CHAPTER - 1
INTRODUCTION

1.0 FOREWORD

Fast reactor is one of the promising energy options for India. Hence, India pursues Research and Development activities in the domain of fast reactor technology. In this direction, a 40 MW thermal power Fast Breeder Test Reactor (FBTR) is being operational at Kalpakkam, India (Srinivasan et al. 2006). Following FBTR, a 500 MWe Prototype Fast Breeder Reactor (PFBR) is under the final stages of construction (Chetal et al. 2006). The flow sheet of a typical pool type fast reactor is depicted in Fig. 1.1 (a). A typical fast breeder reactor consists of three heat transport circuit viz., two sodium circuits to transfer the nuclear heat generated in the core to the steam-water system and convectional power plant circuit.

Fig. 1.1 (a) Flow sheet of typical pool type fast reactor
The close-up view of the primary circuit is depicted in Fig. 1.1 (b). Cold sodium at 670 K enters the bottom of the core subassemblies, cools the fuel pins in the core subassemblies while passing through them and finally transfers the heat to secondary sodium in Intermediate Heat Exchanger.

Fig. 1.1 (b) Vertical section of Primary circuit of typical Fast Reactor
1.1 THERMAL HYDRAULICS OF FUEL PIN BUNDLE

The fast reactors are characterized by high power density and compact core. To extract large heat flux without pressurizing the coolant, liquid sodium is used as coolant due to its high boiling point and large heat transfer coefficient. A typical medium size sodium cooled fast reactor fuel subassembly consists of 217 fuel pins kept as bundle inside a hexagonal sheath (Fig. 1.2 (a)). The fuel pins are wound with helical wire-wrap spacer to provide lateral support for the fuel pins and to provide space for sodium coolant to flow through the bundle. The fuel pins are arranged in a triangular pitch and the space between the adjacent fuel pins forms coolant sub-channels (Fig. 1.2 (b)). Due to helical wire-wrap spacer, the coolant not only flows in axial direction but also in a transverse direction. This transverse flow provides better mixing of coolant among the sub-channels. Due to this, the heat transfer coefficient of the coolant increases. Also, the hot spot around the pins gets reduced. But, the frictional resistance to flow also increases which increases the pressure drop through the bundle. Thus, thermal hydraulics of fuel pin bundle exhibit interesting and complex thermal hydraulic features such as (i) secondary flows, (ii) periodic flow exchange among the neighboring sub-channels, (iii) development of swirl flow in the peripheral sub-channels with magnitude varying as function of wire position, (iv) non homogeneous temperature variation among the sub-channels, (v) large circumferential variation in clad temperature and formation of hotspot etc. Experimental determination of these fine-scale features even in an ideal small pin bundle is highly challenging. On the other hand, CFD simulation of thermal hydraulics in pin bundle offers all these features in adequate detail.
Fig. 1.2 (a) Fuel subassembly of a medium size fast breeder reactor
D – Pin diameter

$D_w$ – Wire diameter

g - Ligament gap between the last row of pins and the hexagonal sheath.

P – Triangular pitch distance

A/F – Width across flats

A/C – Width across corners

1 – Central sub-channels

2 – Peripheral sub-channels

3 – Corner sub-channels

Fig. 1.2 (b) Terminology and different types of sub-channels in a subassembly
Investigation of the physics of this complex flow and temperature distributions in a heat generating fuel pin bundle with helical wire from basic principles is very important for the design of the core. Towards this, three dimensional conservation equations of mass, momentum and energy are solved by using finite volume based commercial Computational Fluid Dynamics (CFD) codes for a wide range of parameters employing appropriate turbulence models. As a first step, multi-dimensional modeling of 7-pin bundle with one pitch helical spacer wire has been carried out using the CFD code STAR-CD, (2001). Using the CFD code CFDEXPERT, (2008), the flow and temperature distributions of sodium in 217 pin fuel bundle with helically wound spacer wire have been predicted. The results of the above thermal hydraulic analysis are investigated in the present thesis work. The effect of helical spacer wire on turbulent flow of sodium through the fuel pin bundle, the secondary flow created by the wire and the consequent mixing of sodium coolant have been studied. In order to assess the effectiveness of helical spacer wire and the associated penalty in terms of pressure drop, straight wire-wrap fuel pin bundle is also analyzed. Correlations for Nusselt number for 217 pin bundle with different helical pitch of the wire and wire diameters have been proposed. From clad and sodium temperature distribution, the hot spot factor and the hot channel factors are evaluated and compared with that used in safety analysis. The mixing characteristics of the flow and temperature among the peripheral and central zones and their dependence on number of fuel pins in the bundle are critically evaluated for a 217 pin bundle.

1.2 MOTIVATION FOR THE PRESENT STUDY

Traditionally, thermal hydraulics within the subassembly has been studied by (a) experiments using water as medium and in few cases using sodium as medium, (b) porous body models for pin bundle and (c) 3-Dimensional CFD studies with limited number of pins using 7, 19 and 37 pin bundle models. Experimental and porous body model studies do not provide adequate details of cross flow characteristics in the fuel pin bundle with helically
wound spacer wire. On the other hand, 3-dimensional CFD studies are capable of providing intricate details about them. Number of CFD based numerical studies have been performed for bundles with smaller number of pins. However, studies with large fuel pin bundle such as 217 pins are not reported in open literature. Also, the Nusselt number correlation as a function of helical wire parameters has not been reported. In order to develop deeper understanding on the effect of helical wire wrap induced transverse flow, to optimize the mesh density, to select the turbulence model and finally to validate the CFD model, it is adequate to study pin bundles with small number of pins. But, studies on 217 pin bundle which is used in commercial FBRs is essential for the thermal hydraulic design of the subassembly including the development of correlations for friction factor and Nusselt number. The hotspot and hot channel factors are also required to be estimated for 217 pin bundle for validating the values used in one dimensional safety analysis and finally arrive at the available safety margin. The possibility of extending the results of pin bundles with smaller number of pins to pin bundles with larger number of pins also need to be explored. These form the motivation for the current research.

1.3 OBJECTIVES AND SCOPE OF THE THESIS WORK

The scope of this thesis work is basically computational in nature, wherein, the three dimensional conservation equations of mass, momentum and energy are solved using finite volume based commercial computational fluid dynamics codes for a wide range of parameters employing appropriate turbulence models. Encouraged by the requirement of detailed understanding of thermal hydraulic features, the following objectives have been identified.
a) To investigate the physics of the complex flow and temperature distributions in a heat generating fuel pin bundle with helical wire from basic principles which is very relevant in core thermal design.

b) To develop fundamental understanding in the thermal hydraulics of fuel pin bundle, computational simulation of bundle with small number of pins (7, 19 and 37) with one or two helical pitches.

c) To quantify the magnitude of secondary flow generated by helical spacer wire and its influence on coolant mixing and its dependence on number of fuel pins in the bundle.

d) To assess the effectiveness of helical spacer wire and the associated penalty in terms of pressure drop by comparing the results with that of straight wire-wrap fuel pin bundle.

e) To study the thermal hydraulics of 217 pin fuel bundle using a parallel CFD solver.

f) To understand the effect of helical wire wrap parameters (viz., helical pitch and wire diameter) on the thermal hydraulics of sodium in 217 pin fuel bundle.

g) To develop correlations for Nusselt number as a function of helical wire parameters based on detailed parametric study.

h) To estimate the adequacy of the ligament gap between the peripheral row of the pin bundle and hexagonal sheath and commend the size of the hexagonal sheath.

i) To suggest the optimum helical wire-wrap pitch length and wire diameter.

j) To determine the hot spot factors from the clad and sodium temperature distributions in 217 pin fuel bundle and compare them with traditional values used in safety analysis and arrive at the available safety margin.

k) To extend the results of 7, 19 and 37 pin bundle to 217 pin bundle and compare them with the actual results of 217 pin bundle.
1.4 ORGANIZATION OF THE THESIS

The thesis is divided into five major parts. The first part introduces the research topic along with motivation and objectives of the present study in Chapter-1. The second part comprises of detailed literature review in chapter-2 while the mathematical model and solution method are presented in Chapter-3. The third part comprises of basic studies on bundles with small number of pins, viz., (i) study of 7 pin bundle in Chapter-4 and (ii) the comparative study of 19, 37 and 91 pin bundles in Chapter-5. The fourth part comprises of (i) detailed parametric study of 217 pin bundle employing a parallel CFD code in Chapter-6, (ii) the effect of helical wire parameters in Chapter-7 including development of correlations for Nusselt number in the pin bundle and (iii) the clad and sodium temperature distributions in Chapter-8. The final part of the thesis comprises of (i) the study of hot spot factors in the bundle, its comparison with that used in safety analysis in Chapter-9, (ii) the study of extendibility of 7, 19 and 37 pin bundles results to 217 pin bundle in Chapter-10, and (iii) conclusions of the thesis in Chapter-11.