Transactions, **SMiRT-22**
San Francisco, California, USA - August 18-23, 2013
Division III (include assigned division number from I to X)

Coolant-Fuel Rod Interaction for Rod Bundle with Seven Spacer Grid Assemblies

Hai Lan Jin[1], Young Shin Lee[2], Hyun Seung Lee[1] and Num Gyu Park[3]

[1] Student, Dept. of Mechanical Design Engineering, Chung Nam National University, Korea
[2] Professor, Dept. of Mechanical Design Engineering, Chung Nam National University, Korea (leeys@cnu.ac.kr)
[3] *R&D Center, KEPCO Nuclear Fuel, Korea*

ABSTRACT

In this paper coolant fuel rod interaction for rod bundle with seven spacer grid assemblies were studied to investigate the frequencies and flow induced vibration characteristics of SMART rod bundle. SST turbulence model was used to model the coolant flow fluid. For flow induced vibration simulation, frequencies and mode shapes of fuel rod with seven spacer grid assemblies were studied numerically and experimentally that the test was done at R&D center, KEPCO nuclear fuel. As a result for natural frequency 2 % differences occurred between simulation and test. Also, the simulation results for pressure drops of rod bundle were compared with experiment data showed 8 % differences and demonstrated the simulation accuracy. Then, through the coolant fuel rod interaction analysis fuel rod displacements were calculated with maximum displacement happened at span-1. Through the maximum displacement the displacement PSD at span-1 were calculated according to maximum displacement.

1. INTRODUCTION

Korea Nuclear Fuel (KNF) was established in 1982 to localize nuclear fuel technology, based on various technologies transferred from the former Siemens/KWU, the former Combustion Engineering, and Westinghouse Electric Company. KNF started to supply firstly localized PWR and PHWR fuels from 1989 and 1997, respectively. 17×17 spacer grids used in this paper are under developing spacer grids for SMART(System-integrated Modular Advanced Reactor) consists of a top and bottom spacer grid assembly, three mid spacer grid assemblies and two IFM spacer grid assemblies. 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. The pressure drop is one of the main characteristics to define the fuel rod assembly quality. The mixing vanes attached to the spacer grid assembly to increase coolant mixing and the fuel rod heat transfer ability. The mixing vanes not only affects flow characteristics but also affects the pressure drop of rod bundle. In working reactor core because of the high coolant flow velocity, fuel rods vibrations are induced that may cause structure damage.

The earliest use of LDV to measure the mean horizontal was by Neti[1] who reported that the maximum horizontal velocities are about 1 % of bulk velocity without mixing vane. Vonka [2] successfully resolved secondary flow vortices from LDA velocity measurements in two regular sub-channels of a triangularly arranged "clean" rod bundle concluded that single secondary vortex, having the average tangential velocity(secondary flow velocity) slightly less than 0.1% of the mean bulk velocity, is resolved per minimum symmetry sector of the bundle geometry. From about 1990 onwards flow characteristics in rod bundle started to consider the mixing vanes attached at mixing grid(without spacer grid spring and dimple). Crecy[3] performed an experimental study to investigate the effect of the mixing vanes on the position of DNB(departure from nuclear boling) and CHF(critical heat flux) in 5×5 rod bundle. Yang and Chung[4] investigated the effects of mixing spacer grid on the turbulence in 5×5 rod bundle with LDV measurements. Shin and Chang[5] used experimental method to study the effect of angles and positions of mixing vanes on critical heat flux(CHF) in a 2 × 2 rod bundle. Caraghiaur, et al[6] investigated experimentally on the pressure, velocity and turbulence intensity distributions in a 24-rod bundle .

With the development of computer technology these experiments for rod bundle were replaced by numerical method. In[7] performed CFD analysis to propose the optimum design of flow several mixing vanes which attached at interlaced straps of a grid namely spacer grid assembly without spacer grid spring and dimple. At the first the CFD results of flow velocity and turbulent kinetic energy caused by Split-vanes were compared with experiment results by Karoutas et al.[8] and Yang and Chung[9] to confirm the simulation accuracy. An[10] used the CFD method to compare the flow characteristics with LSVF(large scale vortex flow) mixing vane, with split mixing vane and without mixing vane in 3×3 square rod bundle channel. Lee and Choi[11] used FLUENT code to compared turbulence intensities, maximum surface temperatures of the rod bundle, heat transfer coefficients and pressure drops for four kinds mixing vanes. Liu and Ferng[12] developed 3-D CFD model with RSM turbulence model to investigate the thermal-hydraulic characteristics in the rod bundle with the different types of grid designs. Horvath[13] used numerical method to find an optimal mesh resolution and turbulence model for flows in rod "clean" rod bundle square channel and compared the simulation results with experimental data of Hooper(1980). Jin[14] studied for turbulence models effects in SMART rod bundle and conclude that SST is the optimum turbulence model for this kind of rod bundle. As see above, the numerical methods have a high accuracy for predict the rod bundle flow characteristics.

However, as mentioned above most of flow characteristics affects for the rod bundle for CFD analysis neglected the flow induced vibration effects. Since the coolant normally flows parallel to the rods, the vibration is called an axial flow induced vibration(FIV). One flow characteristic which can cause damage is shedding of vortices at a frequency in resonance with fuel rod vibrations. So determining the amount of vortex shedding is also very important especially in this study. When high speed coolant flows towards rod buddle vortex shedding occurs. If the vortices that shed off the coolant have a frequency equal to the resonance frequency of the fuel rod then it starts swaying out of control. This causes the destruction of the structure. Due to this, prediction of vertex shedding is essential.

In this paper, CFD evaluations on SMART 17×17 rod bundle with seven spacer grid assemblies using the commercial cod CFX 14.0 was performed in testing the new model before it is implemented. Then the simulate result, namely, the pressure drop values were compared with test results which test done at Korea Atomic Energy Research Institute. Secondly, flow induced vibration for rod bundle was done numerically. However, numerical simulation gives an approximate outcome before an experiment is actually conducted, and the results can be used as a guide in designing the experiment and in choosing the right instruments for measurements

2. ANALYSIS MODEL

2.1 Rod Bundle Flow Channel

Figure 1 shows the flow channel for SMART 3 × 3 rod bundle consists of seven spacer grid assemblies and nine fuel rods. With bottom and top assemblies to prevent vibration-induced fretting of the fuel rods due to the high turbulence at the inlet or outlet of the fuel bundle, the mixing vane was not used. The mid and IFM assemblies used SSVF(Small Scale Vortex Flow) mixing vane as shows in Figure 2. The SMART rod bundle was used in this paper that much shorter than general rod bundle especially the axial distance between the fuel rod assemblies. So the SSVF mixing vanes can be used which turbulence caused by them decays rapidly due to its small length scale. Furthermore, the enhanced heat transfer by the turbulence is maintained only within a short distance after the SSVF mixing vanes. From the figure can see that the mixing vanes have alternating direction, namely, one diagonal mixing vane is horizontally split and the other one is vertically split which belong to SSVF-couple arraying method.

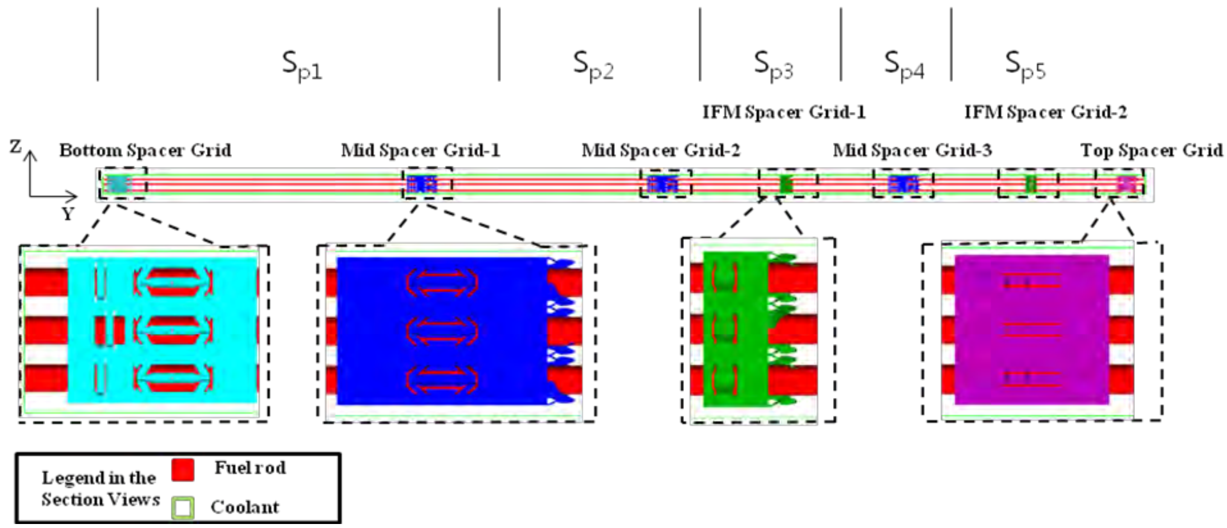


Figure 1. Schematic of 3 × 3 rod bundle

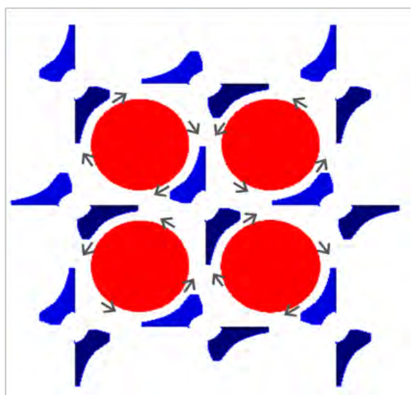


Figure 2. Schematic arrays of SSVF couple mixing vanes

2.2 Boundary Conditions for Rod Bundle[14]

The boundary conditions of the fuel bundle were set as follows: the coolant with higher temperature(265 °C) enters from the bottom surface into the fuel bundle channel with a velocity of 3m/s. 0 Pa average static pressure was employed at outlet of the models. The coolant flows from bottom to top. The reference pressure was 123 bar. No slip smooth wall boundary condition with a constant heat flux 840000 W/m^2 was used for the fuel rods, and no slip smooth adiabatic wall boundary condition was used for modeling the wall and spacer grids

2.3 Grid Sensibility for Rod Bundle

To get a good description of the flow structure in complex rod bundle, it needed a number of dense fluid grids. Excess of grids not only require much computation time to solve the problem but also difficult to proceed post processing. With that in mind, in order to define the proper grid parameters, a grid sensibility study was performed at first. Jin studied turbulence models effect on grid sensibility for this kind of the SMART rod bundle. In her study, SST turbulence model was the optimum to predict the flow characteristics. In this paper used SST turbulence model to study the flow characteristics. In this case the dimensionless distant y+ between boundary layer and fuel rod wall was shown as Figure 3 in the turbulent boundary layer. The maximum value was not exceed 4 which value satisfied dimensionless distant y+[15].

2.4 Fuel Rod Boundary Conditions

The central fuel rod was considered for flow induced vibration. Figure 4 shows the interface configuration for central fuel rod. In the simulation the spacer grid springs and dimples were assumed to bonded contact with fuel rod.

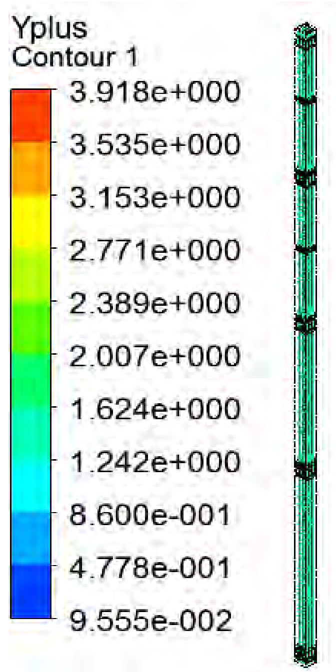


Figure 3. y^+ distribution on the surface of rod

Figure 4. Fuel rod supported by 1×1 spacer grids

3. TEST ARRANGEMENT

The fuel rod vibration test configuration shown in Figure 5 consists of a shaker hanger which can accommodate as maximum of two shakers and a vertical test stand with 7 clamps which holds the 6x6 grid assemblies securely. The test bed was fixed to a concrete wall through 3 I-beams, and the bottom end was fixed to the ground. A force transducer at the tip of a stinger which was linked to the shaker measures the applied force signal, and the shaker was hung in the vertical direction. A connecting jig to provide a flat surface for the rod was necessary to fix the force transducer to the structure as the fuel rod surface was round, as opposed to the force transducer bottom surface which was flat.

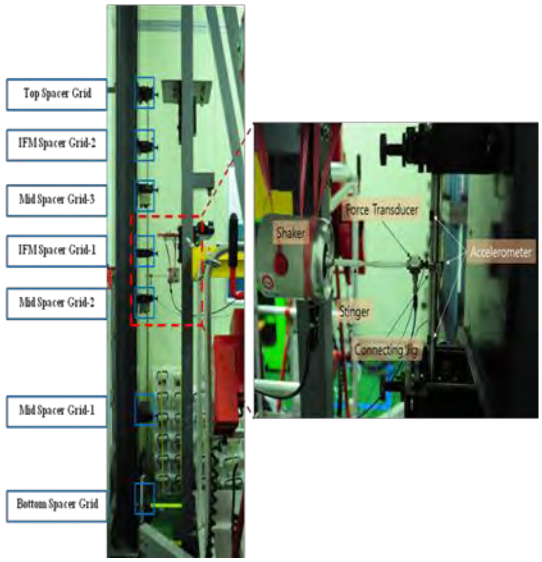


Figure 5. Configuration of the fuel rod vibration test set-up

4. RESULTS AND DISCUSSIONS

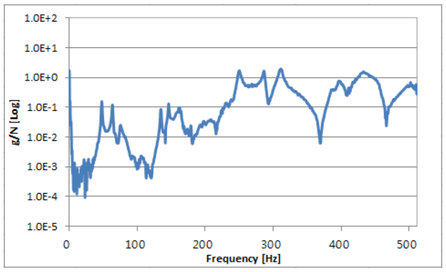
4.1 Test results of Fuel Rod

The vibrational frequencies of SMART fuel rod were obtained from test conducted in air at room temperature. Random force signals were applied to the shaker placed in the middle point of the span-3, and the frequency response functions of a fuel rod and fuel tube were measured. One accelerometer was fixed at the location of the shaker, while nine accelerometers were utilized to simultaneously acquire the vibration signal through 3 spans. The roving accelerometers measured the response signal at every 1/4, 2/4, and 3/4 location along the fuel rod at each span. Unlike the force transducer, which requires fixture, the accelerometers were directly attached to the rod with bees-wax.

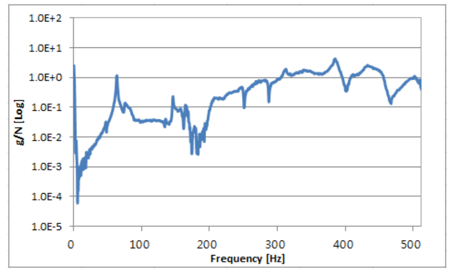
The measured frequency response function is delineated in Figure 6. Since the shaker is placed on the 3rd span, the signal in the neighboring shaker is clear. On the other hand, the response which is farther away from the shaker is contaminated by noise. In spite of the noise, the signal was reached to the end of fuel tube since the SMART fuel rod has a short length, i.e. 2254 mm.

4.2 Fuel Rod Frequencies and Mode Shapes for Test

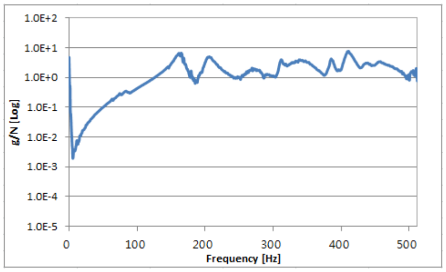
Table 1 shows fuel rod frequencies and mode shapes for test and simulation. Comparing the results, the 1st and 2nd frequencies each has 8 Hz and 4 Hz differences respectively. In the simulation the boned contact boundary conditions were used between fuel rod and spacer grid springs or dimples and these boundary conditions may caused small differences. At both condition can get similar mode shapes of fuel rod. The frequency existing in reactor was about 50 Hz, and according to this the 1st mode may dominate in this situation. This fuel rod model can be used in flow induced simulation.



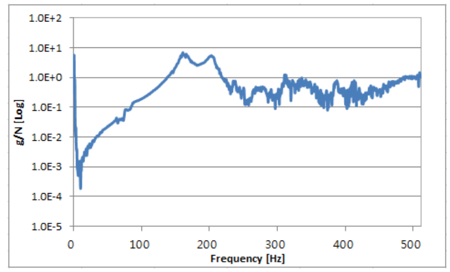
(a) Span-1



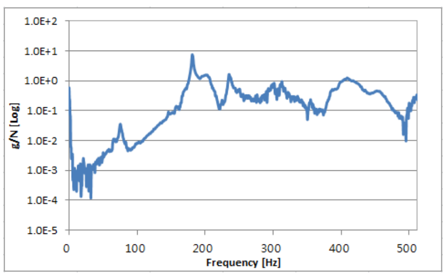
(b) Span-2



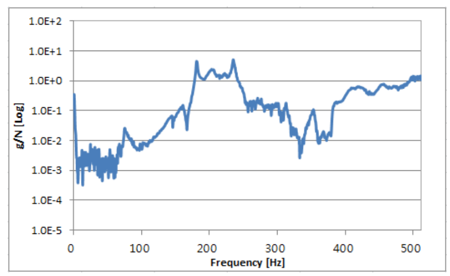
(c) Span-3



(d) Span-4



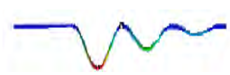
(e) Span-5



(f) Span-6

Figure 6. Frequency response function of fuel rod

Table 1: Frequency and mode shape of fuel rod

Mode No.	Experimental results	Simulation results
Mode 1	 48 Hz	 40 Hz
Mode 2	 64 Hz	 60 Hz
Mode 3	 75 Hz	 100 Hz

4.3 Comparison of Pressure Drop

The simulation was done by commercial package ANSYS-CFX on desktop computer (CPU 2.67 GHz, 16.0 GB of RAM) and terminated when the residual for the mass flux is less than approximately 1E-5 kg/s. A thousand time steps were needed to obtain a converged solution with 10 iterations at each time step. The simulation results of pressure drop compared with test results at the condition with Reynolds number 160,974 and the reactor core reference pressure of 15 MPa. In this case the volume flow rate was 1500 m^3/hr. Hydraulic pressure drop test for SMART rod bundle performed in the hydraulic test loop which is located in the Korea Atomic Energy Research Institute. Similar with Jin`s test, the rod bundle divided into 5 spaces that space contains mid spacer grid assembly-1 was Sp_1, mid spacer grid assembly-2 was Sp_2 and mid spacer grid assembly-3 was Sp_4. The space contains IFM spacer grid assembly-1 was Sp_3 and IFM spacer grid assembly-2 was Sp_5 as Figure 1 shows. Table 2 shows the comparison of simulation results of normalized pressure drop with test results at Sp_1~Sp_5. The data was normalized with Sp_1 data. The maximum error was almost 8 % that the simulation results can be used.

Table 2: Comparison of normalized pressure drop

ID	Sp_1	Sp_2	Sp_3	Sp_4	Sp_5
Experiment	1	0.87	0.624	0.87	0.628
Simulation	1	0.798	0.576	0.818	0.589
Difference (%)	0	8.3	7.7	6	6.2

4.4 Flow Induced Vibration for Fuel Rod

Figure 7 shows Maximum displacement pattern of fuel rod. In the simulation the maximum displacement happened at span-1 because the span-1 had maximum length among span. PSD(power spectral density) noise signature equation and it fourier transform were as follows:

$$S_x(f) = 2\lim_{T\to\infty}\frac{1}{T}[X(f)]^2 \quad (1)$$

$$X(f) = \int_{-T/2}^{T/2} x(t)e^{-j2\pi ft}\,dt \quad (2)$$

The maximum displacement history at span-1 as Figure 8 shows. According to equation (3),(4),(5) can get the displacement PSD history at span-1 as shows in Figure 9. As a result, the maximum displacement PSD appeared at 60 Hz, 85 Hz and 95 Hz.

$$X(f) = \frac{1}{-j2\pi f}6x(t)(e^{-j6\pi f} - e^{j6\pi f}) \quad (3)$$

$$S_x(f) = \frac{1}{-j\pi f}12x(t)^2(e^{-j6\pi f} - e^{j6\pi f}) \quad (4)$$

$$S_x(f) = \frac{24}{\pi f}x(t)^2\sin(6\pi f) \quad (5)$$

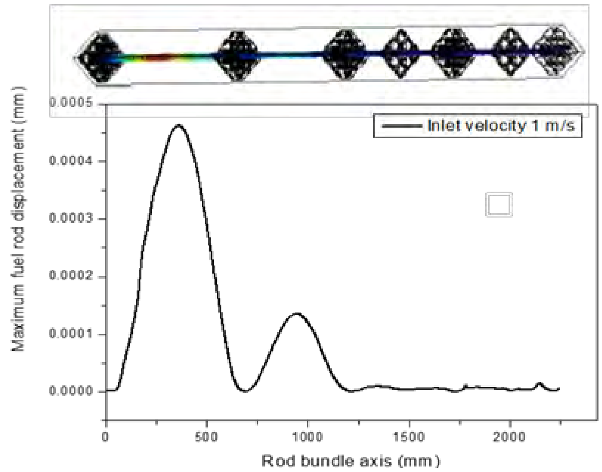


Figure 7. Maximum flow induced displacement pattern of fuel rod.

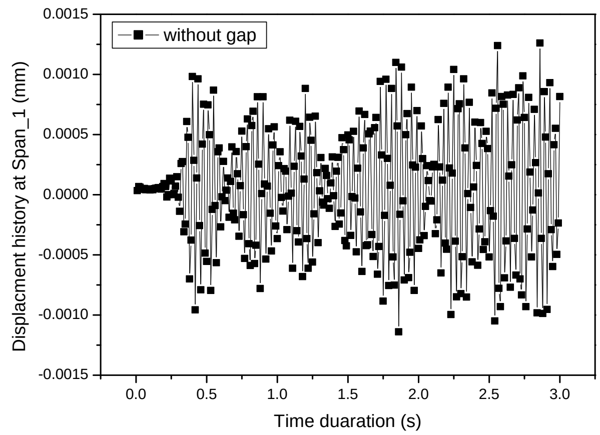


Figure 8. Displacement history at span-1

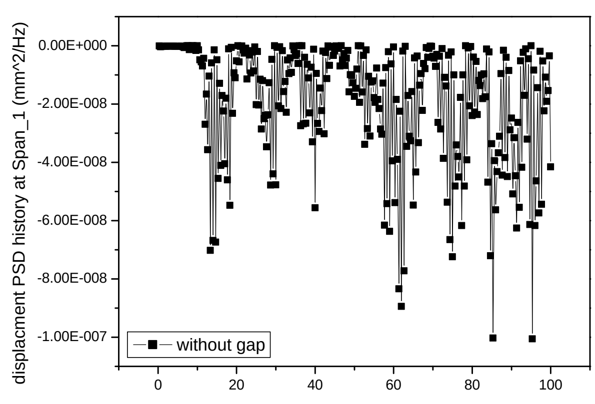


Figure 9. Displacement PSD history at span-1

5. CONCLUSION

In this paper coolant-fuel rod interaction for rod bundle with seven spacer grid assemblies were done numerically. To get reliable numerical results the simulation for frequencies and pressure drops were compared with test and get follow conclusions:

(1) The nature frequency for test and simulation were 48 Hz and 40 Hz respectively that their differences within 2 % with 1st bending moment at span-1

(2) The pressure drops for test and simulation differences within 1 %

(3) The maximum displacement caused by flow induced vibration happened at span-1.

ACKNOWLDGMENT

This work supported by R&D Center, KEPCO Nuclear Fuel, Korea.

REFERENCES

1. Neti, S., Eichorn, R. and Hahn, O. J., V. (1982). "Laser Doppler Measurements of Flow in a Rod Bundle", Nuclear *Engineering and Design*, Vol. 74, pp. 105~116
2. Vonka, V. (1988). "Turbulent Transports by Secondary Flow Vortices in a Rod Bundle", *Nuclear Engineering and Design*, Vol. 106, pp. 209~220.
3. Crecy, F. (1994) "The Effect of Grid Assembly Mixing Vanes on Critical Heat Flux Values and Azimuthal Location in Fuel Assemblies", *Nuclear Engineering and Design*, Vol. 149, pp. 233~241.
4. Chung, J. B., Baek, W. P. and Chang, S. H. (1996). "Effects of the Spacer and Mixing Vanes on Critical Heat Flux for Low-Pressure Water at Low-Velocities", *Int. Comm. Heat Mass Transfer*, Vol. 23, No. 6, pp. 757~765.
5. Shin, B. S. and Chang, S. H. (2005). "Experimental Study on the Effect of Angles and Positions of Mixing Vanes on CHF in a 2×2 Rod Bundle with Working Fluid R-134a", *Nuclear Engineering and Design*, Vol. 235, pp.1749~1759.
6. Caraghiaur, D., Anglart, H. and Frid, W. (2009). "Experimental Investigation of Turbulent Flow through Spacer Grids in Fuel Rod Bundles", *Nuclear Engineering and Design*, Vol. 239, pp. 2013~2021.
7. In, W. K., Oh, D. D. and Chun, T. H. (2001). "Flow Analysis for Optimum Design of Mixing Vane in a PWR Fuel Assembly", *Journal of the Korean Nuclear Society*, Vol. 33, No. 3, pp.327~338.
8. Yang, S. K. and Chung, M. K. (1996). "Spacer Grid Effects on Turbulent Flow in Rod Bundles", *Journal of the Korean Nuclear Society*, Vol. 28, No. 1, pp. 56~71.
9. Karoutas, Z., Gu, C. Y. and Scholin, B. (1995). "3-D Flow Analysis for Design of Nuclear Fuel Spacer", *Proceedings of the NURETH-7（NUREG/GP-0142,Vol.4)*, pp.3153-3174.
10. An, J. S. and Choi, Y. D. (2006). "A Study of Turbulence Generation Characteristics of Large Scale Vortex Flow Mixing Vane of Nuclear Fuel Rod Bundle", *The Society Of Air-Conditioning And Refrigerating Engineers Of Korea*, Vol. 18, No.10, pp.811~818,2006
11. Lee, C. M. and Choi, Y. D. (2007). "Comparison of Thermo-Hydraulic Performances of Large Scale Vortex Flow(LSVF) and Small Scale Vortex Flow(SSVF) Mixing Vanes in 17×17 Nuclear Rod Bundle", *Nuclear Engineering and Design*, Vol. 237, pp.2322~2331.
12. Liu, C. C. and Ferng, Y. M. (2010). "Numerically Simulating the Thermal-Hydraulic Characteristics within the Fuel Rod Bundle Using CFD Methodology", *Nuclear Engineering and*

Design, Vol. 240, pp.3078~3086.
13. Horvath, A., Dressel, B. (2012). "Numerical Simulations of Square Arrayed Rod Bundles", *Nuclear Engineering and Design*, Vol. 247, pp. 168~182.
14. Jin, H. L., Lee, Y. S. and Park, N. G. (2012). " CFD Analysis on a Three by Three Nuclear Fuel Bundle with Five Spacer Assemblies", Journal of Mechanical Science and Technology, Vol. 26, No, 12, pp. 1~9.
15. ANSYS CFX-Solver Modeling Guide, (2009). *ANSYS Inc.*.