FLUID INDUCED VIBRATION EFFECTS ON FLOW CHARACTERISTIC OF FUEL ROD BUNDLES

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ABSTRACT

Mixing vans are attached at the spacer grid assembly of nuclear fuel rod bundle to increase the secondary flow velocity at sub-channel, further more enhance heat transfer. In the present study, 3×3 single sub-channel of rod bundle with LSVF mixing vanes were simulated to induce the secondary flow and the flow characteristics compared with effect of flow induced vibration of fuel rod and without rod vibration and turbulence intensities, maximum surface temperatures of the rod bundle, pressure drops were compared. From the results, fuel rod vibration did not affect the secondary flow intensity and pressure drop while affected the turbulence kinetic energy distributions and with fuel rod vibration got much bigger outlet surface temperature than without vibration conditions.

INTRODUCTION

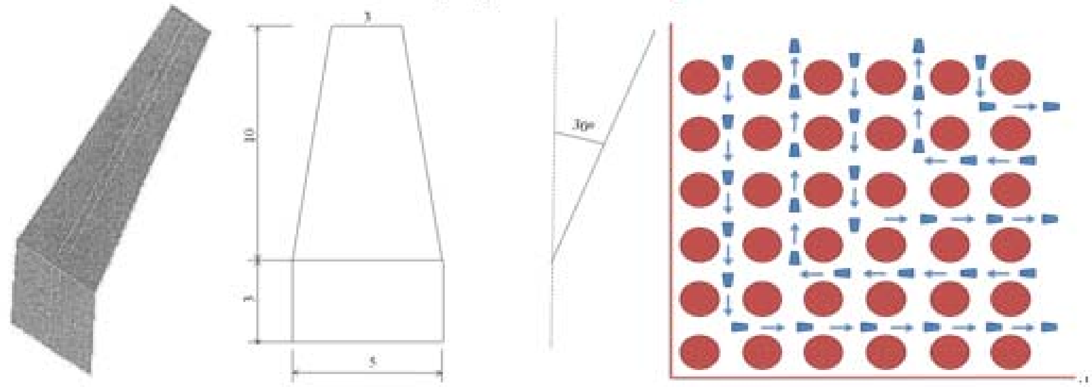
The spacer grid assembly is one of the major components of a nuclear fuel assembly to provide a flow channel between the fuel rods, which assists in the heat transfer from the fuel pellet into the coolant in a reactor[1,2]. Acting as obstacles to the coolant flow, the spacer grid assembly cause additional pressure drop, and so, they add to the economical expense both by material consumption and pumping power. Mixing vans are attached at the spacer grid assembly of nuclear fuel rod bundle to increase the secondary flow velocity at sub-channel, further more enhance heat transfer. In nuclear core, In nuclear reactor core, the estimation of flow characteristics(such as turbulence flow) mainly involves secondary flow in the cross-sectional plane. Lee[3] investigated numerically fully developed turbulent flow through equilateral triangular array fuel bundle. He showed that flow mixing by secondary flow greatly influences thermal diffusion, even if its magnitude is small. The turbulence-induced secondary flow causes the main flow to spiral through the passage and, although it is relatively weak compared with the main flow, it has a significant influence on the local mean flow distributions of interest, chiefly the axial velocity, wall shear stress and turbulent kinetic energy. Because the mixing devices increase the secondary flow velocity at each sub-channel, the heat transfer coefficient also enhanced. If the heat generated from the fuel rods can`t be spread well into the coolant, the heat becomes locally concentrated and consequently, hot spots are generated. The hot spot induces a critical heat flux that can damage rod bundle. Although secondary flow prevent the growth of hot spots which cause thermal crack of the rod bundle most attempts to measure small scale turbulence-driven secondary flow in reactor was in big trouble either due to geometrical tolerances of the test sections which caused cross-flow or due to experimental accuracy. With the significantly development of numerical technology and computer, numerical simulation is getting more utilized owning to its less cost and easily implement. To study the effect on enhance the heat transfer, In[4] performed CFD analysis to propose the optimum design of flow mixing vane on the spacer grid in PWR fuel assembly. As a results, the optimum vane angle is proposed to be 40^0 and 35^0 from the direction of axial flow for the swirl-vane and the twisted vane, respectively. An[5] using the CFD method to compare the secondary flow characteristics with different mixing vane, namely, LSVF(large scale vortex flow) mixing vane and split mixing vane. As a results, the swirling flow decays rapidly so that the heat transfer enhancing effect limited to short length after the split mixing vane while LSVF generated strong secondary flow vortices which maintain about 35 Dh. Theses study all used k-ε model as turbulence model while as Yadigaroglup[6] study who summarized the numerical simulations of Tzanos[7] in a square-lattice rod bundle and concluded that gradient-transport models, like the k–ε model, are not adequate to predict turbulent flow in the narrow gap regions. Toth[8] pointed out that RANS method with BSL Reynolds stress model can provide an accurate prediction for the turbulence quantities in a triangular rod bundle.

Almost studies on flow characteristics of rod bundle mainly focus on the effects of mixing vane without fuel rod vibration which one of the other reason to affect the flow characteristic. In this paper, flow induced vibration on flow characteristics of fuel rod bundles were calculated and compared with without vibration conditions. Two kinds of support conditions were considered namely with fixed support the fuel rod and elastic support the fuel rod.

ANALYSIS MODEL

LSVF(Large Scale Vortex Flow) Mixing Vane

Fig. 1 shows LSVF type mixing vane which bended in one direction. Fig. 2 shows arraying methods of LSVF mixing vanes. Since the LSVF mixing vanes are arranged in the circumferential direction in the whole rod bundle section, large scale vortex flows are generated and flow across the whole sub-channels. The large vortex can maintain enhanced heat transfer rate for longer periods after mixing vane.



(a) vane shape (b) vane dimensions (c) vane arrays

Fig.1: Schematic shape, dimensions and arrays of LSVF-counter mixing vanes

Spacer Grid with LSVF Mixing Vane

A 3×3 single sub-channel of rod bundle is modeled as Fig. 3 shows. The LSVF mixing vanes are attached at the spacer grid to generate the secondary flow around the fuel rod. The spacer springs and dimples are neglected for simplicity because their effect on the flow mixing is judged to minimal only inside and near the spacer.

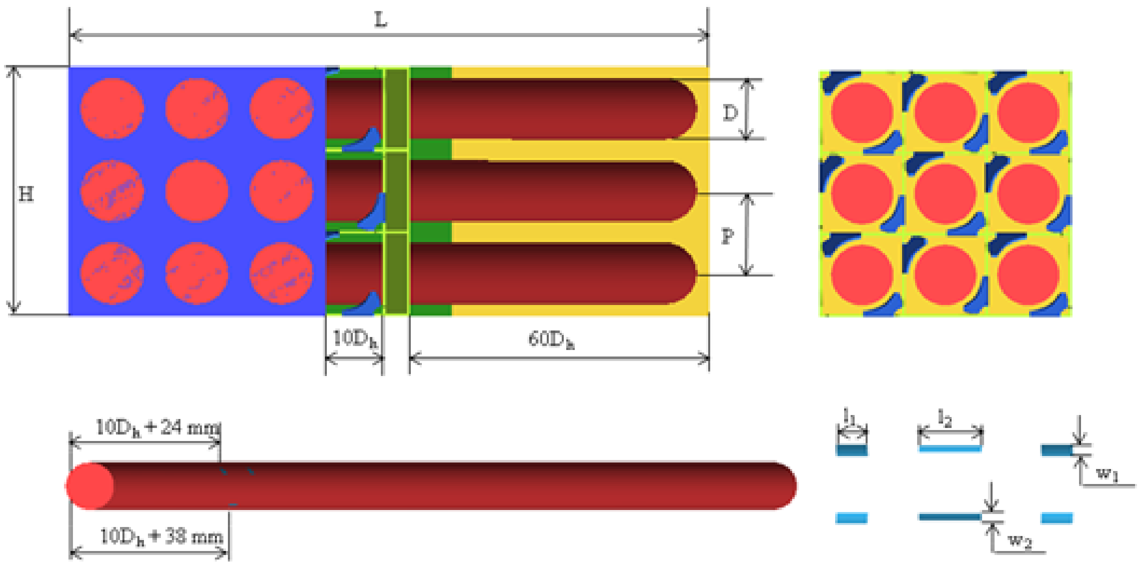


Fig.2: Schematic of rod bundle

In reactor core, each spacer grid has a distance of 60 D_h, and in this paper reference to spacer grid, the distance of forward boundary and backward boundary are 10 D_h and 50 D_h respectively. In reactor core the fuel rod supported by spacer grid spring and spacer grid dimple and normally each sub-channel of the spacer grid assembly consists of two spacer grid springs and four dimple grids. l_1 and w_1 were the spacer grid dimple length and width which contact with fuel rod while l_2 and w_2 were the spacer grid spring length and width which contact with fuel rod. Table 1 show the rod bundle channel data.

Table 1: Rod bundle channel data

Rod diameter (mm)	D	9.4 mm
Rod pitch (mm)	P	12.6 mm
Spacer grid pitch (mm)	L	933 mm
Housing (mm)	H	38 mm
Hydraulic diameter (mm)	D_h	12.1 mm
Supporter length 1	l_1	5 mm
Supporter length 2	l_2	10 mm
Supporter width 1	w_1	1.5 mm
Supporter width 2	w_2	0.9 mm

Boundary Conditions

The boundary conditions of fluid domain were set as follows: the coolant with higher temperature(265 ℃) enters from the bottom surface into the spacer grid channel with a velocity of 6.79m/s. Outlet condition of 0 Pa average static pressure was employed at the top of the models. The reference pressure was 123 bar. No slip smooth wall boundary condition with a constant heat flux 840000 W/m^2 was used for modeling the fuel rods. No slip smooth adiabatic wall boundary condition was used for modeling the wall and spacer grids. Because in this simulation mainly studied the one channel spacer assembly condition, so didn`t used symmetric condition. ICEM ANSYS program was used to proceed the meshing and Fig. 3 shows cross section of rod bundle with 5,960,181 elements. Unstructured prismatic cells in the core region and hexahedral cells close to the fuel rod walls were applied. The distance from the wall to first grid is 0.01 mm and had 10 layers.

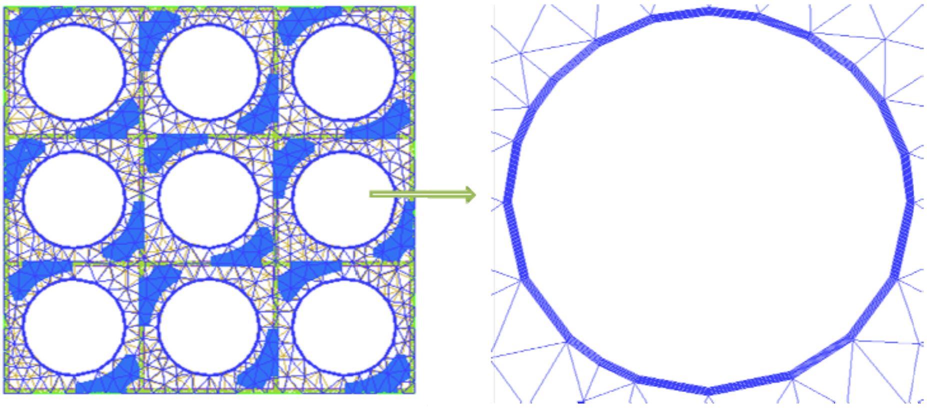


Fig.3: Cross-section of finite element rod bundle

The boundary conditions of solid domain were set as follows. Two cases were considered in this paper. The first case was that assume the fuel rod supporter fixed supported and the other case was that assume the rod supporter elastic supported. Both spring and dimple constants were obtained by actual tests[9] with spring value of 152.8 N/mm and dimple value of 8840 N/mm.

TURBULENCE MODEL

The evaluation of the thermal-mixing performance of rod bundle is very important in the PWR fuel assembly design. Because the fuel rod bundle got very complex geometry, it is important, in particular, to select the turbulence model. BSL Reynolds stress model belong to the second-order closure models in which transport equations for the individual Reynolds stresses are solve. The BSL Reynolds stress model also has the advantage of $k-\omega$ equation(turbulence kinetic energy and turbulence frequency) and $k-\varepsilon$ equation(turbulence kinetic energy and turbulence dissipation rate). The $k-\omega$ equation unlike the $k-\varepsilon$ equation has excellent predictive ability on flow field adjacent wall. Because can directly got the turbulence stress from the RSM transport equation, the equation show the flow characteristics well which have high effect streamline curvature, rapid change train rate and secondary flow. But in the other hand, got more compute time and have low convergence effect. In this paper BSL turbulence model was used to proceed simulation.

DISCUSSIONS AND SIMULATION RESULTS

The secondary flow intensity is defined as the magnitude of the secondary flow vector divided by axial bulk mean velocity as described in equation (1).

$$V_{in} = \frac{1}{A}\int\left(\frac{U_1{}^2+U_2{}^2}{U_{3,bulk}}\right)dA \quad (1)$$

Fig. 4 shows the variation of cross-sectional averaged secondary flow intensity without fuel rod vibration and with rod vibration. The abrupt increase in secondary flow intensities just after the mixing vanes and subsequent rapid decrease as the flow goes downstream. All three cases got the similar values which illustrate that the fuel rod vibration may not affect the secondary flow.

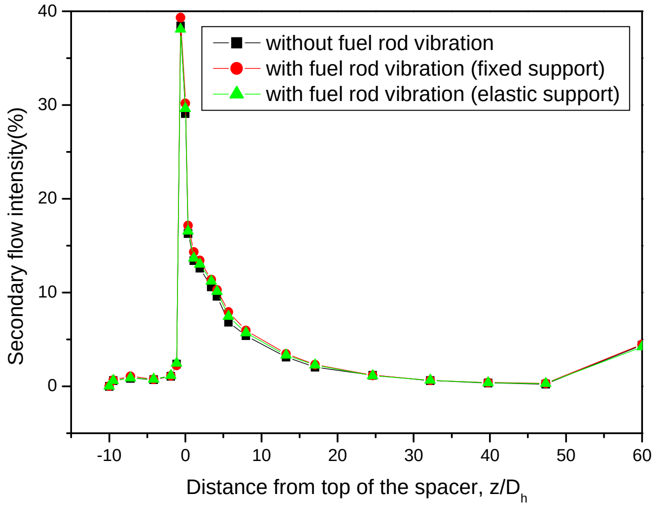
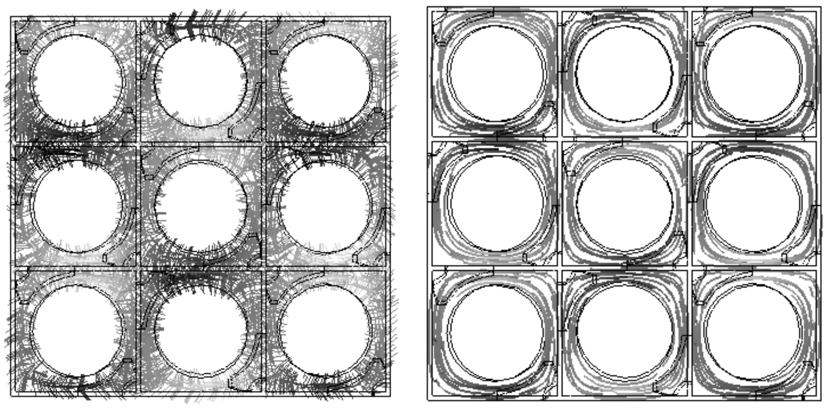


Fig.4: variation of cross-sectional averaged secondary flow intensity

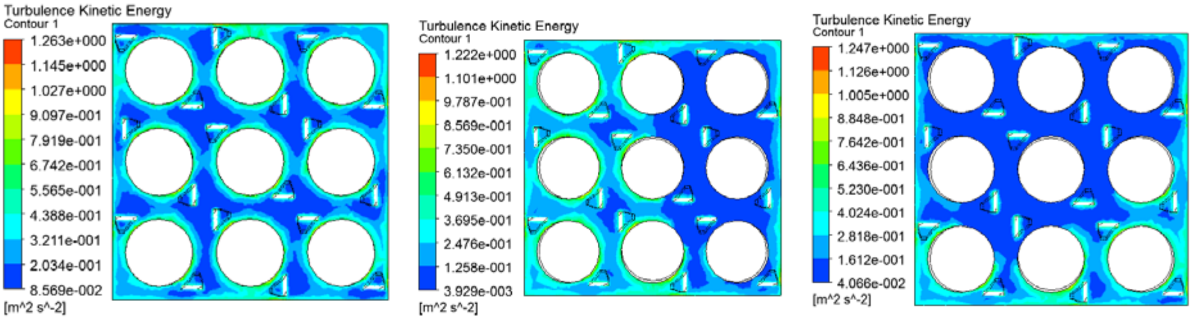
Fig. 5 shows secondary flow pattern after the LSVF counter mixing vanes(1.5 D_h). LSVF counter mixing vanes are generate large scale vortex flows which contain cross-flow between sub-channels as shown in Fig. 5 (b).



(a) Secondary flow vector (b) Stream line

Fig.5: Flow pattern at the center of mixing vane

Fig. 6 shows the turbulence kinetic energy contour of rod bundle at center of the mixing vane. A large difference can be noted at the kinetic energy distribution where without fuel rod vibration the uniform distribution got. The kinetic energy distribution was also different under different support methods conditions. This is because different support conditions results different fuel rod displacement caused by flow.



(a) without fuel rod vibration (b) fixed support fuel rod (c) elastic support fuel rod

Fig.6: Cross-section view of turbulence kinetic energy contour at the center of mixing vane

Fig. 7 shows the comparison of pressure drop in the axial direction. The pressure appears to rapidly decrease across the mixing vane. From the results can see that the fuel rod vibration almost had no effect on pressure drop.

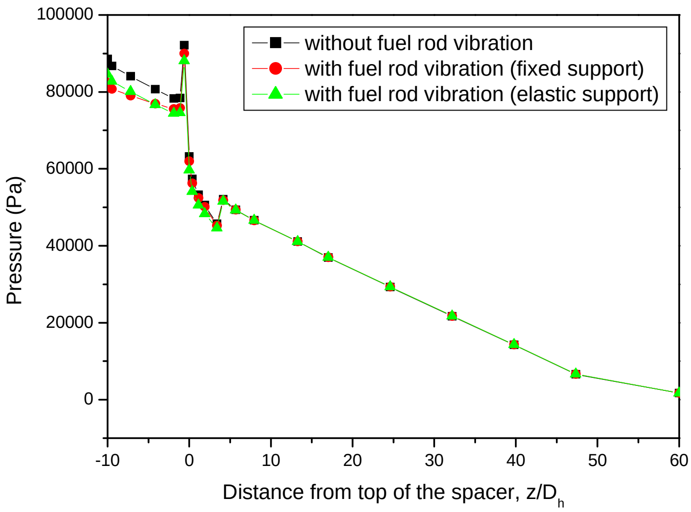
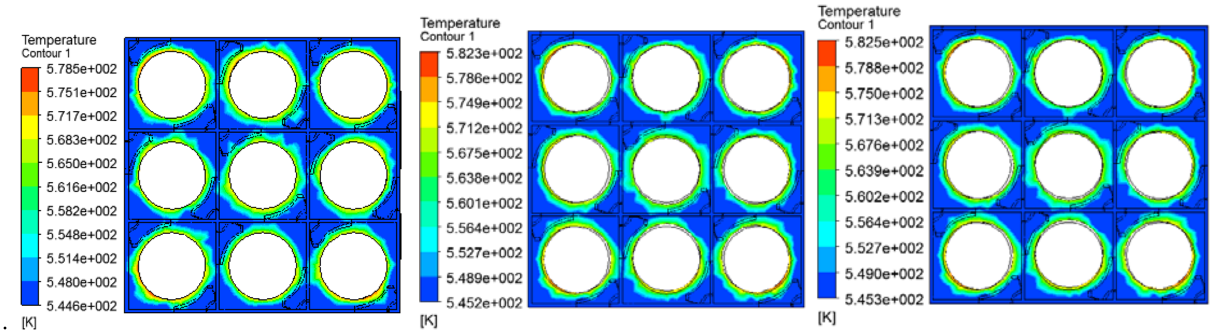


Fig.7: Comparison of the pressure distribution in the sub-channel

Each fuel rod releases a constant heat flux so that bulk temperatures in the cross-sections of rod bundle linearly increase along axial direction after spacer grid. Lowering maximum surface temperature of the rod bundle, is very important to suppress the probation of hot spots. Fig. 8 shows the outlet surface temperature distribution with and without fuel rod vibration conditions. From the results can see that without fuel rod vibration the outlet surface temperature much smaller than with vibration conditions. This means that the fuel rod displacement obstructed to decrease the temperature. And both at fixed support and elastic support the temperature almost got similar values. Although the fuel rod vibrations not affect the pressure drop and secondary flow intensity, it still gave effect on kinetic energy distribution and temperature values. So to study the thermal hydraulic problem of rod bundle, not only secondary flow considered but also the rod vibration taken into considered.



(a) without fuel rod vibration (b) fixed support fuel rod (c) elastic support fuel rod

Fig.8: Cross-section view of temperature distribution at outlet surface

CONCLUSION

In the present study, the 3×3 single sub-channel of rod bundle with LSVF mixing vanes were simulated. The flow characteristics compared without fuel rod vibration conditions and without fuel rod vibration conditions and got the conclusions as follows:

(1) Fuel rod vibration did not affect the secondary flow intensity and pressure drop..
(2) Fuel rod vibration affected the turbulence kinetic energy distributions.
(3) With fuel rod vibration got much bigger outlet surface temperature than without vibration conditions.
(4) Elastic support and fixed support almost had the same values.
(5) To study the thermal hydraulic problem of rod bundle, not only secondary flow considered but also the rod vibration taken into considered.

REFERENCES

[1] Yoon, K. H., Kim, J. Y. and Kim, H. K, "Axial Impact Analysis of a 16by16 Fuel Assembly by the FE Method", *Transactions, SMiRT 19*, Toronto, C05/2, 2007.
[2] Korea Nuclear Fuel Co., Ltd., "Fuel Design Report for 17×17 Fuel Assembly", 1994.
[3] K. B. Lee, H. C. Jang and S. K. Lee, "Study of the Secondary Flow Effect on the Turbulent Flow Characteristics in Fuel Rod Bundles", Journal of the Korean Nuclear Society, 1994, Vol. 26, pp. 345~354.
[4] In, W. K.., Oh, D. D. and Chun, T. H. "Flow Analysis for Optimum Design of Mixing Vane in a PWR Fuel Assembly", *Journal of the Korean Nuclear Society*, ,2001, Vol. 33, No. 3, pp.327~338.
[5] J. S. An and Y. D. Choi, "A Study of Turbulence Generation Characteristics of Large Scale Vortex Flow Mixing Vane of Nuclear Fuel Rod Bundel", *The Society Of Air-Conditioning And Refrigerating Engineers Of Korea*, 2006, Vol. 18, No.10, pp.811~818.
[6] G. Yadigaroglu, M. Anderani, J. Dreier and P. Coddington, "Trends and Needs in Experimentation and Numerical Simulation for LWR Safety", *Nucl. Eng. Des.,* 2003. Vol. 221, pp. 205~223.
[7] C. Tzanos, "Performance of k–ε Turbulence Models in the Simulation of LWR Fuel-Bundle Flows", *Trans. ANS 84*, 2001, pp.197~199.
[8] S. Toth, A. Aszodi, "CFD Analysis of Flow Field in a Triangular Rod Bundle", Nuclear Engineering and Design, 2010, Vol. 240, pp.352~363
[9] Yoon. K. H., "Mechanical Performance Evaluation Test of Spacer Grid Specimen for Integrated Reactor Fuel", KAERI/TR-1147/98