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Effect of eccentricity of pressure tube on circumferential temperature distribution of PHWR fuel bundle under postulated accident condition

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ABSTRACT

For a large break Loss of Coolant Accident (LOCA) scenario with simultaneous failure of Emergence Core Cooling System (ECCS), the heat removal capability of coolant decreases, resulting in the complete voiding of the core of the reactor channel. In this scenario, radiation becomes dominating mode of heat transfer over the convection heat transfer from fuel bundle to Pressure Tube (PT). Due to this, the deformation of PT takes place either in the form of ballooning or sagging depending on prevailing internal pressure. The present paper aims to capture the circumferential temperature profile over the fuel bundle, PT and Calandria Tube (CT) undergoing sagging deformation of PT under a postulated LOCA with Loss of ECCS scenario. An experimental facility was designed and fabricated to simulate the sagging deformation of PT by changing the eccentricity "e" of PT with respect to the CT. The experiments were conducted at three different positions of PT i.e. e = 0, e = 4 mm and e = 8.5 mm at 1100 °C fuel bundle temperature. The experimental results showed that the eccentricity of PT strongly affected the circumferential temperature distribution over the fuel bundle, PT and CT. The variation of temperature along the circumference of fuel bundle and PT at e = 0 was insignificant, however, for other positions, this variation in temperature was quite significant. The bottom nodes of fuel bundle showed a decrease in temperature with an increase in eccentricity. Similar observations are also made for PT. On the other hand, the temperature at the bottom nodes of the CT increased for higher eccentricity between PT and CT. The experiments predict the temperature behavior for all the channel components for a decay power of 2% full power which is expected during such scenario.

1. Introduction

Under a postulated accident condition such as Loss of Coolant Accident (LOCA) with simultaneous failure of Emergency Core Cooling System (ECCS) in an Indian Pressurized Water Reactor (IPHWR), the heat removal capability of coolant decreases. During such events, the flow of coolant in individual channel is reduced and the coolant present in the channel is converted into steam. Further, the temperature rise results in complete core voiding of the channel, due to which the fuel bundle is deprived of coolant which causes overheating of fuel bundles (Gupta et al., 1997; Mukhopadhyay et al., 2002). In absence of convective cooling, fuel bundle dissipates heat to PT through radiation mode of heat transfer. CT receives heat from PT, though the temperature rise in CT is insignificant as it is surrounded by low temperature heavy water moderator. The temperature rise causes deformation in the PT, either ballooning or sagging or both (Shewfelt et al., 1984; So et al., 1987). The ballooning occurs when the pressure inside the PT is more than 1 MPa. If the pressure inside the PT is lower than 1 MPa, PT sags at a high temperature and comes in contact with the CT. The sagging of PT is due to its own weight and weight of the fuel bundle (Nandan et al., 2010). This physical contact between PT and CT results in high heat transfer to the moderator. Shoukri and Chan (1987) investigated the thermal aspects of pressure tube contact with calandria tube. Experiments were conducted by them to obtain the temperature profiles of the pressure tube and calandria tube under contact conditions. They found that, near the PT/CT contact region a flat temperature profile was obtained which was due to the one direction radial conduction in contact region. It is very important to predict the channel temperature during sagging of pressure tube for reactor safety studies to ensure channel integrity. A study has been carried out to capture the circumferential temperature profile of pressure tube, calandria tube and 19 pins fuel bundle undergoing sagging deformation of pressure tube of IPHWR under fully voided condition by changing the eccentricity of PT with respect to CT.

Abbreviations: PT, Pressure Tube; CT, Calandria Tube; LOCA, Loss of Coolant Accident; ECCS, Emergency Core Cooling System; IPHWR, Indian Pressurized Heavy Water Reactor

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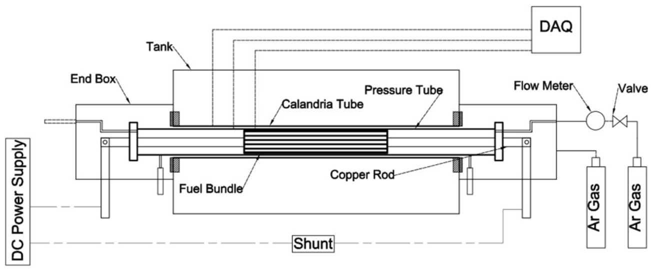

Fig. 1. Schematic diagram of experimental setup.

2. Experimental set-up and procedure

The schematic diagram of the experimental set-up is shown Fig. 1. The set-up consisted 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 wall with the help of gasket and flanges which made the joints leak proof of water. The tank was filled with water, which acted as moderator, so that the CT was submerged into the pool of water. The length of PT was 1250 mm, and the middle 1000 mm length was placed inside the CT, with the remaining 250 mm length outside of the CT (125 mm on each side). The 19 pins fuel bundle of 500 mm length was placed inside the PT.

Two end boxes of 340 mm × 260 mm × 260 mm size with 3 mm sheet thickness were attached to either side of the tank to create argon gas environment inside the annulus gap between PT and CT. The end boxes were provided with the holes at their bottom face with a provision of LVDT installation. The LVDTs were used to measure the displacement of PT with respect to CT. Three lead screws were provided, at the bottom and two end sides of each end box to hold the pressure tube firmly and also helped in the positioning of PT. Argon gas was induced into the PT using a bank of argon cylinders and the flow rate was measured by vortex flow-meter. Thermocouples were provided at both the ends of the tank to measure the inlet and outlet temperature of argon gas. The test-section consisting of the CT, PT and the fuel simulator are shown in Fig. 2. The 19-pin fuel bundle simulator (1 + 6 + 12) was enclosed inside the PT with the help of flanges and rubber gasket was used to make the joint leak proof.

The fuel-pin had a Zircaloy-4 tube of 15.2 mm outer diameter and 0.4 mm wall thickness as shown in Fig. 3(a). The bundle was heated through Joule- heating of a SS-316 rods. The rods were concentrically placed inside the fuel pins and the annular space was filled with alumina powder and compacted. The fuel pins were supported by two identical spacers provided at both the ends. The 19-pins in the bundle are arranged in such a way that one pin was at the centre, 6 pins in the middle and 12 pins in the outer ring. All the pins were made in a parallel electrical connection and both the ends were mechanically fastened to the copper disc of 10 mm thickness acting as a current header. The actual photograph of 19 pin fuel simulator is shown in Fig. 3(b). An input power ratio of 1.4:1.1:1 was maintained in the outer, middle, and centre rods respectively. The above power distribution was attained using different diameter of heating rods in the pins. One copper rod of 35 mm diameter at each end was attached to the current header. These rods were connected to the DC rectifier with the help of bus bars for electric power supply for the purpose of Joule heating of bundle.

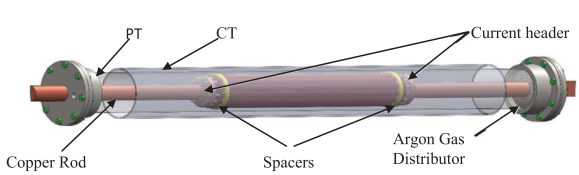

Fig. 2. Experimental test-section.

A total of 126 thermocouples were used to capture the temperature profile over the test section, out of which 54 thermocouples were used in fuel bundle and 36 thermocouples were used in PT and CT respectively. The minerally insulated ungrounded K-type thermocouples with 0.5 mm diameter Inconel sheath were used to measure the temperature of 19 pins fuel simulator and PT while minerally insulated ungrounded J-type thermocouple of 1 mm sheath diameter were used to measure the temperature of CT. The axial and circumferential location of thermocouples on PT, CT and the fuel bundle are shown in Figs. 4 and 5 respectively. Thermocouples were fixed over the surface of fuel pins with the help of zircaloy-2 foils having dimensions 6 mm × 4 mm × 0.1 mm. The thermocouple tip over substrate was covered with the foil which was spot welded to the substrate at a number of places, holding the foil tight to the surface. The thermocouples at the two sections of the bundle were fixed at symmetrical positions, 200 mm axially apart from the centre of fuel simulator. Small grooves of size 18 mm × 0.5 mm × 0.1 mm and 18 mm × 1 mm × 0.5 mm were made over the PT and CT surfaces respectively, in which thermocouples were inserted and fixed with the help of zircaloy-2 foils.

The thermocouples were fixed axially at four different sections (A, B, C and D) on PT and CT. At section A and D, thermocouples were fixed circumferentially at six different angular locations i.e. 30°, 60°, 150°, 210°, 270° and 330°, while at section B and C, thermocouples were located at 12 different angular locations circumferentially i.e. 30°, 90°, 150°, 210°, 240°, 255°, 265°, 270°, 275°, 285°, 300°, and 330° as shown in Fig. 5. The nomenclature of fuel pins is shown in Fig. 6. The details of circumferential locations of thermocouples over the fuel bundle is shown in Table 1. Before connecting the thermocouples to Data Acquisition System, all the thermocouples were tested and calibrated.

In the experiment, first, the tank was filled with water, simulating moderator and CT was completely submerged in the pool of water as in the case of reactor. The water in the tank was heated to 55 °C with DC powered auxiliary (mild steel) heater. Initially, vacuum of 80 kPa was created inside the PT and fuel pin. Subsequently the PT was filled with Argon gas at atmospheric pressure. The procedure was repeated 2–3 times to ensure the complete removal of air from in the system. The mass flow rate of argon gas was maintained at 3.6 kg/h and was measured with the help of a vortex flow meter. The experiments were carried out at three different eccentric positions of PT with respect to CT at fuel bundle temperature of 1100 °C i.e. e = 0, e = 4 mm and e = 8.5 mm.

To simulate the sagging deformation, the vertical eccentricity of PT was varied by untightening of the clamping screws provided in the setup at three different positions i.e. PT concentric with CT (e = 0), PT 4 mm eccentric with CT (e = 4 mm) and PT contact with CT (e = 8.5 mm) respectively as shown in Fig. 7. The eccentricity of the PT was monitored by LVDT readings in the DAQ system. For the first experiment, PT was made concentric with the CT and DC power was supplied to the fuel bundle till the average temperature of the centre pin attains 1100 °C. This process was repeated for the other experiments by changing the eccentricity i.e. e = 4 mm and e = 8.5 mm.

3. Results and discussions

From the above experiments, the temperature data for the simulated channel were logged. A significant variation in temperature was observed axially as well as circumferentially over the fuel bundle, PT and CT. As discussed earlier, the temperature measurement was carried out at four stations (A, B, C, and D) of PT and CT and two stations (B and C) on the fuel bundle. As expected, the maximum temperatures were obtained at section B and C. This is due to the presence of the heated fuel bundle which was placed at the middle of the PT. On the other hand, the temperatures at section A and D were substantially lower as the heat transmission in these sections was axial only. Hence the present study has been carried out by considering only these two sections i.e. section