 5.7. The node temperature drop by 72°C and 75°C in 53 seconds at nodes C34 and C34(OS) respectively. The longer period of rewetting in the outer ring pin-35 observed in all cases, shows that the outer ring pins is take higher time to rewet its surface than inner and middle ring pin. The rewetting starts with the end of film boiling heat transfer, once the rewetting starts then the highest rate of temperature drop was recorded and during this rewetting period the temperature drop by 271°C in 2.73 seconds at both node-C34 and C34(OS), although the rewetting time was recorded little higher in outer side node (opposite to jet direction side) compare to inner side nodes (OS node) in outer pin and similar observation was seen in earlier sections result.

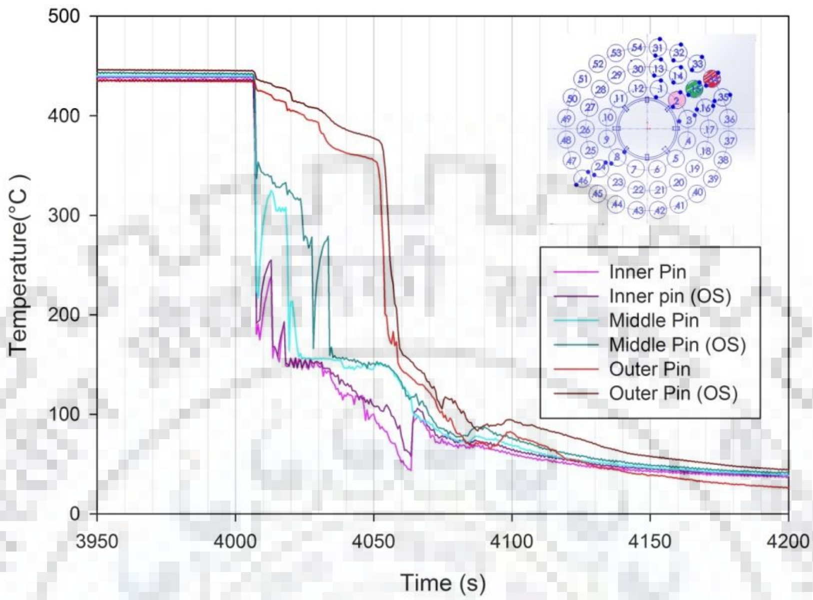

Figure 5.8. Temperature-time graph for section-D at 450°C.

The section-D is 1792 mm down from the top end of fuel bundle and 542 mm from the section-C. The time taken by coolant to reach section-D is more compare to section-A, B and C so the cooling starts 0.02 seconds after the section-A cooling initiation. The nodes of inner pin immediate went under temperature fall with start of the coolant supply. The node-D2 and D2(OS) temperature time trends are approximately similar to each other. The maximum rate of change of temperature was recorded at pin-2 compare to middle and outer ring. The temperature decrease at node D2 by 260°C in 0.87 seconds whereas, the temperature of node D2(OS) drop by 248°C in 0.87 seconds. The rate of change of temperature was recorded more in node D2 compare to node D2(OS) as it can be seen in the above temperature time graph because it receive directly from the water tube in jet form which did not allowed the formation of water vapour on the clad tube surface. Once the rewetting time get over, the temperature time graph went under the high fluctuation of temperature with time and fluctuation continue till inner pin attain the temperature of 100°C in 68 seconds and there after the continuous declination of temperature recorded and finally it attain the supply water temperature.

The middle pin node-D15 and D15(OS) show more fluctuating trends compare to nodes of middle pin at above sections (A, B and C). The node D15 goes approximately under rewetting like inner pin nodes, whereas, the node-15(OS) of inner pin have different trends which do not goes immediately under the rewetting but goes under slow declination of temperature with time i.e. under film boiling heat transfer rather than nucleate boiling regime and high fluctuation of temperature was observed at some point although the outer pin nodes shows similar as nodes of section-A, B and C. The temperature drop starts with start of water supply at node-D34 and D34(OS) and in film boiling heat transfer regime of quenching , the temperature drop by 77°C and 71°C in 45 seconds and 46 seconds at node-D34 and D34(OS) respectively. The most important observation in the film boiling quenching regime is that the opposite side nodes in the outer pin starts undergoing drop in temperature before jet directions node in outer pin at most of the sections, whereas, it occurs in opposite way at inner and middle pin nodes . The node-D34(OS) have shorter rewetting time than node D34 indicate that the coolant reach outer surface more efficiently than inner surface in outer pin. The rewetting time for node D34 and D34(OS) are 4.80 seconds and 6.96 seconds and during this period temperature reduced by 185°C and 206°C respectively thereafter, the gradual decrease in temperature was recorded till it attained the fuel bundle attain supply water temperature

In similar way, the experiments were conducted and analyzed at 500°C, 550°C and 600°C.

6. Organization of thesis

The thesis work presented here has been organized into six chapters. The brief details of all the chapters are as follows:

CHAPTER 1: This chapter presents the introduction of the 220 MWe IPHWR details working principle and varies types of thermal hydraulic failure of the channel during boil-off condition. The AHWR fuel bundle rewetting had been discussed along with loss of coolant accident scenario.

CHAPTER 2: This chapter presents the thermal hydraulic failure of the channel during boil-off condition and completely void condition of PHWR. The advancement in research for the safety of channel had been studied. The AHWR fuel bundle rewetting by varies method has been discussed. The parameters that affect the rewetting phenomena had been also discussed in details.

CHAPTER 3: This chapter provides the details fabrication process and components of the set-up of AHWR & PHWR set-ups.

CHAPTER 4: This chapter provides, the process of preliminary testing before conducting the experiments and experimental process for boil-off condition of PHWR and rewetting of AHWR had been discussed in details.

CHAPTER 5: This chapter covers result and discussion of the experimental output data. The temperature distribution across the channel and effect of eccentricity on temperature had been discussed for PHWR. The AHWR rewetting at 90LPM coolant supply was also discussed at four temperatures.

CHAPTER 6: This chapter embodies the conclusion for the experimental result and discussion for temperature distribution and rewetting phenomena. This chapter also includes the scope for future research in this area.

7. Publication papers

1. Subodh Kumar Yadav, Ravi Kumar, D. Mukhopadhyay, Prasanna Majumdar, (2019), "**Experimental investigation on temperature distribution of channel at elevated temperature of Indian PHWRs under boil off condition during LOCA**", Nuclear Engineering and Design (Under Review)
2. One paper has been communicated to Bhabha Atomic Research Centre (BARC), Mumbai, India for clearance.