

Investigation of Heat Transfer and Turbulence Characteristics of a Triangular Rod Array in lattice-Boltzmann Framework

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Abstract. In present study, triangular subchannel of VVER-440 reactor is simulated using with lattice-Boltzmann and finite volume methods. The heat transfer and flow characteristics such as pressure drop, heat transfer coefficient, temperature and velocity distributions are obtained by using both LBM and FVM. The selected VVER subchannel has pitch-to-diameter ratio of 1.35. Simulations are carried out in two stages: bare rod bundle and rod bundle with spacer grid simulations. The FVM calculations are handled using ANSYS Fluent 15.0 CFD Solver. Smagorinsky (LES) turbulence model and heat transfer modules are implemented to the lattice-Boltzmann framework. The heat transfer module works in conjunction with the turbulent flow computations. For both LBM and FVM, turbulence model study was accomplished and the post-processed turbulence quantities, velocity and temperature profiles, heat transfer coefficient and pressure drop values are compared with experimental data and correlations. The comparisons show that lattice-Boltzmann simulations are in good agreement with the finite volume method based LES simulations and also used experimental data. After completing the validation process of lattice-Boltzmann code, the spacer grid effect on heat transfer characteristics and flow dynamics are then investigated.

Keywords: Thermal-hydraulics, code development, code validation, lattice-Boltzmann, triangular array rod bundle

1 Introduction

In safety concern, predicting the behavior of turbulence in a nuclear reactor fuel bundle is an important subject. Many engineers and scientists studied turbulence both experimentally and computationally. Trupp and Azad [1] were presented their key observations on fuel rod bundle system by doing experiments. Besides experimental studies, numerical simulation of turbulent flows became attractive when considering the evolution of computer technology and improvements in numerical techniques.

In DNS (Direct Numerical Simulation), all turbulent scales must be resolved from smallest Kolmogorov microscale [2] to integral scale l_e . However, this is an expensive process for today's computer technology [3-4] The Kolmogorov scales are defined by $(\nu^3/\varepsilon)^{1/4}$ and the required number of meshes for fully resolving turbulence is proportional to $Re^{9/4}$. Thus, roughly 10^{11} mesh is required to go down to the Kolmogorov microscales which would be a highly affordable process. Recently, the lattice-Boltzmann method is grown up as an alternative CFD (Computational Fluid Dynamics) solver. The detailed information about the formulation of lattice-Boltzmann method will be given in the next section.

The flow behavior of VVER-440 subchannel had been investigated by many researchers both experimentally and numerically. Hazi [5] simulated VVER type rod bundle using standard $k-\varepsilon$ model and showed that the standard $k-\varepsilon$ model could not produce the basic characteristics of the flow. He suggests the Reynolds stress model to be more reliable turbulence model than standard $k-\varepsilon$ model for simulating rod bundle flow. Aszodi et al. [6] investigated the

effect of the mesh sensitivity and turbulence model selection on capturing experimental flow behavior of VVER-440 subchannel. They pointed out that the mesh sensitivity is very important to predict the turbulence quantities. SSG Reynolds stress model and BSL Reynolds stress model are capable of predicting the anisotropic normal Reynolds stresses and secondary flow. Mayer et al. [7] used lattice-Boltzmann method to simulate bare VVER-440 subchannel and compared with the experimental data. They concluded that the long-time averaging is essential for lateral velocities and reasonably good agreement with the experimental results.

In this paper, VVER-440 type subchannel flow is simulated. The effect of spacer grid is investigated by comparing the results of VVER subchannel with/without spacer grids. Based on the recommendations and findings of the previous works, LES (Large Eddy Simulations) turbulence model is selected for both ANSYS Fluent and lattice-Boltzmann simulations. Trupp and Azad's experimental study [1] is used for the validation of lattice-Boltzmann code for bare VVER-440 simulations.

The main goal of this study is to validate the implemented turbulence model and investigate the effect of spacer grid on the flow in the lattice-Boltzmann framework in a single VVER subchannel. The successful validation of the code and including complex geometries in lattice-Boltzmann simulations give hope for the future. Thus, a realistic nuclear reactor subchannel with other auxiliary components could be modeled using the lattice-Boltzmann approach.

The remaining part of this paper is organized as follows: In Section 2, the numerical methods adopted in this study are described. The theory behind the Smagorinsky (LES)

turbulence model and heat transfer in finite volume based and lattice-Boltzmann numerical algorithm is mentioned briefly. In Section 3, LES computations of flow in VVER-440 type subchannel are presented and compared with experimental results. The results are analyzed, and the important things obtained from this work are discussed. Finally, in Section 4, the summary and conclusions are provided.

2 Numerical Method

It is very expensive to resolve all scales of turbulence for highly turbulent and complex flows. Nuclear reactor coolant system can be seen as an example of such flows since Re number is in the order of 10^5 and also it contains in itself obstacles (like spacer grids and mixing vanes) which enhance turbulence. As indicated in the previous section, simulating a nuclear reactor subchannel using Direct Numerical Simulation (DNS) method which resolves all scale of turbulence is almost impossible for at least today computer technology.

Large Eddy Simulations (LES) turbulence method is widely used nowadays especially for subchannel flow analysis for reactor coolant systems. In LES, large eddies interact with and extract energy from the mean flow. These eddies are simulated directly, and the smaller ones (scales smaller than the grid size) are modelled with an appropriate assumption. Smagorinsky model is one of ways for modelling small scale eddies in LES.

2.1 Large Eddy Simulations (LES) with subgrid stress model

The general Navier-Stokes equations are written as,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \mathbf{H} u_i) = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\rho \mathbf{H} u_i) + \frac{\partial}{\partial x_i} (\rho \mathbf{H} u_i \mathbf{H} u_j) \\ = \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \mathbf{H} u_i}{\partial x_j} \right) - \frac{\partial \mathbf{H} p_i}{\partial x_i} + \frac{\partial \mathbf{H} \tau_{ij}}{\partial x_j} \end{aligned} \quad (2)$$

where $\mathbf{H} \tau_{ij} = \rho \overline{u_i u_j} - \rho \mathbf{H} u_i \mathbf{H} u_j$ is called as the subgrid scale stress.

The nonlinear term in Navier-Stokes equations $\left\{ \frac{\partial \mathbf{H} \tau_{ij}}{\partial x_j} \right\}$ is not directly modelled. Boussinesq approximation is used to model subgrid scale stress $\mathbf{H} \tau_{ij}$.

$$\mathbf{H} \tau_{ij} = -2\mu_{sgs} \overline{S}_{ij}, \quad (3)$$

where $\overline{S}_{ij} = \frac{1}{2} \left(\frac{\partial \mathbf{H} u_i}{\partial x_j} + \frac{\partial \mathbf{H} u_j}{\partial x_i} \right)$ is the large-scale strain rate tensor and μ_{sgs} is the subgrid scale viscosity. In Smagorinsky-Lilly model [8], the subgrid scale viscosity is modelled by

$$\mu_{sgs} = \rho (C_s \Delta)^2 \|\mathbf{H} S\| \quad (4)$$

Here, $\|\mathbf{H} S\| = \sqrt{2\overline{S}_{ij} \bullet \overline{S}_{ij}}$ is the magnitude of large-scale strain rate tensor, Δ is the filter length, and C_s is the Smagorinsky constant. The Smagorinsky constant C_s depends on the relevant case study and normally varies between 0.05 and 0.16 [9].

2.2 Lattice-Boltzmann with turbulence and heat transfer

The lattice Boltzmann method (LBM) is a new and growing alternative approach for simulating fluid flows [10-13]. In fluid transport field, isothermal incompressible flow [14-15], turbulent flows [16-17], multiphase flows [18-20] are successfully simulated in the lattice-Boltzmann framework. In this method, the pseudo-fluid particles, which have discrete velocity and densities, make successive collision and streaming process over two different lattices one of them for velocity and the other for the temperature.

$$\begin{aligned} f_i(x + e_i \partial t, t + \partial t) \\ = f_i(x, t) - \frac{1}{\tau} (f_i(x, t) - f_i^{eq}(x, t)), \end{aligned} \quad (5)$$

$$\begin{aligned} g_i(x + e_i \partial t, t + \partial t) \\ = g_i(x, t) - \frac{1}{\tau_c} (g_i(x, t) - g_i^{eq}(x, t)). \end{aligned} \quad (6)$$

In Smagorinsky model viscosity depends on strain rate as shown in Eq. (4). The local strain rate can be computed from the particle distribution functions [21],

$$\overline{S}_{ij} = -\frac{1}{2\tau_{tot} c_s^2 \partial t} \pi_{ij}^{neq}, \quad (7)$$

where momentum flux tensor π_{ij}^{neq} is defined as,

$$\pi_{ij}^{neq} = \sum_m e_{mi} e_{mj} (f_m - f_m^{eq}). \quad (8)$$

And the total relaxation time τ_{tot} is found as [22],

$$\tau_{tot} = \tau + \tau_{sgs}, \quad (9)$$

where

$$\begin{aligned} \tau_{sgs} &= \sqrt{\tau^2 + \frac{18C_s^2 \partial t^2 Q}{c^2}} - \tau \text{ and} \\ Q &= \sqrt{\sum_{ij} 2\pi_{ij}^{neq} \pi_{ij}^{neq}}. \end{aligned}$$

If the particle density distribution is known, the macroscopic quantities such as velocity and density are calculated as,

$$\rho = \sum_{i=0}^{18} (f_i), \quad (10)$$

$$\mathbf{H} u = \frac{1}{\rho} \sum_{i=0}^{18} (f_i e_i), \quad (11)$$

$$\rho h = \sum_{i=0}^6 (g_i), \quad (12)$$

where $h = DRT/2$, D is the dimension, R is the gas constant and T is the temperature.

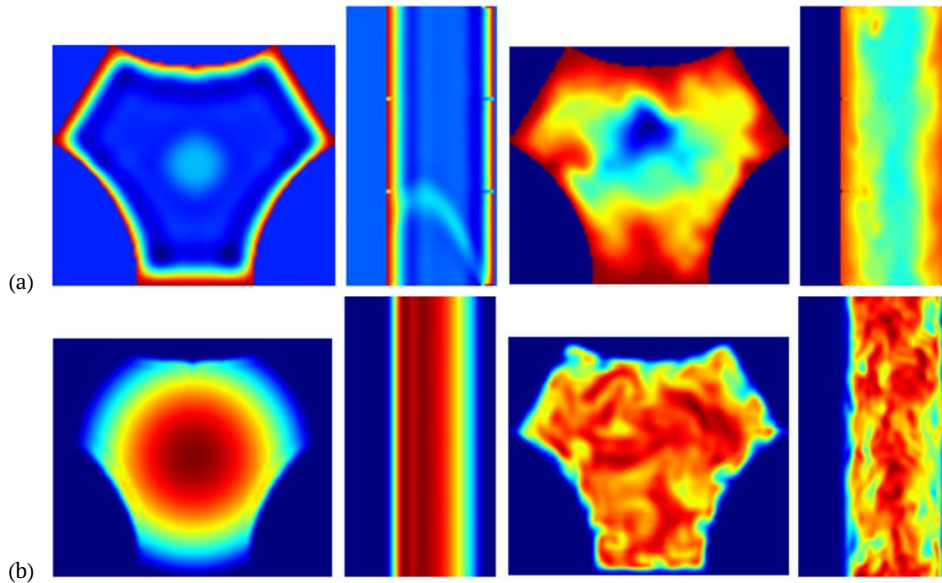


Figure 1. Time evolution of flow in a triangular rod configuration of typical VVER-440 subchannel without spacer grid: (a) temperature profiles; (b) velocity profiles at $t = 0.01$ s and $t = 0.2$ s.

3 Flow in VVER-440

The flow in a single VVER-440 subchannel with a P/D ratio of 1.35 is examined. The wind tunnel experiment made by Trupp and Azad [1] is selected for validation. In this experiment, fully developed air flow in a triangular rod lattice is studied, and detailed experimental data are published for Reynolds number 60,000 and $P/D = 1.35$. Reynolds number in nominal operating conditions of VVER-440 subchannel is approximately 220,000.

3.1 Numerical model description and validation process (FVM and LBM)

The selected unit cell from VVER-440 triangular lattice configuration has 9.1 mm rod diameter and 12.3 mm pitch length [23]. In validation, bare VVER-440 triangular fuel rod configuration is simulated. For lattice Boltzmann simulations, the rod bundle geometry is decomposed in $100 \times 100 \times 265 = 2,650,000$ cubic lattices. The bounce-back mechanism is performed around the fuel rod surfaces [24]. Periodic and symmetry boundary conditions are defined at axial and lateral ends of the channel respectively.

An axial force is applied to meet the flow average velocity $\bar{U} = 3.18$ m/s. The value of Smagorinsky constant C_s has been selected as 0.1 since it gives best results for a wide range of flows [25-27].

A constant heat flux of 1047 kW/m² is applied for the heat transfer calculations. The relaxation parameters are calculated using Chapman-Enskog expansion [28]. The turbulence and heat transfer in bare VVER-440 is demonstrated in Figure 1.

The same geometry and boundary conditions are used in FVM simulations. ANSYS Fluent 15.0 is selected as computational tool. Smagorinsky-Lilly (LES), which is defined in ANSYS Fluent 15.0, is used as subgrid-scale turbulence model with same Smagorinsky constant. 1,888,653 tetrahedral cells are generated using Gambit software for decomposition. Control volumes (meshes) are refined around the fuel rod walls. The post-processed quantities such as temperature profiles are extracted from both LBM and FVM simulations. Figure 2 shows the comparison of the post-processed temperature profiles obtained from LBM and FVM.

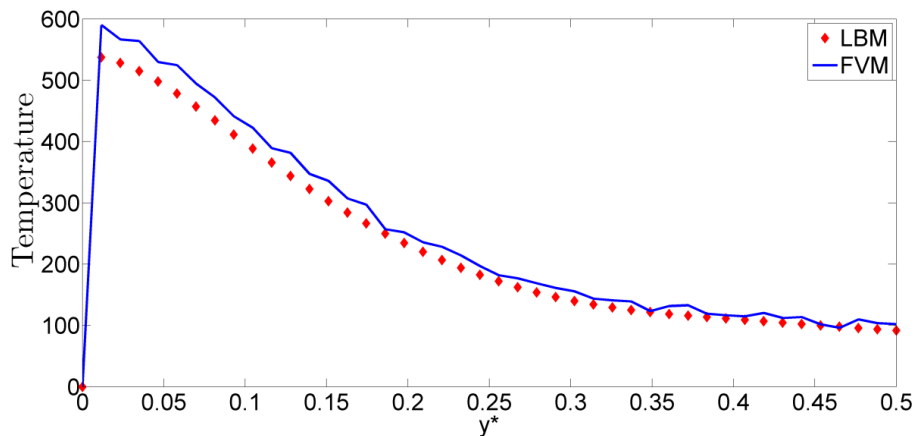


Figure 2. The post-processed temperatures extracted from LBM and FVM simulations.

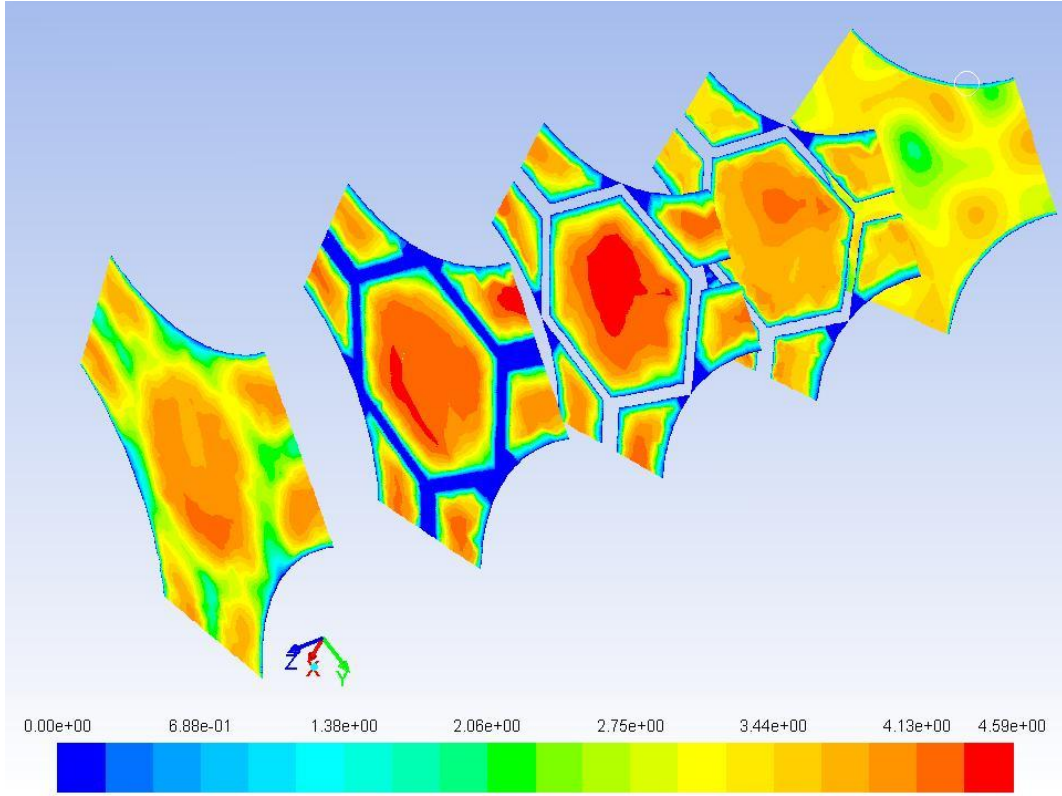


Figure 3. Axial velocity profiles obtained from ANSYS Fluent LES simulations for five selected planes at $z = 0, 0.005, 0.01, 0.015,$ and 0.02 m.

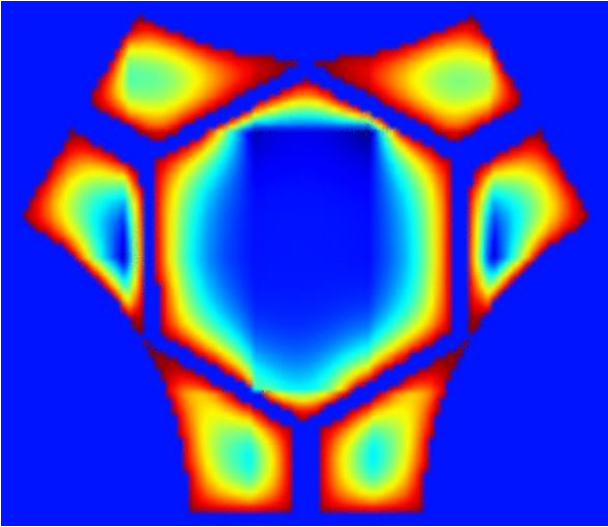


Figure 4. The post-processed temperatures extracted from LBM with spacer simulations.

Reasonable agreement has been achieved for temperature profiles when LBM results compared with finite volume calculations. Nevertheless, there are small deviations with the finite volume results in near wall regions. As described in Section 2, lattice sizes are same in both near wall regions and the main flow region. Thus, a grid refinement around the rod walls may enhance the simulation results and reduce the deviations.

3.2 Spacer grid effect

The spacer grid effect on the single VVER subchannel flow is investigated. Velocity profiles and pressure drop cal-

culations are compared. After validation process is completed, VVER subchannel with spacer grid geometry is modeled. The axial length and width of the spacer is specified as 10 mm and 0.5 mm, respectively [7]. The same lattice resolution with bare VVER-440 simulation is used. In axial directions, velocity inlet and pressure outlet boundaries are used. The symmetry boundary conditions are defined at lateral sides of the subchannel. The bounce-back mechanism is performed around the fuel rods and also spacer grid walls. The same geometry is modelled with ANSYS Fluent code for pressure drop calculations and comparisons with lattice-Boltzmann code. The validation process had been presented in previous work [29]. The resulting axial velocity profiles in ANSYS Fluent LES simulations are represented in Figure 3. Also, the temperature profile obtained from LBM is demonstrated in Figure 4.

3.3 Pressure loss and heat transfer coefficient at spacer

Pressure drop ΔP_s arising from the effect of spacer region is calculated in lattice-Boltzmann framework and compared with the ANSYS 13.0 Fluent simulation results. Pressure loss in LBM is defined as,

$$\Delta P_s = \frac{1}{3} (\rho_{s,in} - \rho_{s,out}) \left(\frac{dx}{dt} \right)^2 \rho_0, \quad (13)$$

where $\rho_{s,in}$ and $\rho_{s,out}$ are average densities just before and after spacer in LB units respectively, ρ_0 is the physical density of water in kg/m^3 .

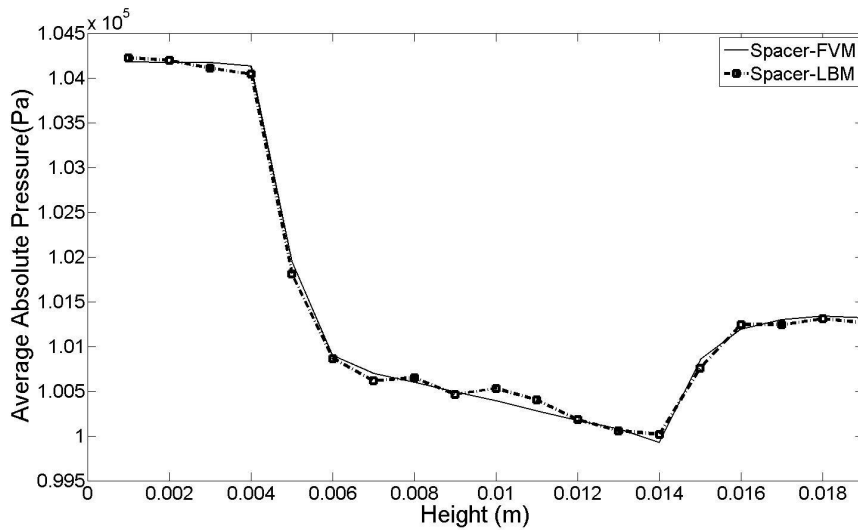


Figure 5. Area averaged absolute pressure values along VVER-440 subchannel simulated with finite volume and lattice-Boltzmann method.

Area averaged absolute pressure values for ANSYS Fluent, and lattice-Boltzmann simulations are extracted from the simulations and these values are averaged over the time domain. The results are graphed out for selected points along the channel. Figure 5 shows the pressure values for VVER-440 fuel rod bundle with spacer grid. The resulting pressure values obtained from both FVM and LBM are in good agreement.

The average heat transfer coefficient is calculated at $z = L/2$ location by, $h = \frac{q''}{\Delta T}$. The Dittus-Boelter correlation is used for experimental result. The results are tabulated in Table 1.

Table 1. Heat transfer coefficient for bare and with spacer configuration

Model	LBM-Bare	LBM-Spacer	Experimental (Bare)
h (W/m ² K)	3.2×10^4	6.3×10^4	3.1×10^4

4 Conclusion

It is demonstrated in this study that a triangular VVER-440 subchannel flow could be modelled with the lattice-Boltzmann method. The validation of lattice-Boltzmann code is made successfully. For the bare VVER geometry, temperature profiles are in good agreement with FVM. In order to get better results especially for temperature, grid refinement around rod walls and spacer regions is essential for LBM simulations. The code is suitable to the implementation of grid refinement and different turbulence and heat transfer models. In addition, the lattice-Boltzmann code has tendency to the parallelization, thus, LBM can be thought as an alternative to the traditional CFD methods. As a future work, the heat transfer mechanism is going to be implemented to the code.

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