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Wall-modelled LES of the turbulent flow in a nuclear fuel rod bundle

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1. Introduction

There are many structures such as fuel rods, mixing vane, and spacer grid in the nuclear reactor core. And these structures lead to complex turbulence flow. Especially, Cross flow can occur around the nuclear fuel rod [1], and flow patterns that induces strong mixed flow in the transverse direction may occur due to its structure [2]. This turbulent flow phenomenon can have a significant impact on the heat transfer between the nuclear fuel rod and the cooling water. Therefore, thermal-hydraulic analysis is very important to prevent nuclear power plant accidents. In particular, the number of studies on factors related to heat transfer are still insufficient, such as wall friction coefficients and Nusselt numbers. So, it is very important to study them.

Currently, one-dimensional system analysis codes have been widely used in evaluating the safety of nuclear power plants. However, it may be difficult to capture the complex turbulent flow. Argonne National Laboratory presented a multi-resolution approach to model thermal-hydraulic behavior in nuclear fuel rod bundle [3]. According to this approach, multi-dimensional and high-fidelity data can be used to validate the one-dimensional analysis code. Also, this data can be provided by optimizing modeling parameters in subchannel code. Therefore, this study aims to obtain multi-dimensional validation data and capture instantaneous turbulent behavior through high-fidelity simulation using Wall-Modeled Large Eddy Simulation (WMLES) [4].

2. Computational Fluid Dynamics Analysis

2.1 Rod Bundle Geometry

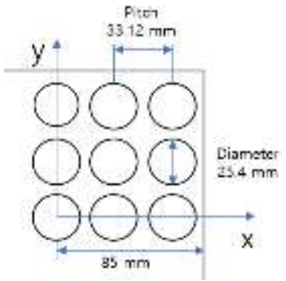


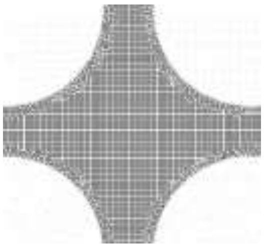
Fig. 1. Cross-section area at bare rod.

As shown in Fig. 1, the geometry of the rod bundle has a total of 25 nuclear fuel rods in a square duct structure of 170 mm x 170 mm. The pitch of rod-to-rod is 33.12 mm, diameter of rod is 25.4 mm, and hydraulic diameter considering cross sectional area and wetted perimeter is 24.27 mm.

2.2 Mesh Information

The overall type of mesh is the poly-hexcore created in Fluent Meshing application. In order to analyze values such as wall friction coefficients and Nusselt number, refined mesh was created with the prism layer near the wall. The picture of mesh and detailed conditions are shown in Table I.

Table I: The mesh information in WMLES simulations

 Fig. 2. Poly-hexcore mesh with prism layers.	Min. size	0.19 mm
	Max. Size	0.75 mm
	Max. Aspect ratio	67.97
	Max. Skewness	0.68
	First Δy^+	1.56
	Cells	2.5 M

2.3 Numerical Modeling

In this study, WMLES was conducted only for 1/4 of the entire area by using symmetric and axial periodic conditions. The working fluid is liquid water. The bulk velocity is 2.07 m/s and Reynolds number is 50,000. The pressure at the outlet is 0 Pa, and the heat flux at each rod is 10,000 W/m^2. The time step is 2 e^{-5} s and the total sampling time is 18.3s. More detailed information about Fluent solver settings is listed in the Table II.

Table II: The information about solver settings

Scheme	SIMPLE
Gradient	Green-Gauss node Based
Pressure	2nd Order
Momentum	Bounded Central Differencing
Energy	Bounded Central Differencing
Transient Formulation	Bounded 2nd Order Implicit

2.4 HPC (High-Performance Computing) Cloud Service

A super computer cluster was used to solve complex simulation. In particular, this method is reasonable when there are quite a lot of meshes and the time step size is very small. A CPU type is the Intel Xeon Platinum 8151 3.4 GHz. There are available 120 cores with 1.9 TB of RAM.

3. Result

3.1 Validation

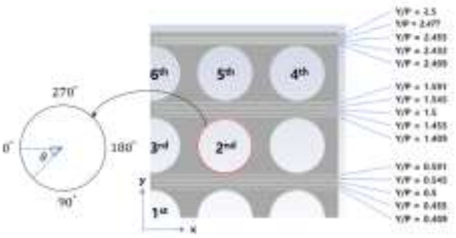


Fig. 3. Validation domain for simulation

Fig. 3. shows the positions of each line to validate the time-averaged and RMS velocity in the X-Y plane with [5], [6].

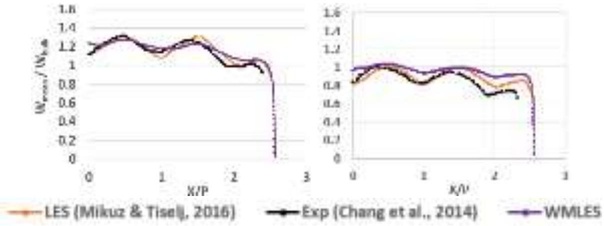


Fig. 4. Comparison of time-averaged axial velocity. The left picture shows the result at the Y/P = 0.5 and the right figure is the result at the Y/P = 2.455.

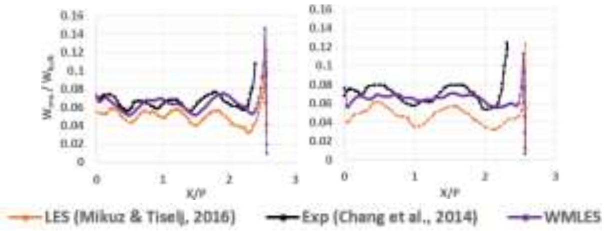


Fig. 5. Comparison of RMS axial velocity. The left picture shows the result at the Y/P = 0.5 and the right figure is the result at the Y/P = 2.455.

According to Fig. 4. and Fig. 5, WMLES predicted well, although it overpredicted in some location.

3.2 Fanning Friction Factor

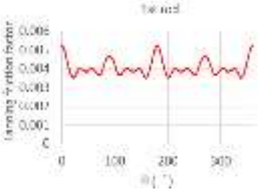


Fig. 6. Distribution of the coefficients of friction.

Fig. 6. presents the distribution of the Fanning friction factor along the nuclear fuel rod. We can find that the peak value of the friction factor appears repeatedly at each specific position.

4. Conclusions

We conducted multi-dimensional and high-fidelity simulation (WMLES) in a 5x5 bare rod bundle. First, the time- averaged and RMS velocity were validated. As a result, it can be said that the result is valid. And then, using the data, we focused on analyzing various results in-depth, such as the distribution of friction factor and the understanding of eddy's behavior.

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