Flow and Convective Heat Transfer Analysis Using RANS for A Wire-Wrapped Fuel Assembly

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This work presents the three-dimensional analysis of flow and heat transfer performed for a wire-wrapped fuel assembly of liquid metal reactor using Reynolds-averaged Navier-Stokes analysis in conjunction with SST model as a turbulence closure. The whole fuel assembly has been analyzed for one period of the wire-spacer using periodic boundary conditions at inlet and outlet of the calculation domain. Three different assemblies, two 7-pin wire-spacer fuel assemblies and one bare rod bundle, apart from the pressure drop calculations for a 19-pin case, have been analyzed. Individual as well as a comparative analysis of the flow field and heat transfer have been discussed. Also, discussed is the position of hot spots observed in the wire-spacer fuel assembly. The flow field in the subchannels of a bare rod bundle and a wire-spacer fuel assembly is found to be different. A directional temperature gradient is found to exist in the subchannels of a wire-spacer fuel assembly. Local Nusselt number in the subchannels of wire-spacer fuel assemblies is found to vary according to the wire-wrap position while in case of bare rod bundle, it's found to be constant.

Key Words : Wire-Spacer, Liquid Metal Reactor, RANS Analysis, Heat Transfer, Fuel Assembly

1. Introduction

The wire spacer fuel assembly for liquid metal reactors (LMRs) generally consists of fuel rods spaced on a triangular pitch and contained within a hexagonal duct. The rods are separated by spacer wires wounded helically around each fuel rod. The presence of wire-wraps inside the fuel assembly increases the pressure drop and thus the pumping power required, but it has the virtue of enhancing flow mixing and heat transfer in the bundle and thereby reducing maximum surface temperature and the temperature gradients.

In LMRs, the fuel and blanket assemblies are subject to severe radial gradients in the rate of heat generation and have a wide range of flow conditions. Presence of wire spacers inside the fuel assembly complicates the fluid flow and heat transfer phenomena in the bundle. This necessitates the basic understanding of these phenomena to achieve the optimum design performance.

Many researchers have carried out experimental as well as numerical works for wire-spacer fuel assemblies. Most popular among the experimental works is the ORNL (Oak Ridge National Laboratory) benchmark test performed for a 19-pin wire-spacer fuel assembly, where Fontana (1973) obtained the measurements for temperature distribution on the duct wall and at the exit of a 19-pin wire spacer fuel assembly. Roidt et al. (1980) investigated experimentally the hydraulic field inside a 217-pin wire spacer fuel assembly. Engel et al. (1980) performed the experiment on heat transfer phenomena in a 61-rod electrically

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heated model of an LMFBR blanket assembly. Recently, Chun and Seo (2001) investigated a 19-pin wire spacer fuel assembly to assess the performance of existing correlations for friction factor. Similar work has been reported by Choi et al.(2003) for a 271-pin wire-spacer fuel assembly.

There have been many attempts using simplified analysis methods for the thermal hydraulic calculations of LMR fuel assemblies as Sha (1980) reviewed. In general, investigators have used subchannel analysis codes for thermal-hydraulic calculations of LMR fuel assemblies. Subchannels are the spaces between three adjacent fuel rods. In the subchannel analysis, it is explicitly assumed that the axial velocity in z-direction is dominant compared to velocity components in other directions (i.e. x- and y- directions). Thus, it is advantageous from both physical and computational points of view to treat axial and transverse momentum equations separately with simplification being applied to the transverse momentum equations. However, in this case the transverse momentum equation cannot be treated with the same rigor as the axial momentum equation. Also, approximation is applied for interfacing information between two different subchannels. Thus, the validity of subchannel analysis to situations with large flow disturbance poses serious concern. SABRE4 (Mcdougall and Lillington, 1984), SLTHEN (Yang, 1997), MATRA-LMR (Kim et al., 2002), etc. are some of the subchannel analysis codes developed so far. Khan et al.(1975a; 1975b) developed another method named 'Porous Body Model' for predicting temperature distributions in the wire-wrapped fuel assemblies. In this method, a set of quasi-continuum governing equations for conservation of mass, momentum and energy for a finite control volume is derived from both integral and differential approach. Volume-porosity, surface permeability, distributed resistance and distributed heat sources (or sink) are symmetrical in the derivation. Though, this method has got some advantage over the subchannel analysis method but in this method also, the fine structure of velocity and temperature is ignored which is very vital for the accurate thermal hydraulic predictions.

However, due to the complicated geometry, the analysis based on three-dimensional Navier-Stokes equations has not been carried out for the wire-wrapped fuel assembly, yet. Thus, comprehensive information about the flow structure and heat transfer in the wire-wrapped fuel assembly is not available. To design the optimum shape of the wire-spacers, it is essential to analyze precisely the three-dimensional turbulent flow and heat transfer in the subchannels of the fuel assembly. Recent development of computational fluid dynamics using three-dimensional RANS (Reynolds averaged Navier-Stokes equations) analysis is, fortunately, very efficient for this purpose.

In this work, the convective heat transfer in wire-wrapped fuel assembly is analyzed with three-dimensional RANS analysis to investigate the flow and heat transfer characteristics, and also to find the effects of wire-wrap on thermal hydraulic performance. Because of the large number of computational nodes required to resolve the flow field properly, the present work concerns with smaller fuel assemblies. Validation of the numerical result is performed for a 19-pin wire spacer fuel assembly and later, the thermal hydraulic analysis is performed for 7-pin cases.

2. Analysis Methods

2.1 Governing equations

The analysis is performed for one period of the wire-spacer using periodic boundary conditions at inlet and outlet of the calculation domain. To adopt the periodic boundary conditions, modifications of source terms in streamwise momentum and energy equations have to be made to calibrate the gradual decrease and increase of pressure and temperature, respectively.

The pressure, $P(x,y,z)$ in periodically fully developed flow can be expressed as

$$P(x,y,z) = -\beta z + P_p(x,y,z) \quad (1)$$

where, β is the mean pressure gradient, $P_p(x,y,z)$ is the periodic part of the pressure, and βz is the pressure drop that takes place in the flow direction (z).

Similarly, the temperature, $T(x,y,z)$ can be expressed as

$$T(x,y,x)=\gamma z+T_p(x,y,z) \quad (2)$$

where, γ is the mean temperature gradient, $T_p(x,y,z)$ is the periodic part of the temperature, and γz is the temperature rise in the flow direction.

Thus, for the three dimensional, steady and incompressible flows, the governing equations using above modifications can be expressed as :

Continuity :

$$\frac{\partial \rho U_i}{\partial x_i}=0 \quad (3)$$

Momentum :

$$U_j\frac{\partial U_i}{\partial x_j}=\frac{\partial}{\partial x_j}\left[v\frac{\partial U_i}{\partial x_j}\right]-\frac{1}{\rho}\frac{\partial P_p}{\partial x_i}+\beta\delta_{ij}/\rho \quad (4)$$

Energy :

$$\frac{\partial}{\partial x_i}(\rho c U_j T_p)=\frac{\partial}{\partial x_j}\left[K\frac{\partial T_p}{\partial x_j}\right]-\rho c\gamma U_j\delta_{ij} \quad (5)$$

where, U_i indicates the mean velocity component, c, the specific heat, and δ_{ij} is the Kronecker delta.

2.2 Numerical methods

Figure 1 shows the configuration of a 7-pin wire-spacer fuel assembly. The analysis is performed for a single period of the wire-spacer (i.e. lead length, H=200 mm). The wire-wrap is mounted on the fuel rods in counter-clockwise direction starting from 12-o'clock position as shown in Fig. 1. This figure also shows the definition of geometric parameter of the test assembly. The specifications of the test assemblies and operating conditions are shown in Table 1. The numbers to

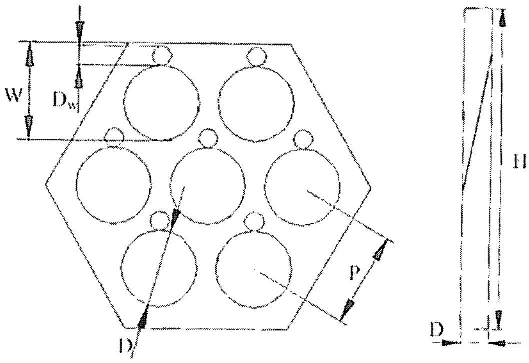


Fig. 1 A 7-pin wire-wrapped fuel assembly

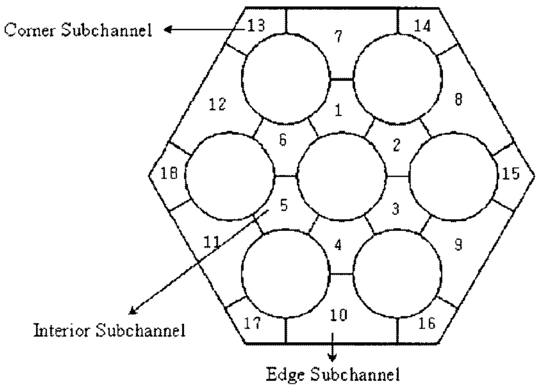


Fig. 2 Subchannels of the fuel assembly

Table 1 Specifications of the test assemblies and operating conditions

Test Assembly	Assembly A	Assembly B	Assembly C
Lead to diameter ratio, H/D	25.0	25.0	–
Pitch to diameter ratio, P/D	1.178	1.256	1.256
Pitch, P (mm)	9.424	10.05	10.05
Equivalent Diameter, De (mm)	3.82	4.84	6.65
Wire Diameter, Dw (mm)	1.4	2.0	no wire-spacer
Lead Length, H (mm)	200	200	–
Number of Fuel Rods	7	7, 19	7
Heat Input (kW/rod)	7.63	7.63	7.63
Reynolds Number	60,840	60,840	60,840
Inlet Temperature (K)	573.15	573.15	573.15
Coolant Used	Liquid Sodium	Liquid Sodium	Liquid Sodium

the subchannels of the fuel assembly are given as shown in Fig. 2.

The Reynolds-averaged Navier-Stokes equations and energy equation have been solved using the commercial CFD code, CFX-5.7 (2004), which employs unstructured grid. SST model (Menter and Esch, 2001) is used as a turbulence closure as this model captures the separation under adverse pressure gradient accurately and, thus, predicts well the near wall turbulence which is vital for the accurate prediction of the turbulent heat transfer. To get a good quality volume mesh, blending between wire-spacers and fuel rods is used. This is used to ease the process of meshing as the wire-spacers and fuel rods are in point contact in two-dimension and in line contact in three dimension, and to have a volume mesh for this kind of geometry is not possible with the available resources.

The fluid flows upward in the fuel assembly. To obtain a fully developed turbulent flow at the inlet of the calculation domain, the periodic conditions are set at the inlet and outlet sections. The calculated values of velocities and turbulence quantities at the outlet section were substituted as the inlet conditions for the next iterations. Constant heat flux is imposed on the fuel rod surfaces while at the hexagonal duct wall, adiabatic condition is used. At all the wall boundaries, the wall function based on empirical wall law for the near-wall turbulence is adopted for mean axial velocity. All the simulations were conducted by means of a segregated method using the SIMPLE scheme (Patanka, 1980) for pressure-velocity decoupling. Nominally second order-accurate schemes were selected for the discretization of the governing equations. A residual reduction factor of 10^{-6} for the mass conservation equation was used to monitor the convergence of the iterative solution.

3. Results and Discussion

Grid dependency of the solution for the 7-pin case of fuel assembly B in Table 1 is tested first. Fig. 3 shows the results obtained by three different grid systems; Grid I - 5.89×10^5, Grid II - 8.80×10^5, and Grid III - 1.19×10^6. From the results, 8.80×10^5 (Grid II) is selected as optimum number of grids. Figure 4(a) shows the mesh structure on the periodic surface and Fig. 4(b)

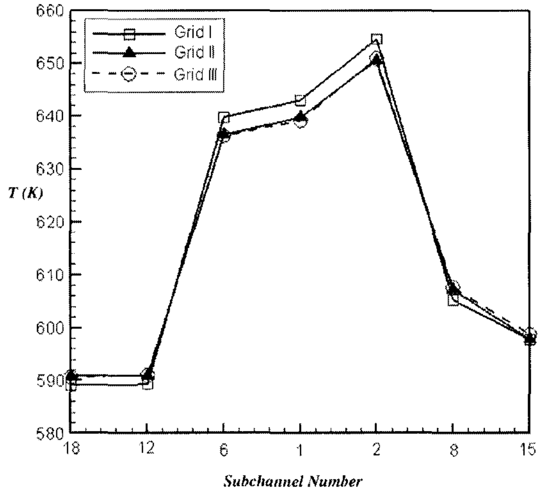
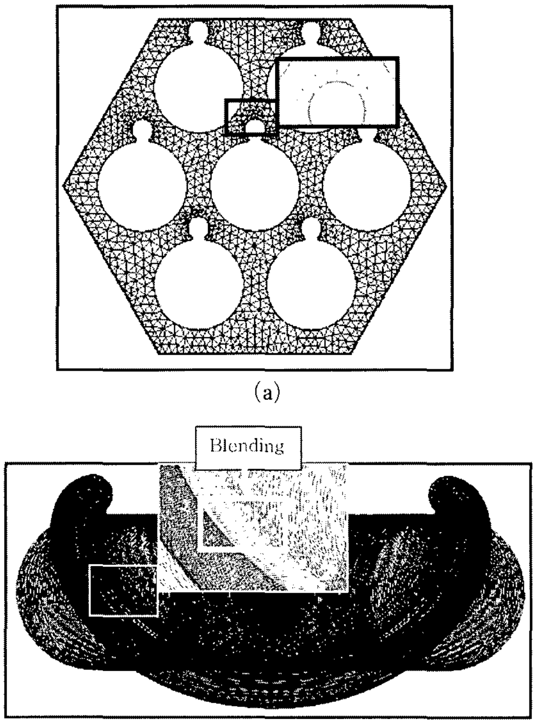


Fig. 3 Grid dependency test (7 pin, assembly B)



(b)

Fig. 4 Computational Grids (assembly B) ; (a) On a cross-section of the assembly, (b) On surface of fuel rod shows the mesh structure on the fuel rod and wire-spacer surfaces. Also, blending has been shown in this figure by magnifying a small portion of the mesh structure.

For validation of the present numerical simulation, pressure drop calculations are performed for a 19-pin wire spacer fuel assembly (assembly B). The results are compared with the experimental data obtained by Chun and Seo (2001), and also with the friction factor correlations of Cheng and Todreas (1986).

The results of the validation test are shown in Fig. 5. The relative difference between experimental and the calculated friction factors at Re= 67,200 is less than 20 percent. Though the difference is a bit high, keeping in view the complexity in the geometry, this can be accepted. The difference is also attributed to the introduction of blending between the wire-spacers and fuel rods.

Calculation has also been performed under similar conditions of flow and heat transfer for a fuel rod without wire spacers. The discussions to be followed are subdivided into two sections for the sake of convenience. In the first section, hydraulic characteristics of the wire-spacer fuel assembly have been discussed while in the second section, results are presented for the temperature field.

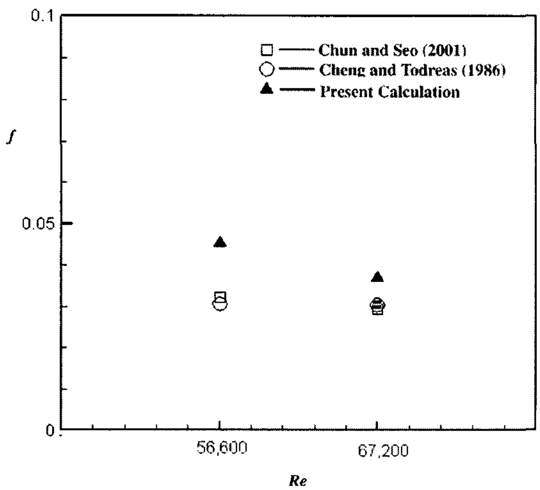


Fig. 5 Friction factor variation with Reynolds number for a 19-pin wire-spacer fuel assembly

3.1 Hydraulic characteristics

The flow patterns in wire-wrap rod bundles are influenced significantly by the presence of wire-wraps. The wire-wrap geometry induces transverse gradients having a characteristic, directional periodicity between adjacent subchannels. Figure 6 shows the distribution of pressure on a cross-section of a wire-spacer fuel assembly. A net transverse pressure difference is found to exist between opposite faces of the bundle. The axial variation of static pressure in case of a wire-wrapped fuel assembly is not constant along the axial direction as shown in Fig. 7. This variation is cyclic and has a period equal to the wire-wrap pitch as it is clear from the graph. Inside the wire-spacer fuel assembly, high pressure zone on the upstream of a wire-wrap, is followed by a low pressure zone on the downstream.

In the exterior bundle region, the flow direction is always in the wire-wrap direction, although the magnitude is a function of the wire-wrap position. In the interior bundle region the transverse flow direction with respect to a single subchannel changes axially and summed over a lead length is not in any preferred direction. The axial velocity variation in an interior subchannel (1 and 3 in Fig. 4) is shown graphically in Fig. 8. The figure

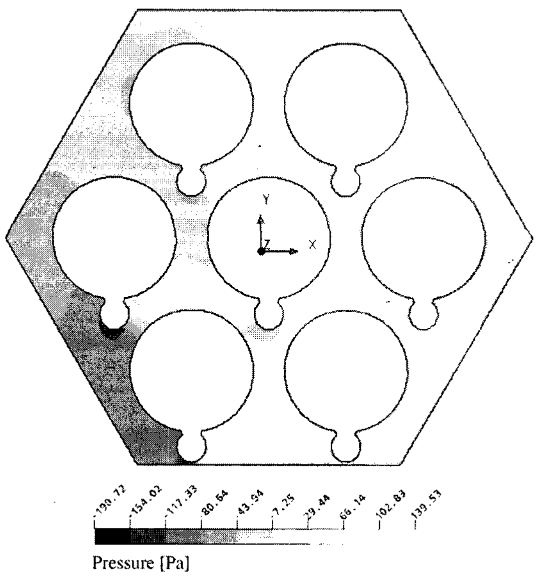
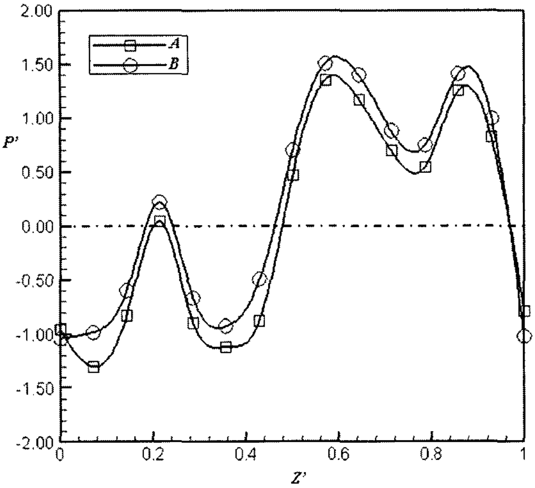
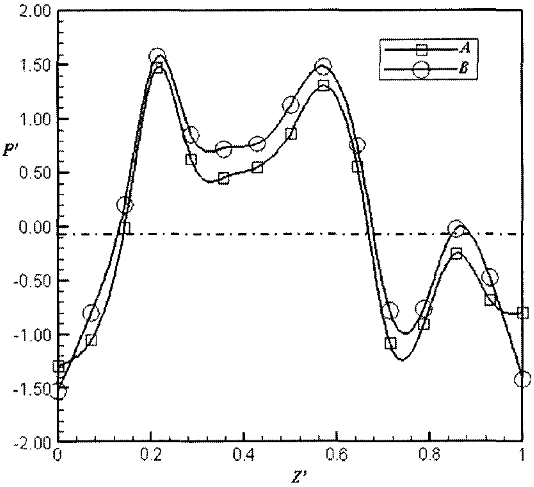


Fig. 6 Pressure distribution on a cross-section (Z= 50 mm, assembly B)

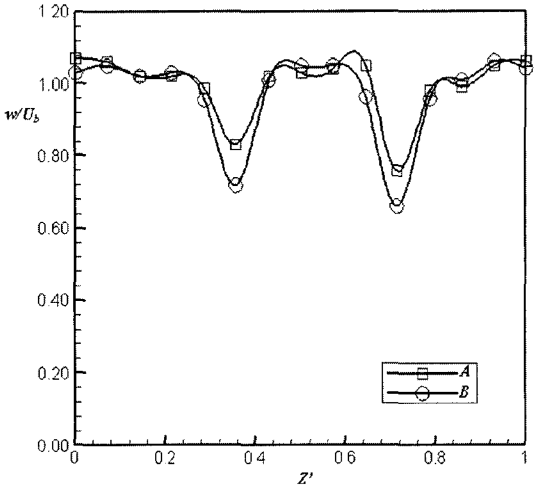


(a)

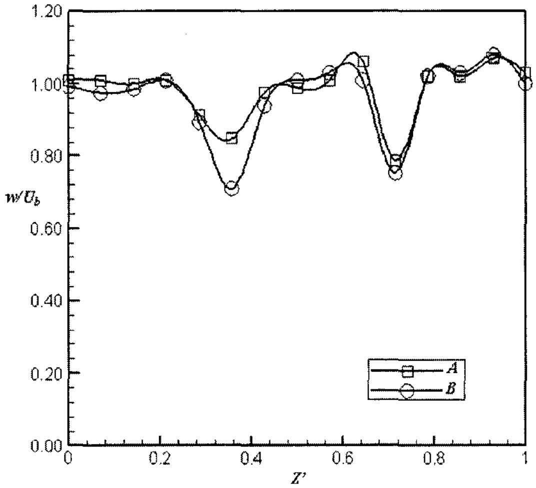


(b)

Fig. 7 Variation of static pressure along axial direction in (a) Subchannel 1, (b) Subchannel 3



(a)



(b)

Fig. 8 Axial velocity variation along axial direction in (a) Subchannel 1, and (b) Subchannel 3

shows that the most extensive low axial velocity occurs behind the wire-wrap as the wire passes through the gap. The local axial velocity in the subchannels of a bare rod bundle (assembly C) is found to be varying linearly.

Figure 9 shows the surface streamlines on a plane perpendicular to axial direction. This helps in understanding the flow structure observed in case of a wire-spacer fuel assembly. A large recirculating flow (A) exists behind the wire-wrap in the interior subchannel. In the edge subchannel, there exists a reverse cross flow (B) against the direction of the wire-wrap in the gap. The local axial velocity in the edge subchannels is always greater than the average axial velocity and this follows the wire-wrap path. In the corner subchanels, no gross back flow is observed. Rather, there is a strong positive sweeping flow (C) and only highly localized back flow.

Figure 10 shows the distribution of sweeping flow averaged on cross-section along axial direction, where, u and U_b indicate the velocity in x-direction averaged over a cross section and average axial velocity, respectively. It clearly shows the periodic nature of sweeping flow.

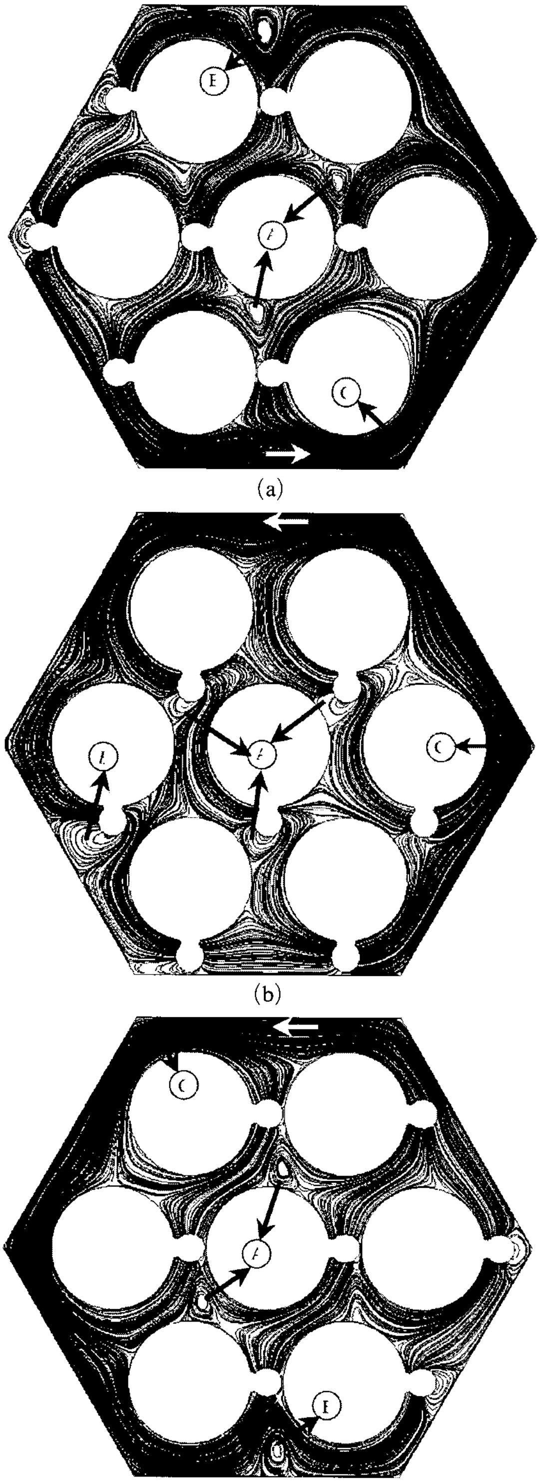


Fig. 9 Streamlines on cross-sections (assembly B) ; (a) $Z=50$ mm, (b) $Z=100$ mm, (c) $Z=150$ mm

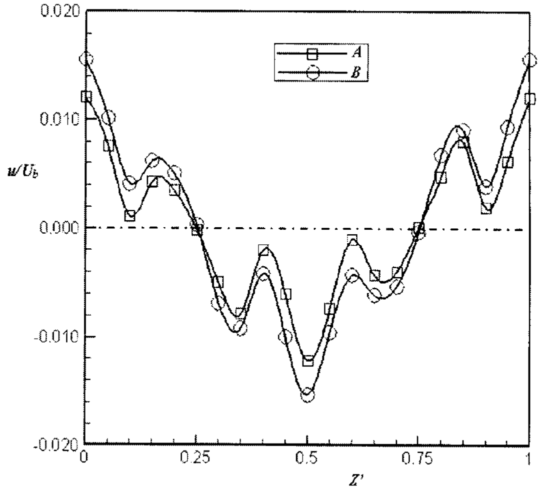


Fig. 10 Peripheral sweeping flows averaged over a cross section along axial direction

3.2 Temperature field

In sodium cooled LMRs, design limits are imposed on the maximum temperature of cladding and fuel pins. This necessitates the accurate prediction of the core coolant temperature inside the fuel assembly. In the present work two wire-wrap fuel assemblies and a bare rod bundle have been analyzed in order to assess the effects produced by the wire-spacers on the heat transfer inside the fuel assembly. Figure 11 shows the temperature contours on a cross section in a wire-spacer fuel assembly as well as for the bare rod bundle. The highest temperature regions are the interior subchanel regions surrounding the central fuel rod. In case of bare rod bundle, the average temperatures in the subchannels surrounding the central fuel rods are found to be equal and this trend continues as the fluid moves-up along the axial direction. While in case of wire spacer fuel assemblies, a large temperature gradient is found to exist between the subchannels surrounding the central fuel rod, and its direction reverses as the fluid moves up along the axial direction depending upon the wire-wrap position. This reversal of temperature gradient is found to follow a periodic path having period equal to the wire-wrap pitch.

Edge and corner subchannel regions are found to be at the lowest temperature. The average tem-

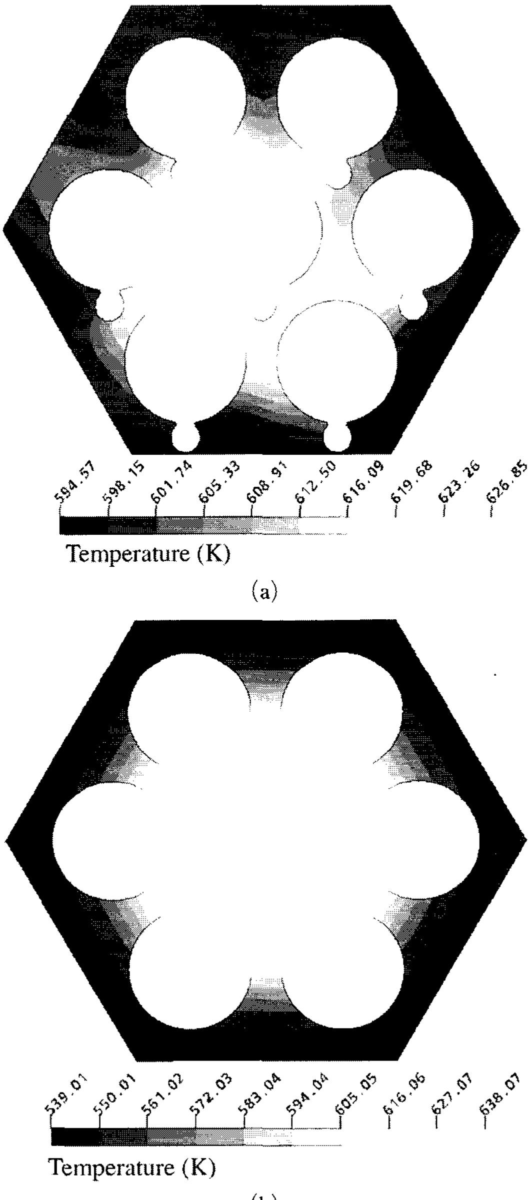


Fig. 11 Temperature contours on a cross-section (Z=100 mm) ; (a) Assembly B, (b) Assembly C (bare-rod bundle)

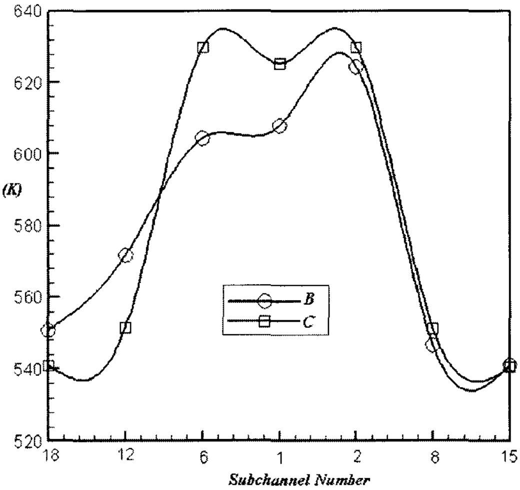


Fig. 12 Subchannel temperature variation in assembly at Z=20 mm

peratures in the edge and corner subchannels of a bare rod bundle are approximately same while in the case of a wire-spacer fuel assembly, a small temperature gradient, the direction of which depends on the wire-wrap position, is found to exist. Fig. 12 shows the comparison of the average temperature profiles at z=20 mm between the fuel bundles with and without wire-spacers. The temperature is averaged on a cross-section of a subchannel. It is found in this figure that the wire spacers reduce the temperature gradients, and thus the region of high temperature in the wire-spacer fuel assembly.

Figure 13 shows the local Nusselt number variation in axial direction in the interior subchannels. The Nusselt number is defined by $Nu=q D_h/k\,(T_w-T_b)$, where q, D_h, k, T_w and T_b are heat flux, hydraulic diameter, heat conductivity of fluid, surface temperature and bulk temperature of fluid flow, respectively. And, Nu_S indicates the Nusselt number for fully developed turbulent flow in smooth circular tubes with constant surface heat flux in case of liquid metals (Incropera and DeWitt, 2002). In the bare rod fuel bundle, the local Nusselt number in all the subchannels is constant along the axial direction and also, its magnitude is found to be the same confirming that the subchannels surrounding the central fuel rod is at the same temperature. In the case of wire-spacer fuel assemblies, the local Nusselt number is found to vary along the axial direction and its magnitude depends on the wire-wrap positions. The overall level of the local Nusselt number in assembly B is found to be higher than that in assembly A. As shown in Table 1, the relative thickness of the wire in

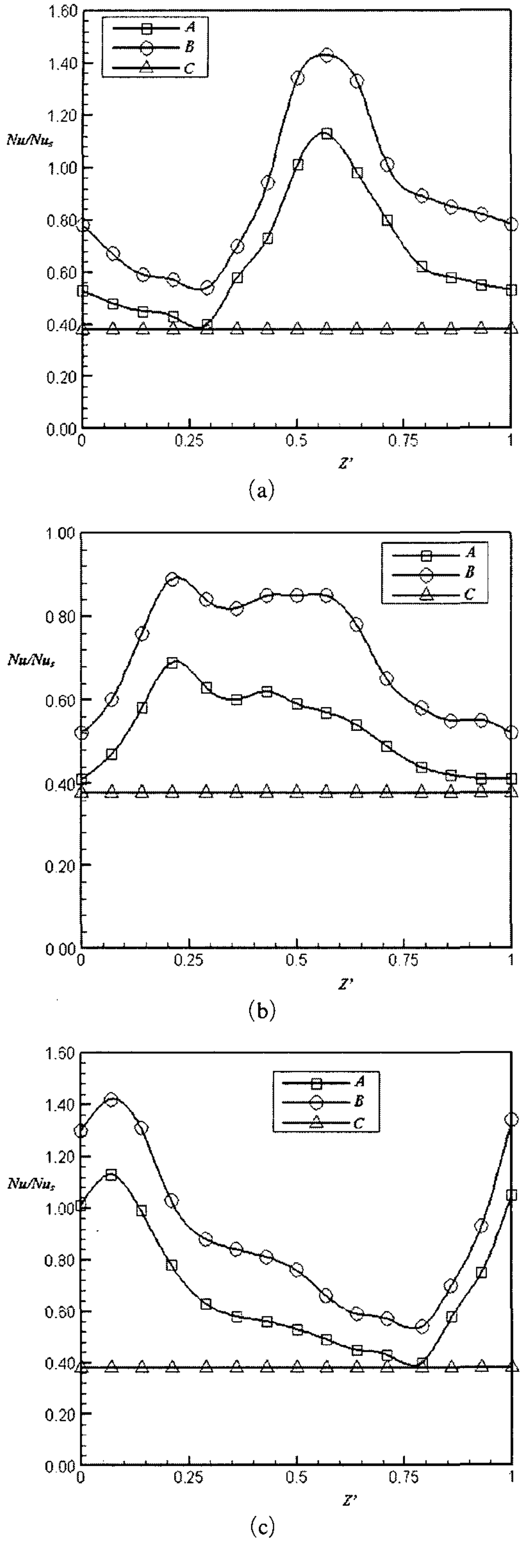


Fig. 13 Nusselt Number distributions in subchannels; (a) 1, (b) 3, and (c) 5

assembly B is larger than that in assembly A, which indicates that the blockage ratio in the flow passage in assembly B is larger than that in assembly A. As discussed by Kim and Seo for the mixing vane in the PWR fuel assembly, the higher blockage ratio in subchannel induces the higher turbulent intensity, and consequently the higher heat transfer rate.

Figure 14 shows the variation of temperature on the surfaces of central fuel rod and wire-spacer. Also, depicted in this figure is the position of hot spots observed. In total, six hot spots are observed in both the assemblies for single period of the wire-spacer. These hot spot centers are observed in the counter clockwise in both the assemblies. The angular separation between the hot spot centers is about 50-55 degree. The first hot spot center is observed at about 1.875 D from the inlet of the calculation domain and its position is about 150 degree clockwise from the initial position of the wire-spacer. The relative position of the first hot-spot observed, its distance from inlet of the calculation domain and also, the angular separation between the hot-spots are found to be same in both the wire-spacer assemblies, A and

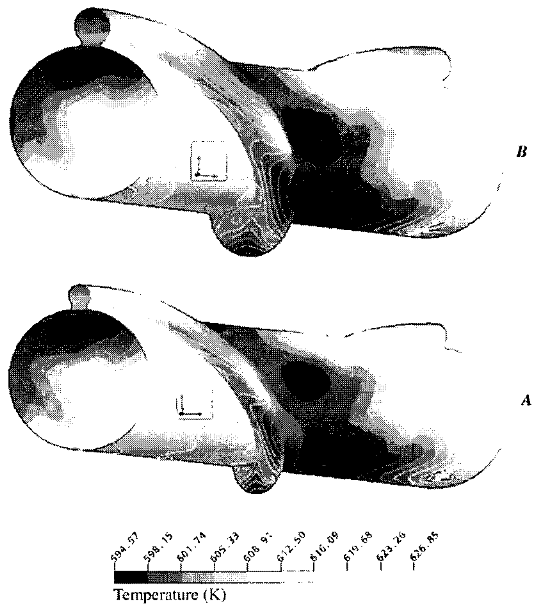


Fig. 14 Temperature distribution on the surfaces of central fuel rod and wire spacer for assembly A and B

B. This indicates that the hot-spot position is dependent upon the initial position of the wire-wrap.

4. Conclusions

Three-dimensional analysis of flow and heat transfer in a wire-spacer fuel assembly has been performed using RANS analysis. Thermal hydraulic analysis has been performed for two 7-pin wire-spacer fuel assemblies with different thickness of the wire and a bare rod bundle under the same conditions of flow and heat transfer. Individual and comparative studies of the flow field and heat transfers have been performed. The wire-spacers induce transverse gradients having directional periodicity between adjacent subchannels. Bare rod bundle interior subchannels are at the same average temperature while there exists a directional temperature gradient in the subchannels of a wire-spacer fuel assembly. Local Nusselt number in the subchannels of a bare rod bundle is found to be constant while in the case of wire-spacer fuel assembly, it varies according to the wire-wrap position. It is found that the wire spacers reduce the temperature gradients, and thus the region of high temperature in the fuel assembly. The number of hot-spots observed and the way it varies is found to be same for both the wire-spacer assemblies and hence, this employs that the hot-spot position is dependent upon the initial position of the wire-spacer. The overall level of local Nusselt number is found to be higher in the assembly with thicker wire due to the larger blockage ratio in subchannels.

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