DESIGN AND INVESTIGATION OF WEIGHT BUNDLE SIMULATOR FOR INDIAN PHWR USING APDL - A THERMAL ASPECT

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ABSTRACT

Under a postulated scenario of Loss of Coolant Accident (LOCA) with un-availability of emergency core cooling system (ECCS) for Indian Pressurized Heavy Water Reactor (IPHWR), the channel integrity needs to be assured. An experimental facility is presently being developed at Indian Institute of Technology Roorkee (IIT R) India to study such a severe event. In this study a CFD simulation of fuel bundle weight simulator is being carried out using ANSYS 19.0 in transient thermal analysis using ANSYS Parametric Design Language (APDL) solver. The test facility aims to estimate the thermal aspect of weight bundle simulator which is the source of heat generation for pressure tube. Thermo-mechanical deformation of pressure tube will depend on the heat source, therefore it is of great importance to check the thermal integrity of weight bundle fuel simulator. Power requirement, weight, and dimensions of weight bundle fuel simulator is similar to the actual fuel bundle used in 700 MWe IPHWR. Simulation was done for 3 % and 2% decay heat. From analysis it was found that the rate of temperature rise in pressure tube with 3 % decay heat reached a maximum of 2 ^{0}C/sec and average rate of temperature rise was around 1 ^{0}C/sec whereas with 2% decay heat, pressure tube maximum temperature rise was 1.5 ^{0}C/sec and average rate 0.8 ^{0}C/sec. Results obtained will be further used for designing of 700 MWe full length channel set-up.

KEYWORDS: LOCA, Pressure Tube, Thermal Integrity, Weight Simulator.

1. INTRODUCTION

Indian Pressurized Heavy Water Reactor (IPHWR) of 700 MWe capacities consists of an integral assembly of 392 reactor channels. Each channel housing consists of 13 bundles having 37 element configurations. For 700 MWe IPHWR the time averaged maximum channel power is 6.5 MW and corresponding maximum time averaged bundle power is 790 kW were provided by S A Bhardwaj [1]. Fuel bundle is of 495 mm length and weighs 23.5 kg each. The fuel pin bundles are placed inside a Pressure Tube (PT) made of Zirconium 2.5% Niobium (Nb) material. Each PT is concentrically fixed inside a Calandria Tube (CT) made of Zircaloy-2. Garter springs are employed to maintain the concentricity between PT and CT. The carbon dioxide gas at atmospheric pressure is filled in gap between CT and PT for thermal insulation. The accidents in a Nuclear Power Plant in the form of Loss of Coolant Accident (LOCA) have been a reason of prime concern in the nuclear industry. Under a postulated scenario of LOCA with Emergency Core Cooling System (ECCS) the channel integrity needs to be assured. During LOCA, break size is an important parameter which determines the PT deformation. Brown et al. [2] conducted an experiment stimulating LOCA condition along with ECCS failure in which correlated a range of break sizes in the heat transport system to the maximum temperature attained by the fuel bundle inside the PT. During channel heat-up scenario, the channel internal convective heat removal is limited and heat is transferred from fuel bundle to

pressure tube is through radiation, therefore it becomes difficult to remove the decay heat from the reactor core after the shutdown due to total or partial loss of coolant flow in the channels. This loss of coolant causes the fuel bundle temperature to rise due to the decay heat and the stored heat of fuel bundle. Under this condition, the temperature of PT also rises, causing deformation of PT either by ballooning or sagging, depending upon the pressure inside the PT. PT sags and comes in contact with CT predominantly due to internal pressure, self- weight and fuel bundle weight. The stratification of the coolant inside the channel may even lead to asymmetrical ballooning of the PT. The sagging and ballooning of PT causes PT-CT contact. When this contact is established, then the deformation and temperature rise is arrested due to dispersion of accumulated heat to the moderator. It is therefore, essential to study the behavior of PT under varying heat-up rate, to assess the temperature variation and PT-CT contact nature. Experiments conducted by Gillespie et al [3] concluded that the ballooning or sagging in PT depends on internal pressure, top of the PT contacted CT first when pressure was above 2.5 MPa and the bottom of the PT contact the CT first when the pressure was less than 1 MPa. PT deforms only around the lower face in sagging while the full tube balloons in case of ballooning. If PT- CT contact occurs as a result of PT deformation, the mode of heat transfer changes from radiation to conduction through the point of contact, which greatly enhances the heat transfer. Sujay et al. [4] experimentally investigated the thermal behavior of the Indian-made full-length PT of an Indian PHWR and concluded that the initiation of sagging occurs at around 460 ^{0}C. The PT-CT contact took place at a contact temperature of 665–669 ^{0}C at the bottom of the PT. Nandan et al. [5] experimentally studied the heat up behavior of an Indian PHWR specific reactor channel under different heat up conditions in a PT of 2.5-meter length. It was concluded from the study that sagging initiation occurred at around 450^{0}C. With the occurrence of PT-CT contact the rise in temperature got limited. Breach of PT was not observed and moderator as heat sink was found to be effective to remove power continuously from PT after PT-CT contact got established. Ashwini et al [6] experimentally investigated to study thermo-mechanical behavior of PT under asymmetric heating conditions for a 220 MWe PHWR. The asymmetric heating of PT was carried out at a pressure of 2 MPa and 1 MPa, respectively, by supplying power to upper region heating elements thus creating an half-filled stratified flow conditions and it was found out that 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 was 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. Nitesh et al. [7] carried out Experimental investigation of transient behavior of IPHWR underheat up condition. Experimental setup was designed and fabricated to simulate the debris bed scenario. Experiments were conducted at different moderator levels, in the Calandria vessel and at different rated power showed that the temperature of the exposed rods gets stabilized with time due to steam cooling. It was observed that, the temperature is well below the melting point of the cladding, PT and CT material.

In the wake of nuclear accident occurring in various parts of world, it is essential for Indian PHWR program to ensure the safety of the nuclear reactors. CANadian Deuterium Uranium (CANDU) reactors observations and results cannot be applied for Indian PHWR Pressure tubes as they have different manufacturing methods and dimensions. However, none of the past studies conducted in reference to Indian PHWR safety have been conducted using fuel bundle weight simulator for 700 MWe IPHWR. In the present paper, results from simulation of fuel bundle simulator have been discussed. Numerical model was simulated using transient thermal analysis in ANSYS 19.0 to get a preliminary insight of thermal integrity of fuel bundle weight simulator. The experimental facility is presently being developed at Mechanical and Industrial Engineering Department of the Indian Institute of Technology, Roorkee, India.
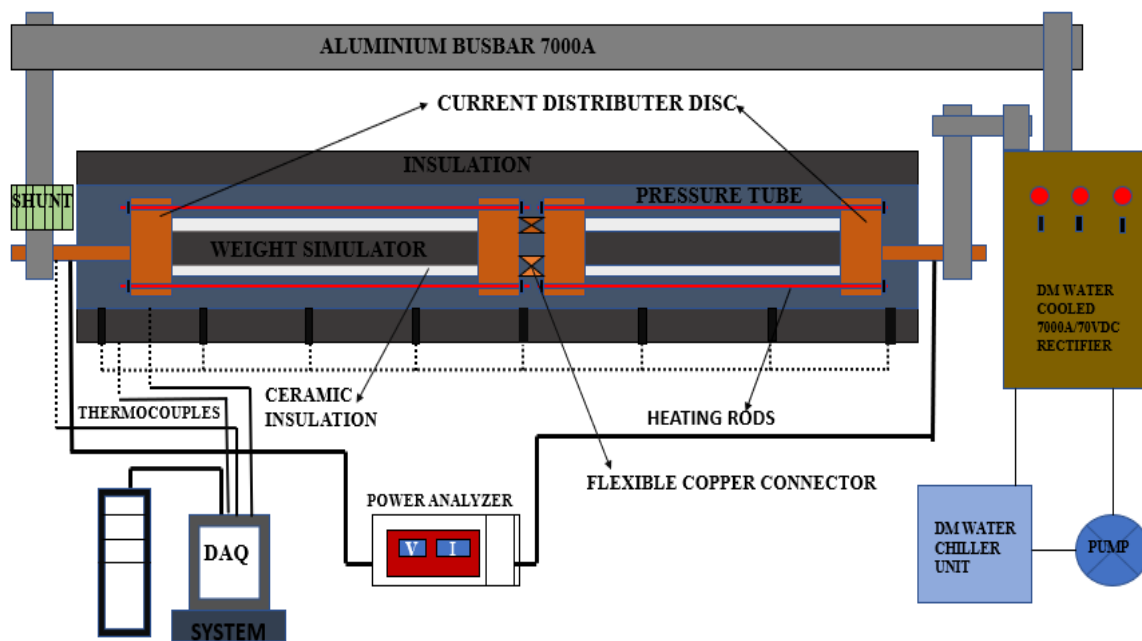
2. EXPERIMENTAL SET-UP

There are various constraints while designing the fuel bundle simulator. IPHWR 700 MWe reactor has a Design (maximum) channel power of 6.5MW (thermal) and decay heat is 2.95% of maximum channel

power i.e. 192 kW. The power to be supplied to the test-section was decided according to the approximate decay heat produced in the fuel bundle during LOCA with ECCS failure. Fuel bundle simulator should be able to provide a maximum power of 192 kW.
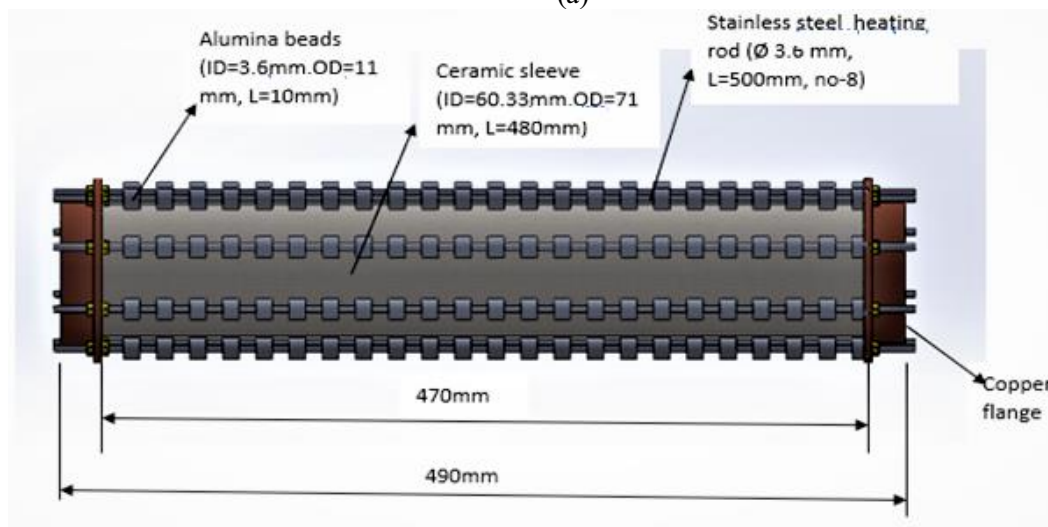
The experimental set-up consists of mild steel tank of 6 m length. Full length channel consists of calandria tube of material zircaloy 2 and PT of material Zr, 2.5 wt.% of Nb alloy. Schematic of experimental set up is shown in figure 1.Fuel bundle simulator comprises of a stainless steel pipe having length 480 mm with inner diameter 54.792 mm and thickness 2.769 mm. Ceramic sleeves of inner diameter 61 mm and thickness 4.5 mm having length 480 mm.The ceramic sleeve prevents undesirable heat transfer to the Stainless steel pipe during the experiment as well as provide electrical insulation between PT and bundle weight simulator. Weight bundle simulator consists of 8 stainless steel rods arranged in a circular arrangement for heating of PT. Heater rod having a diameter of 3.6 mm, a total of 16 heating rods will be used in this test set-up. Alumina beads of inner diameter 4 mm and thickness 4 mm having length 10 mm will be placed over heating rods. The purpose of alumina beads is to provide electrical insulation and avoid any contact between heater rod and pressure tube during heating of fuel bundle simulator. Weight bundle consists of stainless-steel pipe containing tungsten rod to stimulate the weight of actual fuel pin bundle. Electrical connectivity will be ensured by copper flange which will be used as current distribution disc. The connections between fuel bundles will be provided by stack of flexible copper strips. The fuel bundle simulator will be directly heated by using a thyristor controlled 490 kW (70 VDC/7000 A) rectifier which supplies a continuous DC power supply at fluctuations around ±1 kW.

Table I : Specification of experimental test set -up

Description	Weight assembly-Stainless steel pipe containing tungsten rod	Tungsten rods	Heating rods	Calandria tube	Pressure tube	Insulation Over stainless steel pipe	Alumina Beads	Current distributio-n disc
Outer Diameter (mm)	60.33	50	3.6	132	112.64	70	12	91
Inner Diameter (mm)	54.792			129	103	61	4	71
Length (m)	0.48	0.48	0.49	5.8	6.44	0.48	0.010	0.020
Material	Stainless steel and tungsten	Tungsten: 1 nos	Stainless steel :8 nos	Zircaloy 2	Zr, 2.5 wt.% of Nb alloy	Ceramic	Al_2O_3-95% SiO_2 - 2.3% Fe_2O_3- .75% TiO_2- 1.3%	Copper

(a)

(b)

Figure 1. a) Schematic representation of test section   b) Fuel bundle weight with dimension

3.   NUMERICAL METHODOLOGY

ANSYS 19.0 Transient thermal analysis was used to investigate heat transfer within the test section. Numerical simulation was done using Mechanical ANSYS Parametric Design Language (MAPDL) solver. MAPDL is based on finite element method. Implicit scheme is used for transient analysis. Surface to surface (S2S) radiation model is used to solve radiative heat transfer in the numerical simulation. Governing equation used in analysis of radiation model (S2S) and energy equation is given in equation 1 and 2 respectively [10,11].

$$Q_{out,k} = \varepsilon_k K \sigma T_k^4 + \rho_k q_{in,k} \tag{1}$$

$$\frac{\partial(\rho e)}{\partial t} + \nabla.(\rho e \vec{v}) = -\nabla.(k\nabla T) + \nabla.(\bar{\bar{\tau}}.\vec{v}) + S_e \tag{2}$$

3.1. Geometric Model

2D model of test set up was created in the design modeler available in ANSYS workbench. As shown in schematic figure 2 containing pressure tube, calandria tube, heater, alumina bead and ceramic insulation was validated. Other components of test set-up were not taken into consideration because axial heat transfer is neglected.
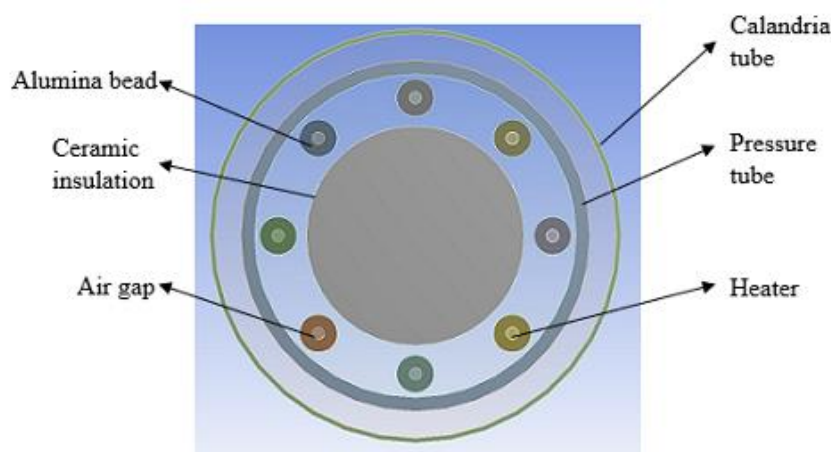

Figure 2. 2D model of test section

3.2. Mesh Generation

The computational domain is discretised using ANSYS Workbench. The two-dimensional mesh of test section is generated using combination of all triangular method and multizone quad/tri method as shown in figure 3. Such regular and near regular triangle-quad hybrid meshes provide two key advantages: first, novel-looking polygonal patterns achieved by mixing different arrangements of triangles and quads together; second, a finer discretization of angle deficits than utilizing triangles or quads alone [8]. The number of the elements used is 321963 and the number of nodes is 723508. Inflation layer was used near fluid solid interfaces for smoothing the temperature profile. The minimum cell size used in final mesh was 0.1mm.

3.3. Material Properties

The materials used in the considered domain are same as experimental set up. Materials used for various components are mentioned in table I. The emissivity's of inner and outer surfaces of the pressure tube are assumed to be constant and equal to 0.8. The emissivity of the inner surface of the Calandria tube is set to 0.34 and alumina emissivity is taken as 0.3 whereas heater emissivity is 0.8.
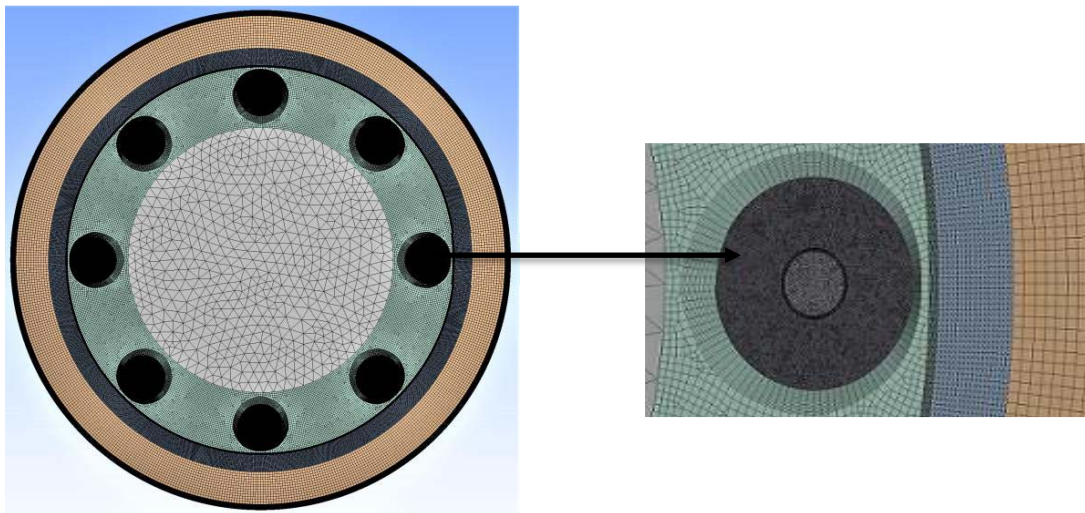
Figure 3. Mesh geometry of Test section

3.4. Boundary Conditions

The boundary conditions used for test section are illustrated in figure 4. Convection boundary was used to model same condition as moderator, outer surface of calandria tube is at initial temperature of 65 ^{0}C and heat transfer coefficient was calculated from Churchill and Chu (1975) [8] correlation for natural convection over horizontal cylinder given in equation 3.

$$Nu = \left(0.6 + \frac{0.387 Ra_D^{1/6}}{\left(1+(0.559/Pr)^{9/16}\right)^{8/27}} \right)^2 \qquad (3)$$

Nusselt number used in equation 3 is a function of Rayleigh Number and Prandtl number.
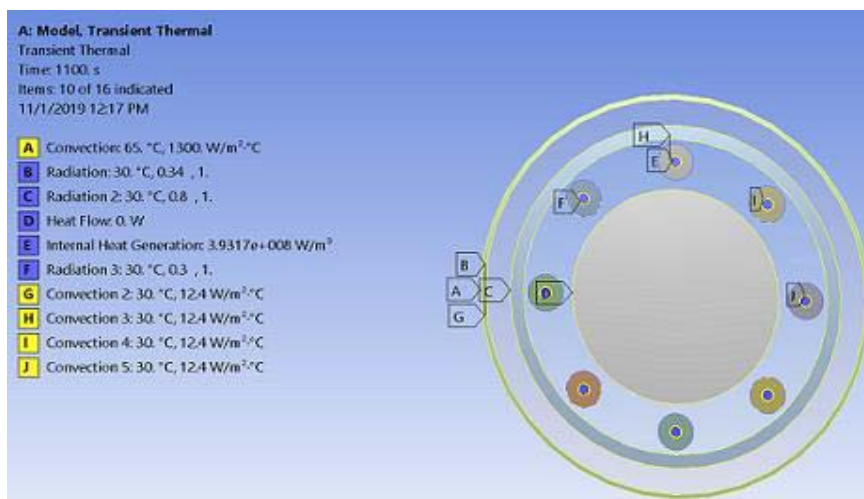

Figure 4. Boundary conditions used in Analysis

4. RESULTS

A 2D model was meshed using elements of different sizes and shapes. Simulation was performed on six different mesh type to perform grid sensitivity analysis. The detailed description is mentioned in figure 5

and table II respectively. It is observed that percentage deviation in temperature using different element size is less than 0.1 %. Therefore, mesh type having 321963 elements is used for transient heat transfer analysis.

From the finding of Nandan et.al it is observed that pressure tube sagging initiates at around 500-600 seconds whereas, in this study Simulation was run for 1100 seconds to check the thermal integrity of fuel bundle weight simulator in worst case scenario.
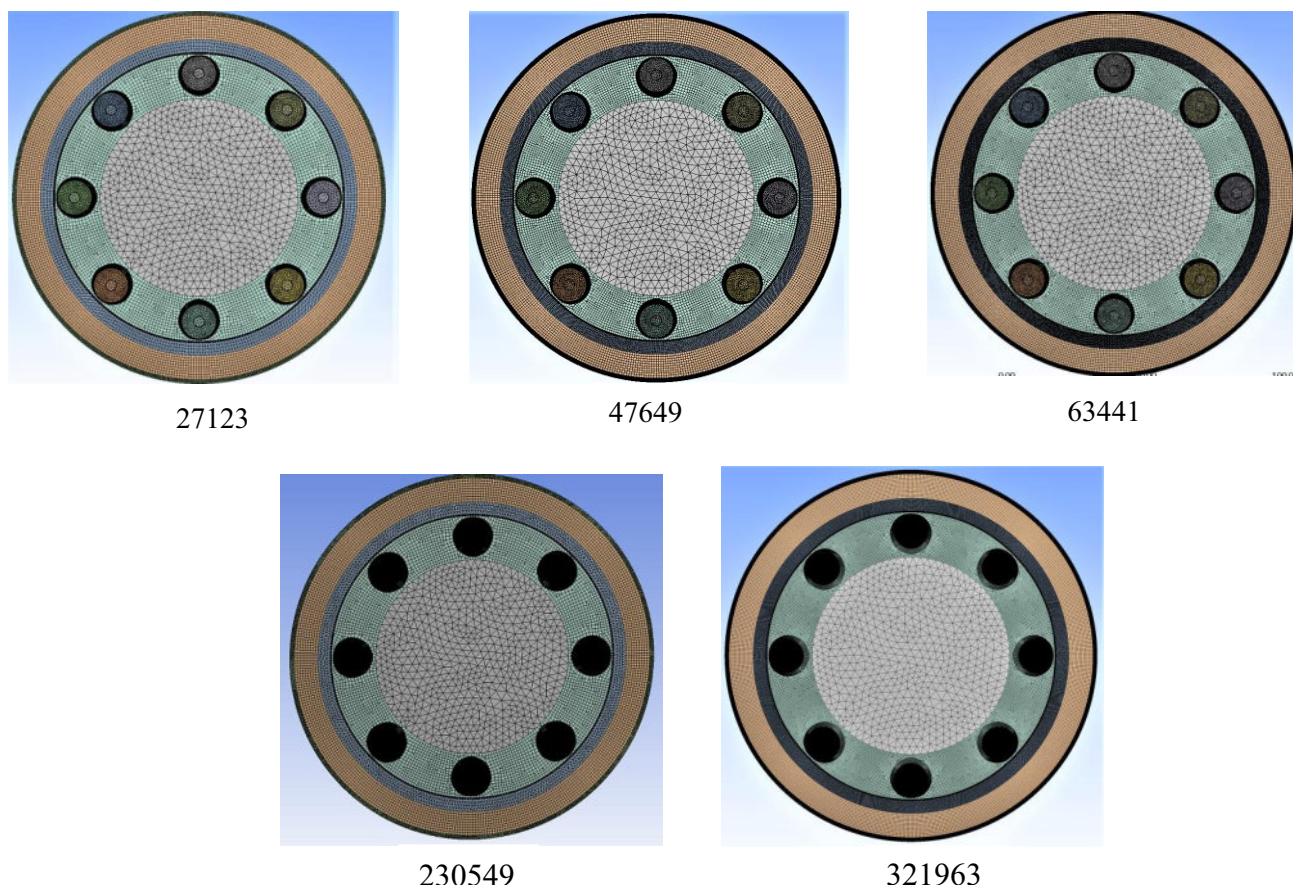

27123

47649

63441

230549

321963

Figure 5. Different grid sizes of mesh

Table II: Comparison of temperature for different mesh size (3 % decay heat)

Mesh Elements	Temperature (^{0}C)		
	heater	Pressure tube	Calandria tube
27123	1466.3	1005.2	101.06
47649	1466.5	1005.4	101.08
63441	1466.5	1005.4	101.08
230549	1466.6	1005.5	101.1
321963	1466.6	1005.5	101.1

Temperature contour of the fuel bundle simulator, pressure tube and calandria tube for 3% and 2% decay heat at 1100 seconds is shown in figure 6. With 3% decay heat maximum temperature attained by heater is 1466.6 ^{0}C and temperature of pressure tube and calandria tube is 1005.5^{0}C and 101.1^{0}C respectively,

whereas with 2% maximum temperature reached by heater is 1247 ^{0}C, pressure tube and calandria tube is at 812 ^{0}C and 84^{0}C respectively.

Figure 7 shows the temperature variation in fuel bundle simulator for 3% and 2% decay heat. With 3% decay heat it is observed that in fuel bundle simulator maximum 2 ^{0}C/sec rise in temperature is between 300 -800 sec after that rise in temperature is not significant. However maximum of 1.5 ^{0}C/sec temperature rise is observed with 2% decay heat.
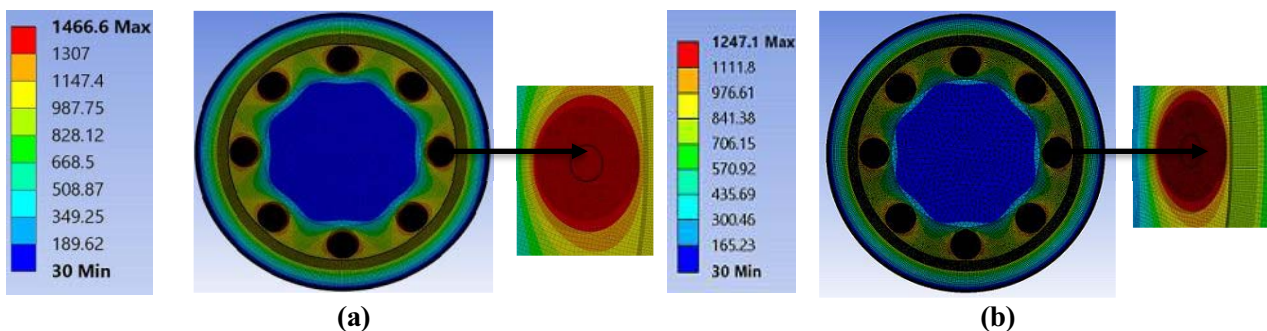

(a)   **(b)**

Figure 6. Temperature contour of Test section a) 3 % decay heat and b) 2% decay heat

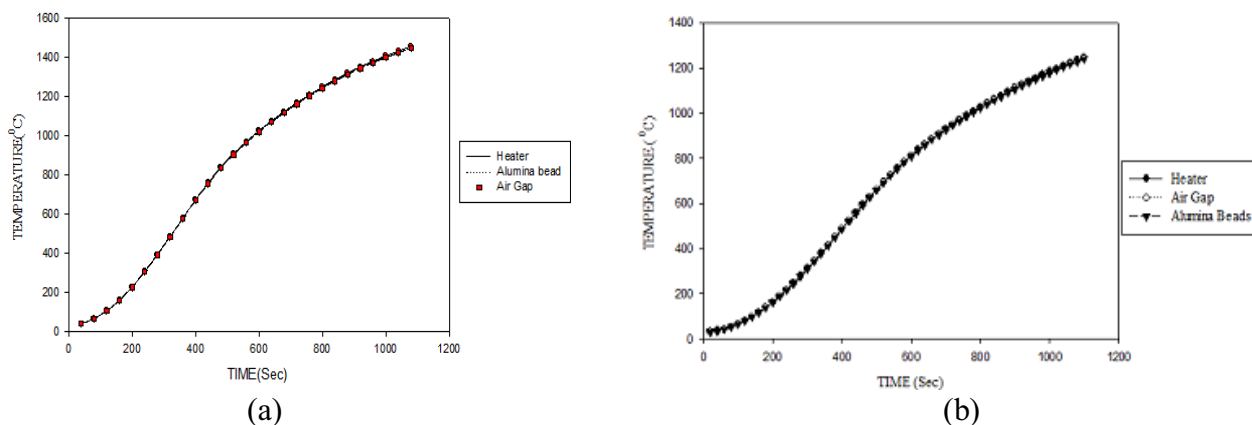(a)   (b)

Figure 7.Variation in different components of fuel bundle simulator temperature with time for a)3% decay heat   b) 2% decay heat
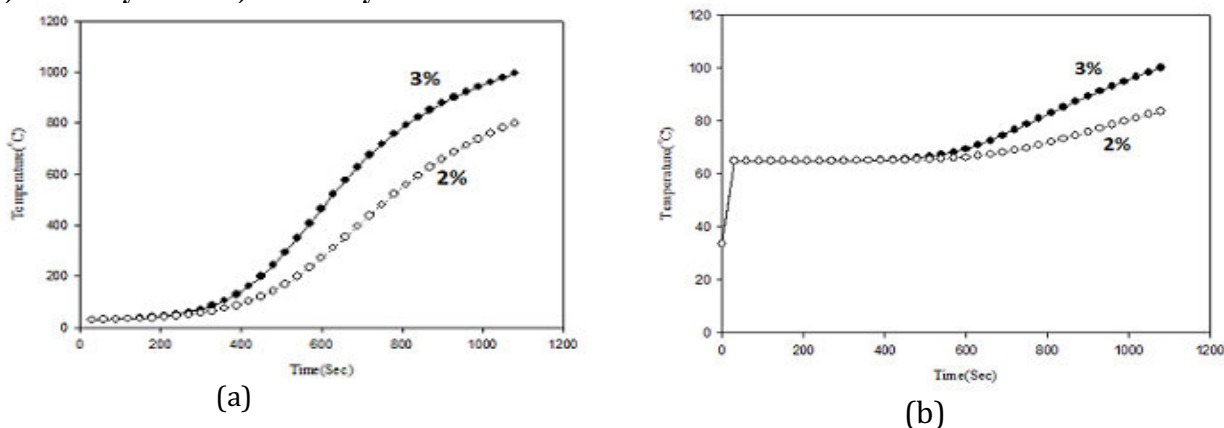

(a)   (b)

Figure 8. a) Variation of Pressure tube temperature with time for 3% and 2% decay heat   b) Variation of calandria tube temperature with time for 3% and 2% decay heat

Figure 8 shows transient temperature of PT and CT for different decay power. In pressure tube there is a steep rise in temperature after 400 seconds and it continues till 800 seconds because rate of radiation heat transfer is maximum during that interval. After 1100 sec there is no significant variation in temperature as it approaches near to steady state condition and steady state is expected to achieve at 1500 sec. In calandria tube there was no change in temperature up to 500 sec after that there is a rise in temperature reaching to a maximum of 101 ^{0}C, this is due to rise in temperature of pressure tube above 500 ^{0}C.

5.   CONCLUSIONS

Numerical Simulation of fuel bundle weight simulator for Indian PHWR was carried out by supplying the calculated decay heat to a 700 MWe full length specific reactor channel. The thermal behavior of fuel bundle simulator for an input power of 192 kw and 130 kw were studied. Observations from the analysis are:

1. Maximum temperature attained by heater at 1100 sec was 1466.6 ^{0}C for 3% decay heat. Thus, thermal integrity of fuel bundle weight simulator is expected to be maintained during experiment as temperature is below melting point of heater.

2. Maximum rise in temperature of Pressure tube was at a rate of 2^0C/sec and average rise in temperature was 1^0C/sec for 3% decay heat and maximum temperature rise rate for 2% decay heat was 1.5 ^{0}C/sec, which is required during experiments.

3. For a 3% decay power, calandria tube temperature was maintained at 65^0C up to 600 sec and reached a maximum of 101.1 ^{0}C when pressure tube temperature surpassed its sagging temperature of 550 ^{0}C. Similar trends where found for 2% decay heat as well and maximum temperature attained was 84^0C.

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