Numerical Investigations on Complex Flow Pattern inside the Fuel Bundle of a LMFBR

G Padmakumar
Indira Gandhi Centre for Atomic Research
gpk@igcar.gov.in

P Lijukrishnan *
Indira Gandhi Centre for Atomic Research
* liju@igcar.gov.in

G K Pandey
Indira Gandhi Centre for Atomic Research
gkp@igcar.gov.in

K Velusamy
Indira Gandhi Centre for Atomic Research
kvelu@igcar.gov.in

B V S S S Prasad
Indian Institute of Technology, Madras
prasad@iitm.ac.in

V Vinod
Indira Gandhi Centre for Atomic Research
vvinod@igcar.gov.in

V Prakash
Indira Gandhi Centre for Atomic Research
prakash@igcar.gov.in

P selvaraj
Indira Gandhi Centre for Atomic Research
pselva@igcar.in

ABSTRACT

A three dimensional Computational Fluid Dynamics analysis of a Fast Breeder Reactor fuel bundle has been carried out in order to investigate the complex flow pattern inside the fuel bundle. With sodium as coolant, the flow hydraulic analysis of a representative 7 pin fuel bundle has been carried by solving continuity and momentum equations by Standard k-ϵ turbulence model at various flow regimes, Reynolds number (Re) ranging from 4×10^4 to 2×10^5. From the numerical analysis, it is observed that the coolant flow is maximum in the peripheral sub-channels and minimum at the central sub-channels. Since the heat generation is more at the area near central sub-channels, it requires more coolant in the central sub-channels. Further analysis is carried out to examine the variation of friction factor in the 7 pin bundle with coolant flow. The friction factor for 7 pin fuel bundle has been numerically predicted as 0.0193 for the reactor conditions. The acceptability of CFD model has been confirmed by verification of the CFD model. Verification of CFD model has been carried out by comparing computed values of frictional factor with correlations proposed by various studies.

NOMENCLATURE

D_h	Hydraulic diameter
Re	Reynolds Number
V	Velocity
ρ	Density
μ	Kinematic viscosity
f	Friction factor
ΔP	Pressure drop
l	Length

INTRODUCTION

In a medium size pool type Liquid Meal Fast Breeder Reactor (LMFBR), the heat generated in the core due to the nuclear fission is removed by circulating liquid metal through the core. Sodium is the best choice among the liquid metal coolants due to its very high heat transfer coefficient (~25, 000 W/m^2K), high boiling point (880^oC) and low melting point (98^oC). LMFBR fuel pins operate at high power density due to its compact reactor core and it is very much essential to remove very high heat flux values (~ 1·5MW/m^2). A larger capacity (500 MW_e) pool type LMFBR called as Prototype Fast Breeder Reactor (PFBR) is in an advanced stage of commissioning at Kalpakkam, Tamil Nadu.

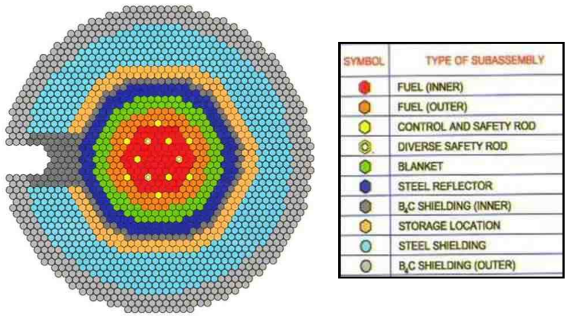


Figure 1 - Core structure of PFBR

The core structure of PFBR is shown in figure 1. The core consists of 1758 subassemblies, out of which 181 are fuel subassemblies. Each subassembly consists of a hexagonal wrapper tube (also called hexcan) which contains 217 smaller circular clad tubes (also called fuel pins) containing fuel pellets. The fuel pins are arranged in a triangular pitch and are vertically held in the form of bundle .The gap between the fuel pins forms the sub-cahnnels for the sodium flow and heat transfer from the fuel pin to sodium takes place when sodium flows through these sub-channels.

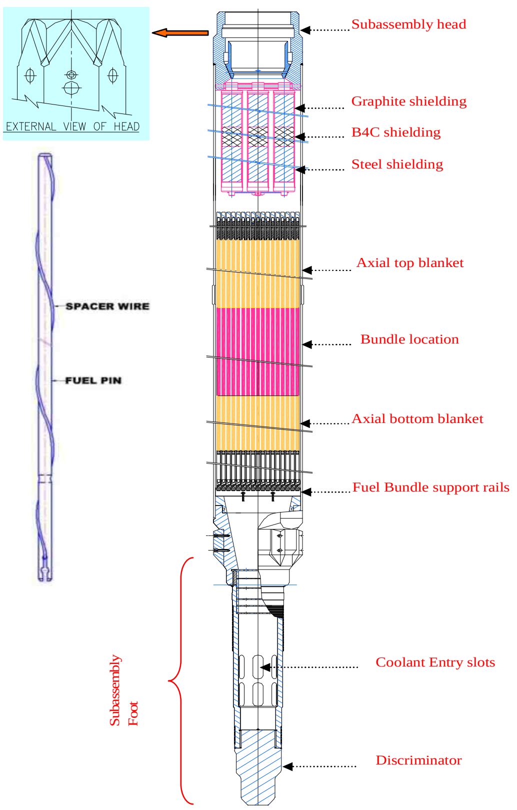


Figure 2 - Structure of a typical fuel subassembly in FBRs

In the core, the average heat flux in a fuel pin is nearly 2 MW/m^2 and the heat generation rates from all the fuel pins are not the same. The heat generation in fuel pins changes both in axial and radial directions because of the variation in neutron flux. The mass flow rate of coolant is not uniform in all the sub-channels. As a result of these factors, there are strong temperature variations around the fuel pins which give rise to local hot spots at locations of lower coolant flow. In order to take care of this issue, the fuel pins are separated by spacer wires which are helically wound around the pins. Spacer wires provide support for the fuel pins and due to its helical profile it also assist in proper mixing of coolant among the sub-channels. The heat transfer coefficient of the coolant increases because of the transverse flow movement of sodium in the sub-channels and attain more uniformity in the outlet temperature in the fuel subassembly. Furthermore, the helical movement of sodium reduces the formation of hot spot around the pins. Figure 2 shows the detailed structure of a typical fuel subassembly in FBR.

Even though spacer wires help in mixing of sodium flow inside the subassembly, temperature profile is not uniform within the fuel subassembly. There are non-uniform sun-channel flow areas in the sub-assembly mainly central sub-channels, edge sub-channels and corner sub-channels which give non-uniform sub-channel flow of coolant around the fuel pins. Also the heat generation near each sub-channel is different. The peripheral sub-channels have more coolant flow area and less heat generation compared to central sub-channels. This results in temperature variations around the fuel pins which again create the local hot spots around fuel pins. The setting up of hot spot can create safety issues in reactor. A proper balanced sub-channel flow corresponding to heat generation can enhance the heat transfer between fuel pins and sodium so as to get uniform sodium outlet temperature and lower hot spot temperature. Figure 3 shows the various sub-channel areas in a representative 37 pin fuel bundle.

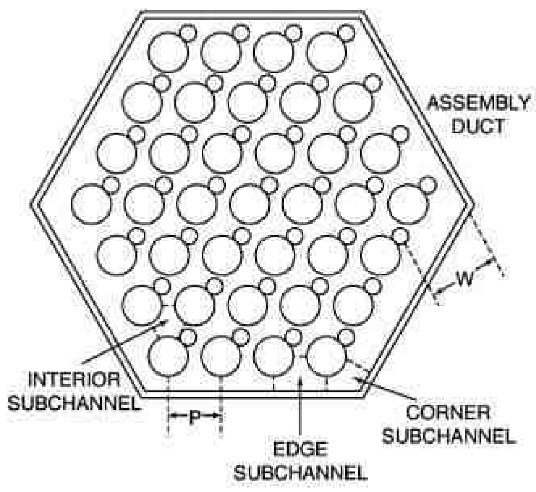


Figure 3 - Various sub-channel flow areas in a subassembly

A proper sub-channel flow corresponding to heat generation can be possible by reducing the flow area in the peripheral sub-channels by insertion of solid devices between the gaps between pins and hexcan walls. The addition of any kind of inserts to a fuel subassembly requires a comprehensive study on thermal-hydraulics of fuel pins bundle. As an initial attempt to solve this objective, a numerical study on a 7 pin fuel bundle has been carried out to understand the complex flow pattern inside a fuel bundle assembly. Figure 4 shows the flow bypass area between spacer wire and hexcan walls in a 7 pin bundle assembly.

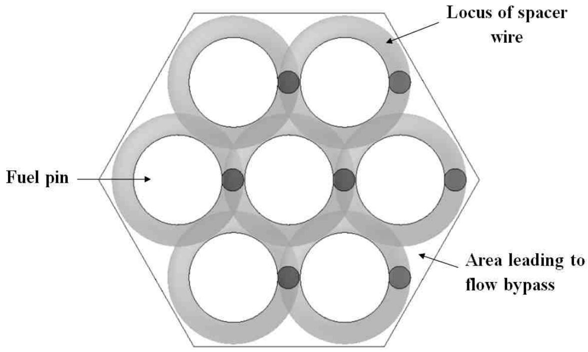


Figure 4 - Flow bypass area in a fuel subassembly

COMPUTATIONAL MODEL DETAILS

A 3 dimensional computational model of 7 fuel pin bundle has been modeled as per the actual dimensions with sodium as the coolant. The diameter of fuel pin is 6.6 mm. The fuel pins are arranged in a triangular pitch of 8.28 mm and the spacer wire of diameter 1.65 mm is helically wounded over the pins. The helical pitch of spacer wire is 200 mm and the 7 pin bundle has been modeled for a single pitch length of spacer wire. The contact between fuel pins and spacer wire is a line contact. The difficulty in meshing due to the line contact between the pin and wire has been overcome by providing a radial offset of 0.05 mm for the wire toward the center of the fuel pins and thereby converting line contact to surface contact. Figure 5 show the 3-dimentional view of the computational model developed for 7 pin bundle.

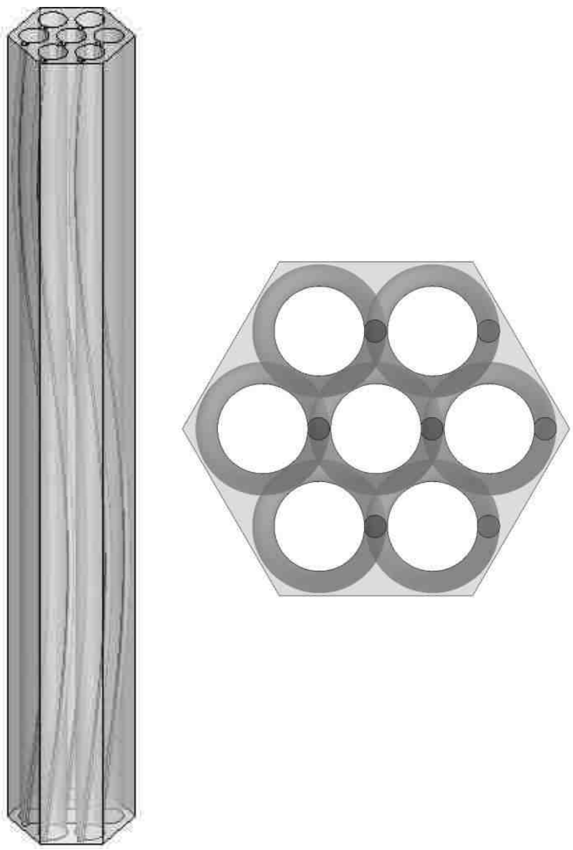


Figure 5 - Computational model of 7 pin bundle

- ## Governing equations

The steady state incompressible Navier-Stokes equations are the governing equations to be solved. To model the turbulence statistically, Reynolds-Averaged-Navier-Stokes (RANS) equations are used. The governing equations solved in this analysis are given below.

Continuity equation

$$\frac{\partial U_i}{\partial x_i} = 0 \quad (1)$$

Momentum Equation

$$\rho U_i \frac{\partial U_j}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\overline{u'_i u'_j}\right] - \frac{\partial P}{\partial x_j} + \rho g \delta_{j3} \quad (2)$$

$$\delta_{j3} = 0\ (if\ j\ \neq 3)$$
$$\delta_{j3} = 1\ (if\ j\ = 3)$$

- **Boundary Conditions**

The overall boundary conditions for the hydraulic analysis of 7 pin bundle are shown in figure 6. At the inlet to the pin bundle, specified velocity has been provided as boundary condition. The inlet turbulence intensity and eddy viscosity ratio are 2% and 10 respectively. The outlet boundary condition is specified as pressure condition (atmospheric pressure). No slip conditions are given to clad walls, hexcan walls as well as spacer wire walls.

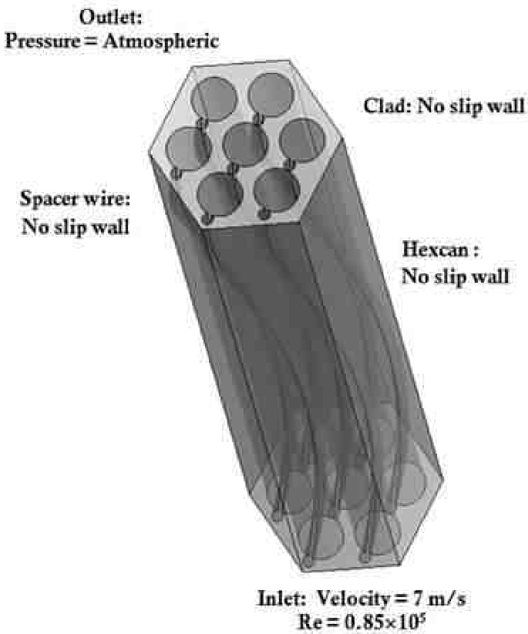


Figure 6 - Boundary conditions

- **Grid independent study**

Tetrahedral meshes have been used for the meshing of 7 pin bundle numerical model. Grid independent study for four different mesh patterns of the same CFD model has been carried out with different grid sizes ranging from very fine (9 million grids) to coarse (4 million grids). The number of grid points around the pin and the spacer wire are varied from 20 to 40 and 5 to 15 respectively. It was found that reduction of grids from 9 million to 6 million doesn't cause change in solution and number of 6 million grids is sufficient for the accurate solution and the solution is independent of the mesh size beyond this value. The mesh arrangement for CFD model is shown in figure 7.

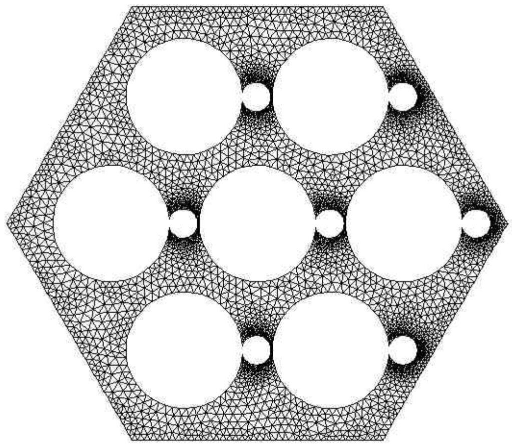


Figure 7 - Mesh for CFD model

- **Turbulence models**

Turbulence models are applied to model $\rho\overline{u'_i u'_j}$ for closing the system of governing equations. In the present study, the turbulence model effects are observed by considering, (i) Standard k-ϵ model, (ii) RNG k-ϵ model , (ii) Realizable k-ϵ model, (iii) Standard k-ω model and (iv) SST k-ω model. The comparison of various turbulence models are shown in figure 8. The cross flow velocity at the outlet of 7 pin bundle for Re = 0.85×10^5 has been calculated using various turbulence models and is compared. After the turbulence model comparison studies, it is observed that there is no significant variation in prediction of Standard k-ϵ model from the prediction by others. Hence the results from standard k-ϵ model are adopted for further discussions in this paper.

Standard wall function approach has been adopted to capture the boundary layers adjacent to the walls. The y^+ values close to the pin surface is maintained in the range 30 – 100. The governing equations are solved by a Finite Volume based CFD code. First order upwind scheme is used for combing convective and diffusive fluxes in transport equations. The pressure velocity coupling has been resolved using SIMPLE algorithm. For declaring convergence, the tolerances on the residual values for all governing equations are set as 10^{-6}.

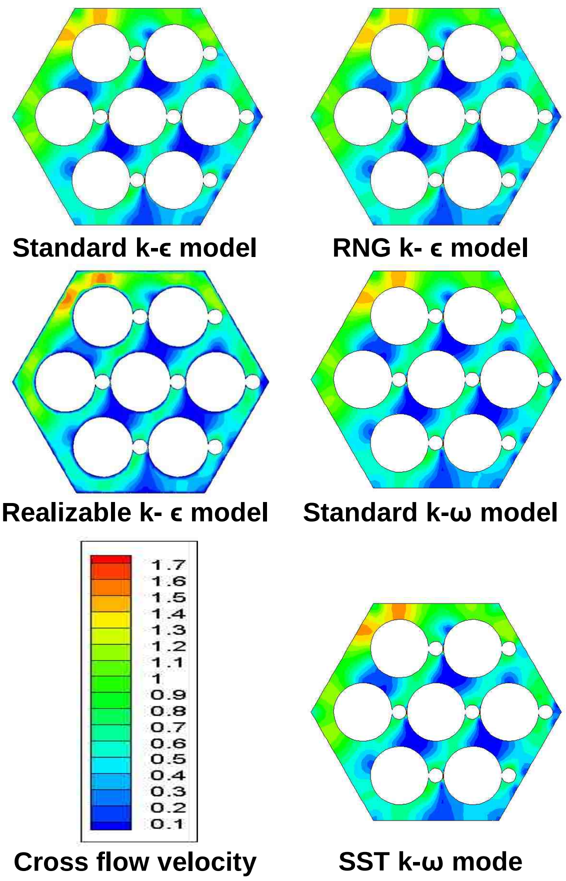


Figure 8 - Comparison of turbulence models

VERIFICATION OF CFD MODEL

Hydraulic analysis has been carried out using numerical model of 7 pin bundle at different Reynolds number ranging from 4 x 10^4 to 2 x 10^5. The acceptability of CFD model has been confirmed by verification of the CFD model. Verification of CFD model has been carried out by comparing numerically predicted values of frictional factor with correlations proposed by various studies such Baxi and Dalle-Donne (1981), Rehme (1973), Modified Engel (1979) and Govinda rasu (2013).

Frictional factor in the 7 pin fuel bundle is calculated for the sodium flow through the sub-channels. For the 7 pin fuel bundle assembly in the hexcan with fuel pins of 6.6 mm diameter and 1.65 mm diameter spacer wires, the equivalent hydraulic diameter has been calculated as 3.99 mm. Darcy frictional factor has been calculated from the pressure drop in the fuel pin bundle from the CFD study.

Hydraulic diameter,

D_h = 4 * (Area / Wetted perimeter) (3)
= 3.992 mm

Reynolds number,

$$Re = \frac{\rho V D_h}{\mu} \quad (4)$$

Darcy formula, friction factor,

$$f = \frac{2\Delta P\, D_h}{l\rho\, v^2} \quad (5)$$

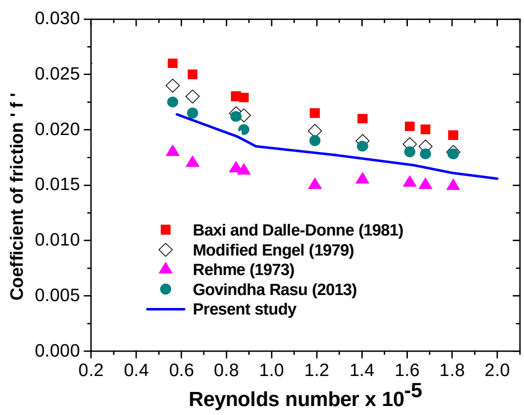


Figure 9 - Comparison of numerically predicted frictional factor with correlations proposed by various studies

The comparison of predicted value of frictional factor with correlations is shown in figure 9 and it is seen that the CFD results are in good agreement with the correlations.

RESULTS AND DISCUSSION

The CFD analysis of 7 fuel pin bundle has been carried out with an inlet axial velocity of 7 m/s (Re = 0.85×10^5). The observations on vertical velocity, cross flow velocity, total velocity magnitude and frictional factors are discussed in the following paragraphs.

- **Cross-flow velocity**

The cross flow development in the 7 pin fuel bundle form inlet plane to outlet plane is shown in figure 10.

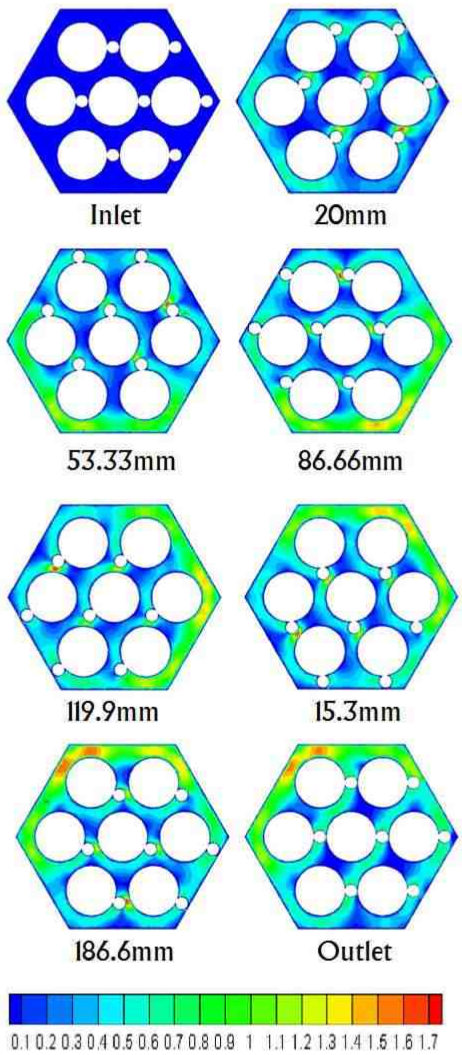


Figure 10 - Cross flow velocity (m/s) development in the 7 pin fuel bundle form inlet to outlet

It is seen that the flow gets developed within 86 mm from the inlet of the bundle after which the changes in the flow is marginal. The sodium cross flow velocity occurring at the peripheral sub-channels is found to be periodic and is found to be a function of wire position. From the figure it can be seen that, from the inlet plane to outlet plane in the axial direction, the locus of spacer wire moves in anti-clockwise and as a consequence of this, the sub-channel sodium flow is developed in anti-clock wise direction. This circumferential flow developed due to the helical wire is very important from the thermal hydraulics point of view, as it enhances mixing of the coolant between the sub-channels which enhances the heat transfer and helps to attain uniform coolant temperature at the outlet of the subassembly. It can also be seen that the circumferential velocity is maximum in the peripheral sub-channels which are diametrically opposite to the sub-channels blocked by the spacers. There is a local maximum value of 1.54 m/s for the cross flow velocity in the peripheral sub-channels at the outlet. This can cause non-uniformity in the outlet temperature profile.

- **Vertical velocity**

The vertical velocity profile at the outlet plane of 7 pin bundle is shown in figure 11. The maximum value of vertical velocity is 7.7 m/s and the velocity is maximum at the peripheral sub-channels. The higher vertical flow at the peripheral sub-channels is due to the lower resistance path offered to the coolant.

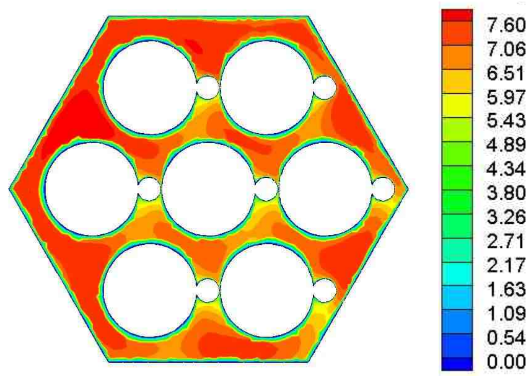


Figure 11 - Vertical velocity (m/s) at the outlet (Re = 0.85×105)

- **Selection of pitch for analysis**

The 7 pin bundle is numerically modeled up to one full pitch of helically wounded spacer wire, ie, 200 mm. The length considered for analysis is 50 times of the hydraulic diameter of the model (3.9 mm) and it is observed that the flow though the sub-channel area is fully developed at length of 200 mm. In order to ensure that flow is fully developed, a separate numerical model of 7 pin fuel pin bundle with length up to 2 pitch length i.e., 400 mm has been modeled and flow parameters at the outlet plane is analyzed. The 3-D view of 7 pin fuel bundle model with one pitch length of spacer wire and two pitch length of spacer wire is shown in figure 12.

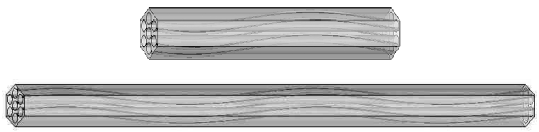
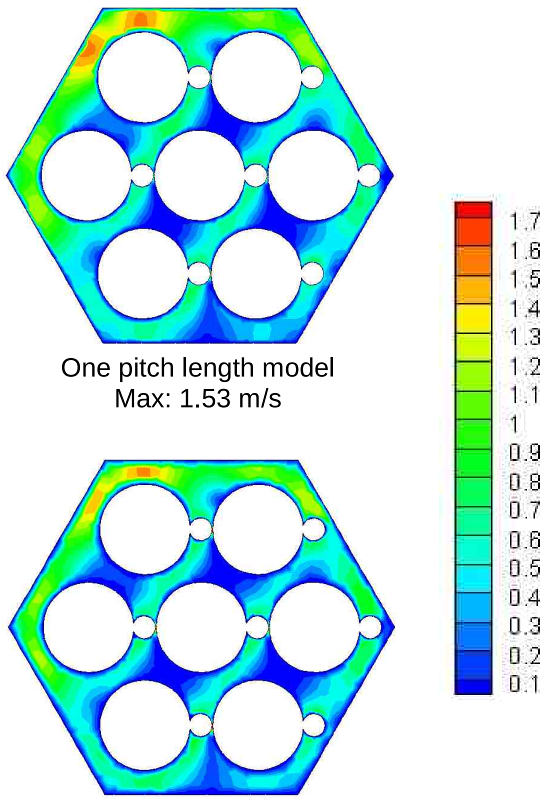


Figure 12 - 3-D view of 7 pin fuel bundle model with one pitch length and two pitch lengths

The cross flow velocities at the outlet for both cases are compared and are presented in figure 13. The variation of cross flow velocity is negligible beyond the length of one pitch, it has been observed that the flow has attained full development and hence once pitch length of model is adequate for the next level analysis.



One pitch length model
Max: 1.53 m/s

Two pitch length model
Max: 1.519 m/s

Figure 13 - Comparison of cross-flow velocity (m/s) for 7 pin bundle with one pitch length and two pitch lengths

- **Selection of number of pins for the analysis**

The actual fuel subassembly in the reactor contains 217 fuel pins within the hexcan. Due to the complication in the modeling and difficulties in carrying out numerical analysis of 217 pins with the helical wounded spacer wire inside the hexcan and the limitations on the computational capabilities lead to the choice of 7 pin bundle model representing the 217 pin bundle. The 7 pin fuel bundle includes the central fuel pin and one row of surrounding fuel pins, where the one row of fuel pins with the helical spacer wire ensures the swirling motion of sodium inside the subassembly as in the case of subassembly with 217 pins. This point has been confirmed by comparing the velocity patter in a 7 pin bundle model with another model of 19 pin bundle. The 19 pin bundle model includes the central fuel pin and surrounding two rows of pins. 3-D view of 19 pin fuel bundle model has been shown in figure 14.

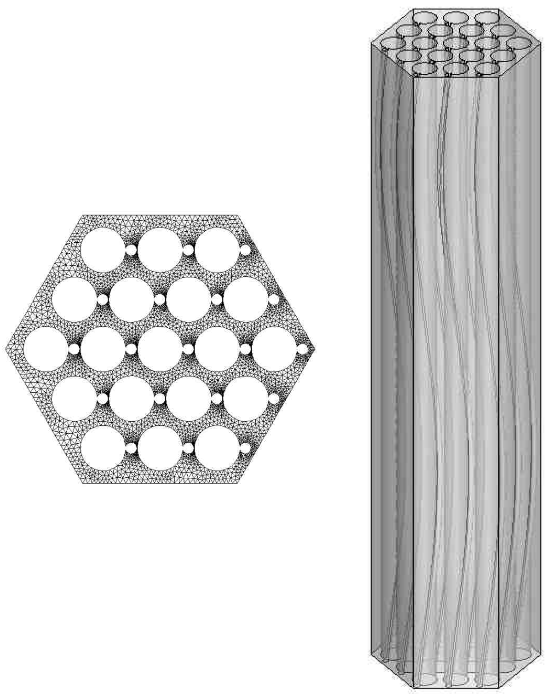


Figure 14 – Mesh and 3-D view of 19 pin bundle model

The comparison of sodium cross-flow velocity through the sub-channel area at the outlet for both the cases is presented in figure 15. The maximum values of cross flow velocity at the outlet are comparable for both 7 pin bundle and 19 pin bundle models and the results are comparable. Hence a 7 pin bundle model is considered adequate to study the hydraulic characteristics of 217 pin fuel bundles in the reactor.

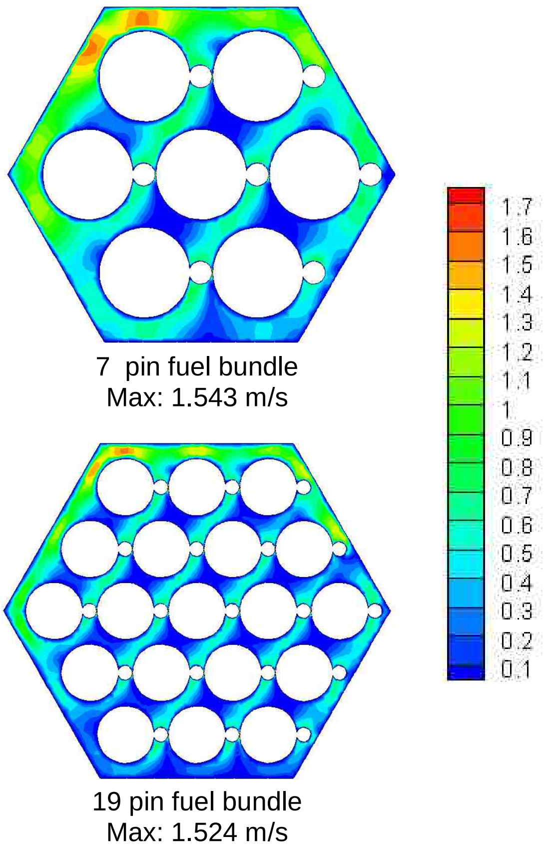


Figure 15 - Comparison of cross-flow velocity (m/s) at the outlet for 7 pin and 19 pin bundles

- **Friction factor**

Another important parameter considered in the hydraulic analysis of 7 pin bundle is the friction factor. The addition of spacer wire offers resistance to the coolant flow and further addition of any insert geometries to make the sodium outlet temperature uniform inside the subassembly will offer more pressure drop in the subassembly. Numerical analysis of 7 pin fuel bundles has been carried out for various flow regions ranging from $Re=5x10^4$ to $Re=2x10^5$ to observe the variation of friction factor with flow.

The friction factor for 7 pin bundle without inserts has been estimated from the CFD analysis as 0.0193 for a flow with Reynolds number $0.85x10^5$ (Reactor condition).

CONCLUSIONS

A numerical study has been carried out in order to investigate the complex flow pattern inside the fuel bundle of a LMFBR. A three dimensional computational model of 7 fuel pin bundle has been modeled with sodium as coolant and the governing equations are solved with Standard k-ϵ turbulence model. The analysis has been carried out for various Reynolds numbers, ranging from 4 x 10^4 to 2 x 10^5. The acceptability of CFD model has been confirmed by verification of the CFD model. Verification of CFD model has been carried out by comparing computed values of frictional factor with correlations proposed by various studies.

From the CFD analysis, it is observed that the sodium vertical velocity is maximum at the peripheral sub-channels since more flow area is available at these sub-channels. The cross flow velocity is also higher at the peripheral sub-channels. The cross flow occurring at the peripheral sub-channels is periodic and is found to be a function of wire position. It is also observed that the cross flow velocity is maximum in the peripheral sub-channels which are diametrically opposite to the channel area blocked by the spacer wire. The variation of friction factor in the 7 pin fuel bundle with flow has also been studied. The friction factor for 7 pin fuel bundle has been numerically predicted as 0.0193.

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<u>**Presenting author Biodata**</u>

Name : Lijukrishnan P

Designation : Scientific Officer D

Company : Indira Gandhi Centre for Atomic Research

Qualification : M Tech in Mechanical Engineering from Homi Bhabha National Institute

Area of Expertise **:** Thermal hydraulics of Fast Breeder Reactors

Significant Achievements: Development of gas entrainment mitigation devices in surge tank of future Fast breeder Reactors

Number of Papers Published in Journals: 0

Number of Papers Published in Conferences: 3