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CFD Analysis of the Coolant Flow in Fuel Assembly of the VVER1000 Type Reactor

Václav Heidler[a], Jan Vimmr[b], Ondřej Bublík[c]

[1]Department of Mechanics, Faculty of Applied Sciences, University of West Bohemia, Univerzitni 8, 306 14 Pilsen, Czech Republic

[a]v.heidler@kme.zcu.cz, [b]jvimmr@kme.zcu.cz, [c]obublik@kme.zcu.cz

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Abstract: The paper deals with the simulation of 3D coolant flow in a fuel assembly of the reactor VVER 1000 of the Temelín Nuclear Power Plant. Because of a very complex geometry and a large computational domain, it is a very computationally-demanding task. With this in mind, some measure of simplification is inevitable. The mathematical model of 3D coolant flow is solved using in-house software based on the lattice Boltzmann method.

Introduction

Due to the transverse coolant flow in the core of a pressurized water reactor (PWR), fuel rods are excited to oscillate. Provided that there are some inaccuracies in manufacturing of fuel rods and grids, it is quite likely that the mechanical vibrations cause excessive wear of their cladding in the areas of contact with the grids. This grid-to-rod fretting phenomena (GRTF) can, during the operation, results in breaking the first safety barrier with subsequent leakage of fissile products into the primary coolant. Predictive simulations of GRTF involve turbulence flow, structural dynamics, contacts and wear.

The aim of the present study is to compute the turbulent flow in the fuel rod assembly using the lattice Boltzmann method (LBM) to find out if it is an appropriate numerical method for this type of computationally-demanding calculations.

Methods

The lattice Boltzmann equation is directly derived from the Boltzmann equation, which describe the time evolution of the particle distribution function $f = f(\boldsymbol{x}, \boldsymbol{u}; t)$, by discretization in both time and phase space.

$$f_\alpha(t + \Delta t, \boldsymbol{x} + \boldsymbol{e}_\alpha \Delta t) = f_\alpha(t, \boldsymbol{x}) + \Omega_\alpha, \tag{1}$$

where f_α, α = 1,2,…19 are the distribution functions corresponding to each microscopic velocity. We discuss the D3Q19 model, which is shown in Fig.1. The collision operator on the right-hand side of Eq. (1) is for the multi-relaxation time model [4]

$$\boldsymbol{\Omega} = \boldsymbol{M}^{-1}\boldsymbol{S}[(\boldsymbol{M}\boldsymbol{f}) - \boldsymbol{m}^{\boldsymbol{eq}}]. \tag{2}$$

Matrix $\boldsymbol{M}$ is the transformation matrix composed of the 19 orthogonal basis vectors. The moments of distribution functions $\boldsymbol{m} = \boldsymbol{M}\boldsymbol{f}$ are labeled as

$$\boldsymbol{m} = \left(\rho, e, \epsilon, j_x, q_x, j_y, q_y, j_z, q_z, 3p_{xx}, 3\pi_{xx}, p_{ww}, \pi_{ww}, p_{xy}, p_{yz}, p_{xz}, m_x, m_y, m_z\right). \tag{3}$$

$\boldsymbol{m}^{eq}$ is the vector composed of the equilibrium moments given in Eq. (4) and $\boldsymbol{S}$ is the diagonal collision matrix containing collision parameters (the eigenvalues of the collision matrix $\boldsymbol{M}^{-1}\boldsymbol{S}\boldsymbol{M}$). The some recommended values can be found in [4].

$$
\begin{aligned}
m_0^{eq} &= \rho, \\
m_3^{eq} &= \rho_0 u_x, \\
m_5^{eq} &= \rho_0 u_y, \\
m_7^{eq} &= \rho_0 u_z, \\
m_1^{eq} &= e^{eq} = \rho_0\left(u_x^2 + u_y^2 + u_z^2\right), \\
m_9^{eq} &= 3p_{xx}^{eq} = \rho_0\left(2u_x^2 - u_y^2 - u_z^2\right), \\
m_{11}^{eq} &= p_{zz}^{eq} = \rho_0\left(u_y^2 - u_z^2\right), \\
m_{13}^{eq} &= p_{xy}^{eq} = \rho_0 u_x u_y, \\
m_{14}^{eq} &= p_{yz}^{eq} = \rho_0 u_y u_z, \\
m_{15}^{eq} &= p_{xz}^{eq} = \rho_0 u_x u_y,
\end{aligned} \qquad (4)
$$

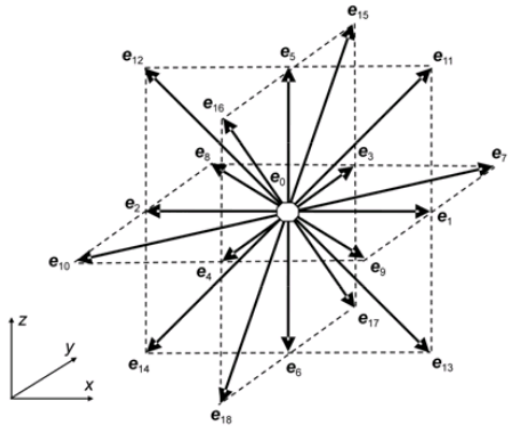

Fig. 1: D3Q19 lattice model

where ρ_0 is a constant density and ρ a density variation. The macroscopic quantities density and momentum are given by

$$\rho = \sum_\alpha f_\alpha, \qquad \rho_0 \boldsymbol{u} = \rho_0 \sum_\alpha \boldsymbol{e}_\alpha f_\alpha. \qquad (5)$$

Summary

We have implemented the lattice Boltzmann method for solving large-eddy simulation of the coolant flow in the fuel assembly using multiple-relaxation-time model, recursively refined meshes using hierarchical block structured grids and parallelization using Coarray Fortran. Next task is to add energy equation into our in-house software and consequently the buoyancy force.

The obtained numerical results will be presented and discussed in detail at the conference.

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