Design and Development of Fuel Rod Cluster Simulator

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Abstract

The designer of a nuclear reactor system, has to ensure its safety during normal operation as well as accidental conditions. This requires, among other things, a proper understanding of the various thermal hydraulic phenomena occurring in the reactor core. In a nuclear reactor core, the fuel elements are the heat source and highly loaded components of the reactor system. Therefore, their behaviour under normal and accidental conditions must be extensively investigated. The complex nature of these phenomena calls for exhaustive experimental investigations. Fuel Rod Cluster Simulator (FRCS) is a very important component, required for the experimental investigation of the thermal hydraulic behaviour of reactor fuel elements. This paper brings out various design aspects and challenges in the design of the FRCS. Some of the main features of directly heated FRCS have also been presented in the paper.

Keywords: Fuel Rod Cluster Simulator, Fuel Rod Simulator; Critical heat flux

Introduction

Thermal hydraulics plays a vital role in the safety evaluation of a nuclear reactor. The safety analysis envisages prediction of the thermal hydraulic parameters under normal operating conditions and anticipated transients as well. The licensing criteria demand, that critical parameters like fuel temperature, clad temperature and critical heat flux, should be well within the prescribed limit, for the safe operation of the reactor. To meet this requirement, various computer codes are developed, to analyze the normal operating conditions and the accidental scenarios. However, these codes need to be validated to minimize, the prediction uncertainties of various models, incorporated in the code. Thus validation of the codes demands generation of experimental data, under conditions of interest. Since thermal hydraulic experiments in the actual operating nuclear fuel bundle is not possible due to radiation hazard and limitations on the instrumentation of the fuel bundle, in-pile experiments are generally ruled out. Also, this data needs to be made available, before the licensing of the reactor at the commissioning stage. Thus, in view of the safety requirement and limitation of the in-pile experiments, the research community generally relies on the out-of-pile experiments. In the out-of-pile experiments, the nuclear fuel bundle is simulated using electrical heating and other systems like MHT, ECCS etc. are simulated to conduct transient experiments. The success of the experiments depends on the simulation of the fuel bundle using the electrical heating and
measurement of the important parameters like fuel clad surface temperature. Also, a part of the FRCS needs to be instrumented heavily in order to detect the location of dryout. For this purpose, probable location of dryout needs to be decided judiciously. Thus, the design of Fuel Rod Cluster Simulator (FRCS) poses challenges in terms of the required electrical resistance, power profile simulation (radial and axial), geometrical simulation and mounting of a large number of instruments like thermocouples, on the fuel rod surface. Various thermal hydraulic facilities world-wide use the FRCS which are proprietary in nature and hence complete design details are generally not made available in open literature. The various thermal hydraulic facilities like ATLAS, Heat Transfer Research Facility Columbia, HTL (PNC), ITF[6], ATTF[7] etc. use either directly heated FRCS or indirectly heated FRCS.

V. Casal [10] described different design aspects of FRCS and developed high performance indirectly heated FRCS for thermodynamic experiments. S. M. Balahov et al. [9] presented various FRCS designs used for thermal-hydraulics investigations for different facilities simulating VVERs. Erbacher et al. [5] designed tight-lattice FRCS of Advanced Pressurized Water Reactor (APWR) to carry out experiments on reflowing and deformation behaviour during LOCA. A. Borgohain et al. [1], A. K. Pal et al. [2] and A. K. Vishnoi et al. [3] developed high power rating directly-heated 54 - rods and 37- rods FRCS, simulating AHWR and PHWR fuel clusters respectively. N. K. Maheshwari et al. [8] developed indirectly heated FRCS. The FRCS developed in BARC is a vital equipment for design validation of the AHWR and are used in different facilities like Integral Test Loop (ITL), Facility for Integral System Behaviour Experiments (FISBE) and AHWR Thermal hydraulics Test Facility, Tarapur (ATTF).

**Design Requirement of FRCS**

The FRCS has to meet a number of requirements. These include:

i) Simulation of geometry of the fuel bundle including the spacer.

ii) Simulation of heat flux, power and coolant volume of the reactor fuel channel.

iii) Capability of withstanding high temperature, high pressure conditions simulating reactor conditions.

iv) Adequate instrumentation for experimental data generation, control & safety purposes.

v) Achieving required electrical resistance to suit power supply for maximum power generation.

vi) Proper insulation (electrical) of the heater pin from the rest of the experimental setup.

vii) Capability to withstand repeated cyclic (temperature & pressure) operations.

viii) Ease of assembly and disassembly.

Two types of FRCS commonly used are: direct resistance heating type and indirect resistance heating type.

i) **Direct resistance heating type**: In this type of FRCS, current is passed directly through the tube, which geometrically simulates the cladding of a nuclear fuel rod. This type of FRCS finds application in experiments related to steady state heat transfer in single and two-phase flow of fluids, which are non-conductors of electricity. Very high uniform heat flux can be easily achieved. However, for unsteady state tests, simulation of stored heat is extremely difficult in directly heated FRCS design.

ii) **Indirect resistance heating type**: In this type, a heater pin having central resistance heating element is insulated from the outer tube, which simulates the fuel clad. Heating element is concentrically located within the outer tube. This type of FRCS can be used for all types of fluids. Both steady state and unsteady state tests with single and two-phase flow can be carried out. But it is very essential to maintain uniform and minimum thermal resistance between heating element and the outer (cladding) tube. Special equipment is required for the fabrication of FRCS. All these result in considerable increase in cost and complexity during fabrication. If the gap between
outer tube and heater is filled with gas gap for better insulation; then the FRCS is called gas type indirectly heated FRCS.

**Design and Development of Direct Resistance Heating type FRCS**

A directly heated FRCS has been designed and developed in the Reactor Engineering Division of BARC, Mumbai. The design of the FRCS is based on power-to-volume scaling philosophy. The FRCS (Fig. 1, Fig. 2, and Fig. 3) consists of 54 Fuel Rod Simulators (FRS), which generates heat electrically, shell assembly, center tube for ECCS and provision for electrical connection and insulation. Each FRS is made up of a heater section, both ends of which are welded to connector rods, which simulates the unheated portion and provides electrical connection to the heater section. The connectors are made of nickel rods. The downstream connectors are connected to stainless steel electrical bus bars through top tie plate. On the other end, the connector rod is connected to bus bars through silver coated flexible copper braided wires, to accommodate thermal expansion. Six stainless steel spacers are provided, to maintain the spacing among the FRS.
which exactly simulate the spacers of the reactor. The top tie plate and bottom tie plate could not be simulated exactly, because of the provision required for electrical connections. Ceramic liner tubes are used, to electrically insulate the current carrying heaters from the outer flow tube, which simulates the flow tube. Compressed asbestos material is selected as flange gasket, which also isolates the FRS electrically from the rest of the system. The main design parameters and other details are given in Table 1.

Table 1: Design Parameters of the FRCS

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Pressure</td>
<td>100 bar</td>
</tr>
<tr>
<td>Temperature</td>
<td>315°C (Shell) and 550°C (heater tube)</td>
</tr>
<tr>
<td>Max. Flow rate</td>
<td>6 kg/s</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>3 MW (with 30kA current rating)</td>
</tr>
<tr>
<td>Number of heater rods</td>
<td>54</td>
</tr>
<tr>
<td>Tube material (Cladding)</td>
<td>INCONEL-600</td>
</tr>
<tr>
<td>Filler material</td>
<td>Ceramic (99% and above Alumina)</td>
</tr>
<tr>
<td>Heater length (mm)</td>
<td>3500</td>
</tr>
<tr>
<td>Heater tube outer diameter(mm)</td>
<td>11.2</td>
</tr>
<tr>
<td>Heater Tube thickness (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>Heater Rod PCD (mm)</td>
<td></td>
</tr>
<tr>
<td>Inner</td>
<td>51.39</td>
</tr>
<tr>
<td>Middle</td>
<td>77.39</td>
</tr>
<tr>
<td>Outer</td>
<td>103.69</td>
</tr>
<tr>
<td>Max. linear heat rating</td>
<td>159 W/cm</td>
</tr>
<tr>
<td>Connector rod material</td>
<td>Nickel</td>
</tr>
<tr>
<td>Coolant</td>
<td>Light Water</td>
</tr>
<tr>
<td>Inlet Coolant Temperature</td>
<td>270°C</td>
</tr>
<tr>
<td>Shell Material</td>
<td>SS316L</td>
</tr>
<tr>
<td>Insulating Material</td>
<td>Ceramic and Compressed Asbestos</td>
</tr>
<tr>
<td>Sealing Material</td>
<td>Graphoil</td>
</tr>
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</table>

Conclusion

FRCS is a vital element of a thermal hydraulic facility, to simulate the nuclear heating in the coolant channel. However, the simulation of the nuclear fuel bundle using electrical heaters for out-of-pile experiments poses a lot of challenges. Different types of Fuel Rod Cluster Simulators have their own advantages and disadvantages. Direct resistance heating type FRCS is easy to design and fabricate and a very high heat flux can be easily achieved, but it cannot be used for transient cases and electrical conductive coolants. Indirect resistance heating type FRCS is somewhat difficult to fabricate, but can be used for steady state as well as transient cases. In this type of FRCS, axial variation can also be easily achieved, by varying current carrying conductor thickness. The detailed design of a 3 MW power rating directly heated FRCS has also been presented and compared with the actual fuel assembly.

References

5. Erbacher, F.J.; Wiehr, K., “Experimental investigations on the reflooding and deformation behavior of an advanced pressurized water reactor tight-lattice fuel


