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Thermal-Hydraulic Analysis of A Wire-Spacer Fuel Assembly

Imteyaz Ahmad*, Kwang-Yong Kim**

Abstract--This work presents the Thermal Hydraulic analysis has been performed for a 19-pin wire-spacer fuel assembly using three-dimensional Reynolds-averaged Navier-Stokes equations. SST model is used as a turbulence closure. The whole fuel assembly has been analyzed for one period of the wire-spacer using periodic boundary condition at inlet and outlet of the calculation domain. The overall results for a preliminary calculation show a good agreement with the experimental observations. It has been found that the major unidirectional flows are the axial velocity in sub-channels and the peripheral sweeping flows and the velocities are found to be following a cyclic path of period equal to the wire-wrap pitch. The temperature is found to be maximum in the central region and also, there exist a radial temperature gradient between the fuel rods. The major advantage of performing this kind of analysis is the prediction of thermal-hydraulic behavior of a fuel assembly with much ease.

Key Words : Liquid Metal Reactor(LMR), Wire-Spacer Fuel Assembly, Lead Length, Sub-Channels, Computational Fluid Dynamics

1. Introduction

The wire-spacer fuel assembly for Liquid Metal Reactors (LMRs) consists of fuel rods spaced on a triangular pitch and contained within a hexagonal duct. To minimize the hot spots and permit adequate cooling, the rods are separated by spacer wires wounded helically around each rod. The presence of wire-wraps increases the pressure drop and thus pumping power required, but it has the virtue of enhancing flow mixing in the bundle and thereby reducing temperature gradients. Also, it introduces structural complexity making the analysis painfully difficult.

In a LMR, 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. Core designers have evolved a number of numerical methods for predicting temperature and pressure distributions within these assemblies in order to determine cladding hot spots, assembly housing bowing and deformation, and the points of incipient boiling and voiding. Needless to say, for a safe design, the temperature distribution in the coolant must be known at all operating points.

In general the investigators have used sub-channel (the space between three adjacent rods in a LMR is used to define a sub channel) analysis for rod bundle thermal hydraulic calculations[1,2]. Other methods, which have been used so far, are porous medium formulation[3,4,5] and benchmark rod-bundle thermal hydraulic analysis[1]. In the present thermal hydraulic analysis for a 19-pin wire-spacer fuel assembly, the whole hexagonal duct including the wire spacer and fuel rods has been analyzed for one period of the wire-spacer(i. e. for Lead length, H = 200mm) using three-dimensional Reynolds-averaged Navier-Stokes equations with periodic boundary conditions at inlet and outlet of the calculation domain.

The key accomplishment of this paper is the description of the complex thermal hydraulic phenomena in a LMR with a relative ease. Temperature, pressure and velocity fields can be

* CFE Lab., Inha University
E-mail : g2041587@inhavision.inha.ac.kr

found in different sub-channels and at a different transverse and axial locations. Temperature distribution in flow blockage channels[6,7], where the flow disturbance may cause fuel pin damage due to a reduced local cooling capability, can easily be predicted.

2. Calculation methods used in rod bundle thermal-hydraulic analysis

The analysis methods, which have been used so far, can be classified into three broad categories:
(i) Sub-channel analysis, (ii) Porous medium formulation, and (iii) Benchmark rod bundle thermal hydraulic analysis using a boundary fitted coordinate system.

2.1 Sub-channel Analysis:

The sub-channel analysis is the most widely used method in rod bundle thermal hydraulic analysis to date. It explicitly assumes that one of the velocity components (axial velocity) is dominant, compared to cross-flows in other directions. Thus it is advantageous from both physical and computational points of view to treat axial and transverse momentum equations separately, so that simplifications can be applied to the transverse momentum equation.

Basic Limitations:

(i)The fine structure of both velocity and temperature within a sub-channel is ignored.

(ii)The transverse momentum equations can't be treated with the same rigor as the axial momentum equations because of the non-orthogonal characteristics of sub-channel arrangement.

(iii)To facilitate calculations, approximations are necessary for interfacing the required information at various locations between control volumes for the axial and transverse momentum equation. These basic limitations are inherent; therefore, validity of sub-channel analysis to situations with large flow disturbances poses serious concern.

2.2 Porous medium formulations: 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. The system consists of a single-phase fluid with discrete stationary solid structures. Volume porosity, surface permeabilities, distributed resistance and distributed heat source (or sink) are symmetrically included in the derivation. Surface permeability in porous medium formulation greatly facilitates characterization of an anisotropic medium.

The unique advantage of the volume-porosity, surface permeability, and distributed resistance and distributed heat source approach eliminates limitations (ii) and (iii) employed in the sub-channel analysis; however, limitation (i) is still retained.

3. Present Analysis

The whole fuel assembly including the fuel rods and wire-spacers has been analyzed for one period of the wire spacer using periodic condition on the inlet and outlet of the domain. To get a good quality volume mesh, blending has been used between the wire-spacer and fuel rods. The radius of the blend has been kept as minimum as possible. This blending may increase slightly the pressure drop but the overall effect on the temperature field has been found to be negligible. The major advantage of using this approach is that the momentum equation can be treated with equal rigor in transverse as well as in axial directions.

4. Numerical Analysis and Boundary Conditions

The thermal hydraulic analysis is performed for a 19-pin wire spacer fuel assembly for single period of the wire-spacer (i. e. Lead length, H = 200mm). The specifications of the test section[8] and input parameters are shown in table 1. Figs. 1 and 2 show the definition of different parameters and the calculation domain, respectively. The Reynolds-averaged Navier-Stokes equations and energy equation have been solved using the commercial CFD code, CFX-5.7, which employs unstructured grids. SST model is used as a turbulence closure. To obtain a fully developed turbulent flow at the inlet of the analytical domain, the periodic condition is set at the inlet and outlet section.

The following boundary conditions[9] have been used; at inlet and outlet, for each dependent variable except pressure, the inlet value is same as the outlet value. In case of pressure, pressure drop is taken into account. The calculated values of dependent variable and turbulence quantities at the outlet section were substituted as inlet condition for the next iteration.

Uniform heat flux and no-slip condition is used at the fuel rod boundary. On the hexagonal duct wall, adiabatic and no-slip condition is used. At all wall boundaries, the wall function based on empirical wall law for near-wall turbulence is adopted for mean axial velocity.

Table 1
Specifications of the test section and input parameters

Test Section	
Lead to Diameter ratio, H/D	25.0
Pitch to Diameter ratio, P/D	1.256
Outer Diameter, D (mm)	8.0
Pitch, P (mm)	10.05
Length, L (mm)	1300.0
Wire-Diameter, d (mm)	2.0
Lead Length, H (mm)	200.0
Equivalent Diameter, D_e (mm)	4.75
No. Of Fuel Rods	19
Coolant	Na Liq.
Total Heat Input from 19-rods	145KW
Active Core Height (mm)	600.0
Inlet velocity (m/s)	0.6445

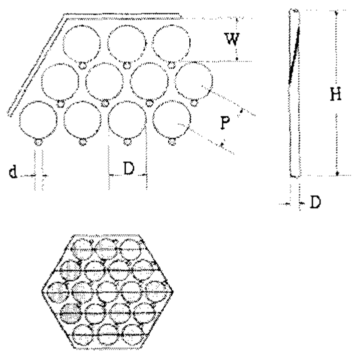

Fig. 1. A 19-pin wire spacer fuel assembly

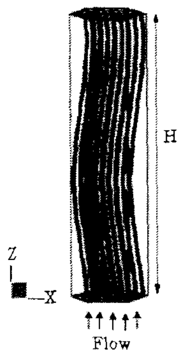

Fig. 2. The calculation Domain

5. Results and discussion

5.1 Velocity field

Experimental observations[10] of the flow in a wire-wrapped bundles indicate that the wire wraps have two main effects, firstly they increase the over all pressure drop in the bundle and secondly, they direct the flow locally in the direction of wraps. Contours of the axial velocity, as shown in Fig. 3, clearly show this effect. From this figure, it can easily be concluded that the flow patterns in wire wrapped rod bundles are influenced significantly by the presence of wire wraps. The major unidirectional flows are found to be the axial velocities in sub channels and the peripheral sweeping flows, which is consistent with the experimental evidence[10]. It has also been found experimentally that the axial velocity and the peripheral sweeping velocity are cyclic and the period is equal to the length of the wire wrap pitch, i. e. lead length, H. From the contour plots of axial velocity as shown in Fig 4, it can easily be seen that the contours of axial velocity in Fig. 4(a) are almost similar to those in Fig. 4(d). This confirms that the present analysis if carried rigorously, will lead to a revolutionary result in the thermal hydraulic analysis of the wire wrapped fuel assemblies.

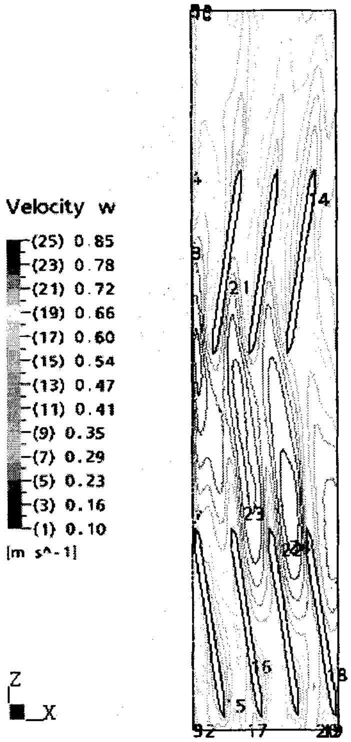

Fig. 3. Contour Plots of axial-velocity at y =13.2mm

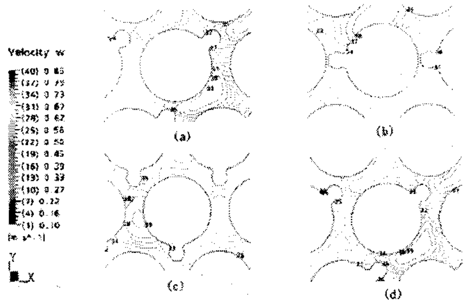

Fig. 4. Axial Velocity Contours in the vicinity of central fuel rod at (a) Inlet, (b) z =100 mm, (c) z = 150mm, and (d) Outlet

5.2 Temperature field

In Sodium cooled LMRs design limits are imposed on the maximum temperatures of cladding and fuel pins. An accurate prediction of the core coolant temperature is thus essential to the LMR core thermal hydraulic design. In the present analysis, it is found that the maximum temperature exists in the central region, which is consistent with the experimental observations. It is also found that the temperature variation on the surface of the fuel rod follows cyclic path as shown in Fig. 5, which is obviously due to the effect produce by the wire spacers. It has also been found that a severe radial gradient exits between fuel rods [3]. In Fig. 6, a comparison has been draw between two different wire spacer assemblies but calculated under similar flow and heat flux conditions. From Fig. 6(b) and Fig. 6(c), it's not difficult to find that the variation of temperature in the sub-channels as shown in Fig. 6 (a), is very much similar.

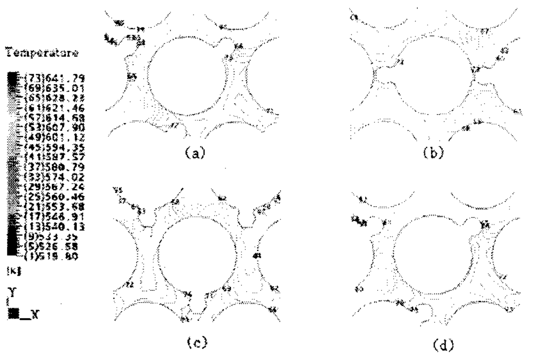

Fig. 5. Temperature Contours in the vicinity of central fuel rod at (a) Inlet, (b) z =100 mm, (c) z =150mm, and (d) Outlet

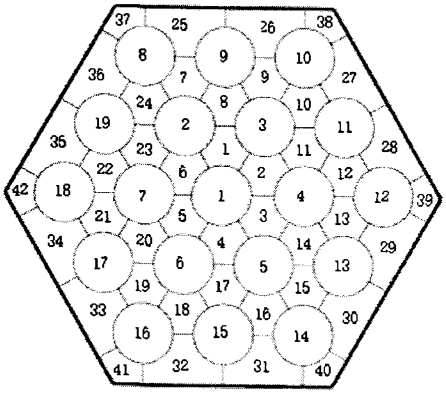

Fig. 6(a) Sub Channels of a 19-pin wire spacer fuel assembly

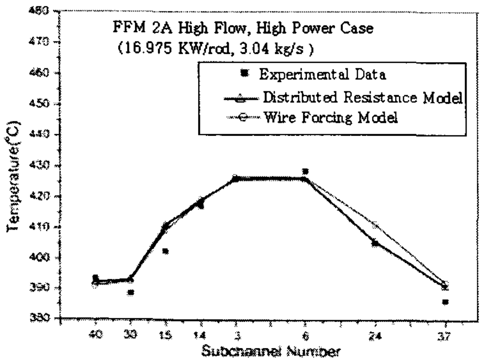

Fig. 6(b) Temperatures in subchannels

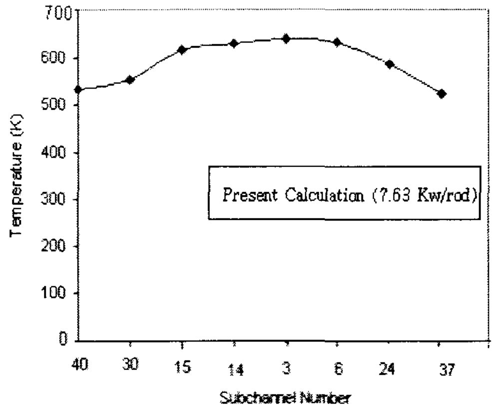

Fig. 6(c) Temperature in subchannels

6. Conclusion

The result of a preliminary calculation for a 19-pin wire spacer fuel assembly has been presented in this paper. The overall result for this analysis is found to be in good agreement with the experimental observations. The main advantage of doing this type of analysis is the description of the complex thermal hydraulic phenomena in a LMR with a relative ease. Temperature, pressure and velocity distributions can be found easily in different sub channels and at a different transverse and axial location. Prediction of temperature distribution in flow blockage channels is much easier. The major obstacle in the thermal-hydraulic analysis of a wire-spacer fuel assembly is the absence of sufficient experimental data. The present analysis, if carried extensively, has the virtue of filling this gap and providing a very detailed information about the fuel-assembly behavior under different flow conditions to the researchers in this field.

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