Development of MHD Heat Transfer Database at Design Conditions of Advanced Blanket System in Fusion Reactor

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The large-scale direct numerical simulation (DNS) of a Magneto-Hydro-Dynamics (MHD) turbulent heat transfer has been developed specifically for 128 nodes configurations on the Earth Simulator 2 (ES2). In this project of this fiscal year, we focused on optimizing the algorithm of the inter-node communication to run with maximizing the computational power of the ES2. As the results, the computational speed of our DNS code was measured up 21 Tflops, in which computational performance was attained about 20% of the theoretical peak of ES2.

Keywords: MHD, DNS, Turbulent Heat Transfer, High-Re, High-Pr

1. Introduction

FLiBe which is the molten salt mixture of LiF and BeF is one of the coolant candidates in the first wall and blanket of the fusion reactors, and has several advantages which are little Magneto-Hydro-Dynamics (MHD) pressure loss, good chemical stability, less solubility of tritium and so on. In the contrast, the low thermal diffusivity and high viscosity are the key issues of the FLiBe utilization as a coolant[1]. Moreover, the development of MHD turbulence model with high accuracy is highly demanded to predict the MHD pressure loss and the heat transfer for the fusion reactor designs.

A direct numerical simulation (DNS) of turbulent flows is one of the most powerful methods to understand turbulent structures and heat transfer. Molten salt fluids such as FLiBe are the higher Pr fluids (Pr=ν/α:Prandtl number=20-40, ν is the kinetic viscosity, α is the thermal diffusivity), however the previous DNS studies have conducted at the only lower Pr condition. Therefore, MHD turbulent heat transfer on higher Pr fluids hasn't been understood well. Furthermore, a problem of DNS studies limited to lower-Re (:=$U_b 2h/\nu$ is the bulk Reynolds number, U_b is the bulk mean velocity, h is the channel height) and -Pr conditions would be depended on the computational resources limitation.

In this study, we developed the large-scale DNS code of a MHD turbulent heat transfer for 128 nodes configurations on the Earth Simulator 2 (ES2) in order to establish the database at the design conditions of the advanced Blanket System in Fusion Reactors.

2. Numerical methods

2.1 Basic equations and boundary conditions

The target flow is the incompressible MHD turbulent flows at the low magnetic Reynolds number ($Re_m = U_b 2h/\eta$, η is the magnetic diffusivity) with passive scalar transport. The objective flow geometry and coordinate system are shown in Fig. 1.

Basic equations of the present DNS were the continuity equation (1), the momentum equations (2) with the electric field described using the electrical potential approach[3], Poisson equation (3) of the electrical potential, and the energy equation (4), respectively.

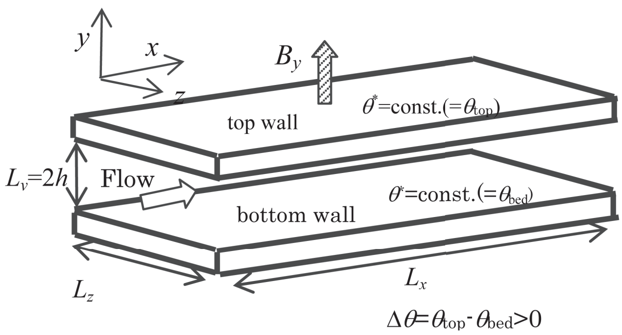

Fig. 1 Flow geometry and coordinate system.

$$\frac{\partial u_i^*}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i^*}{\partial t} + \frac{\partial u_i^* u_j^*}{\partial x_j} = F\delta_{i1} - \frac{\partial}{\partial x_i}\left(\frac{p^*}{\rho}\right) + \nu \frac{\partial^2 u_i^*}{\partial x_j \partial x_j} + \frac{\sigma}{\rho}\varepsilon_{ijk}\left(-\frac{\partial \phi^*}{\partial x_j} + \varepsilon_{jlm} u_l^* B_m\right) B_k, \tag{2}$$

$$\frac{\partial^2 \phi^*}{\partial x_i \partial x_i} = \frac{\partial}{\partial x_i}\left(\varepsilon_{ijk} u_j^* B_k\right), \tag{3}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial \theta u_j}{\partial x_j} = \alpha \frac{\partial^2 \theta}{\partial x_j \partial x_j}. \tag{4}$$

Here, u_i (:=u,v,w (i=1,2,3)) is the streamwise velocity (i = 1), the vertical velocity (i = 2) and the spanwise velocity (i = 3), t is time, x_i (: = x,y,z (i = 1,2,3)) is the streamwise direction (i = 1), the vertical direction (i = 2) and the spanwise direction (i = 3), F is the streamwise mean pressure gradient, p is the pressure, ρ is the density, σ is the electrical conductivity, ϕ is the electric potential, B_i= (0, B_y,0) is the Magnetic flux density, and θ is the temperature. Super script * denotes instantaneous value and δ_{ij}, ε_{ijk} (i,j,k = 1-3) is the Kronecker delta and the Levi-Civita symbol, respectively.

Non-slip and periodic conditions were imposed for boundary conditions of velocity and the constant temperature at top and bottom boundaries ($\theta_{top} > \theta_{bed}$, θ_{top} : top wall temperature, θ_{bed} : bottom wall temperature), and the periodic conditions were imposed for a passive scalar field. Total electric current in the flow domain was kept zero and the boundary condition of the electric potential was non-conducting condition at all walls and the periodic condition imposed on the horizontal directions.

2.2 Numerical Procedures

The spectral method is used to compute the spatial discretization in the stream (x) and spanwise (z) directions. To remove the aliasing errors, the phase-shift method was used in horizontal (x and z) directions. The derivative in the wall normal (y) direction is computed by a second-order finite difference scheme at the staggered grid arrangement. Time integration method is 3rd-order Runge-Kutta scheme for the convection terms, Crank-Nicolson scheme for the viscous terms and Euler Implicit scheme for the Pressure terms, respectively. The Helmholtz equation for the viscous (diffusion) terms and the Poisson equations of the pressure and the electrical potential are solved by a TriDagonal Matrix Algorithm, TDMA in Fourier space.

2.3 Parallelization

In this DNS study, the Message Passing Interface (MPI) was adapted for a distributed memory parallel programing tool. Domain decomposition in the y direction was used in order to calculate 2D-FFTs for the horizontal directions (x, z). Before performing the TDAM along the y direction, we need to transpose the data form the domain decomposition along the y axis to the one along the z axis as shown in Fig. 2-1) and 2). In this process, we used the data transposition method by remote memory access (RMA), called one-sided communication with the packed 1D continuous data.

To avoid the excessively concentration of the data communication between the specified rank and others, scheduling [2] the multi-stages internode data communications via the two-tier Fat-Tree crossbar network, were implemented as shown in Fig. 3.

To reduce the data communication traffics, a hybrid parallelization by MPI and Microtasking was implemented.

2.4 Numerical condition

Numerical conditions of DNS for 2-D fully-developed turbulent channel flows imposed wall-normal magnetic field, were tabled in Table 1, where super-script + denotes the nondimensional quantities normalized by the friction velocity and the kinematic viscosity. In the computations, KOH solution (Pr = 5.0) were used. Note that the KOH solution was used as the FLiBe simulant fluid in the previous experimental study [3]

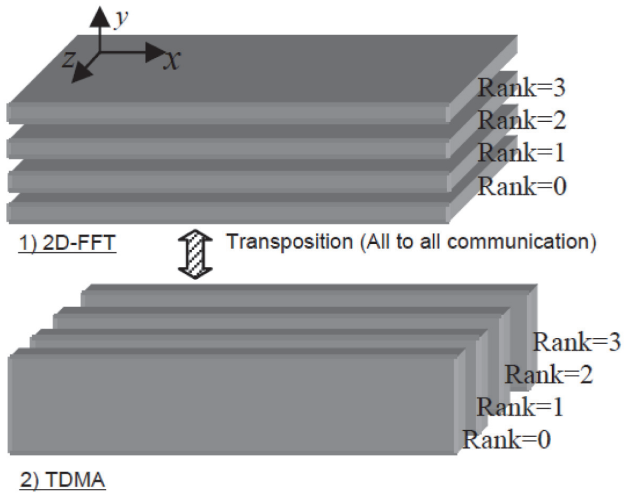

Fig. 2 1-D domain decomposition and transposition between 2D-FFTs and TDMA algorithms in case of 4 PEs.

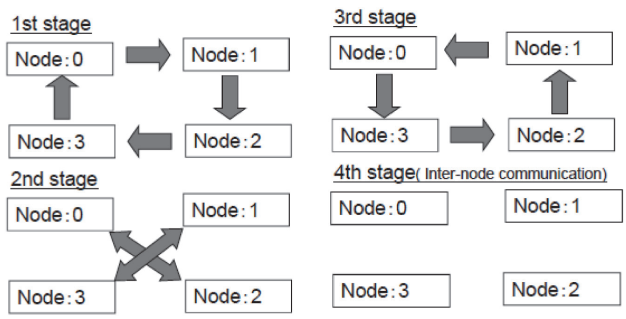

Fig. 3 Scheduling the multi-stages inter–node data communications in case of 4 nodes.

Table 1 Numerical condition.

Re_τ	Ha	Pr	Domain L_x, L_y, L_z	Grid number N_x, N_y, N_z	Resolution Δ_x^+, Δ_y^+, Δ_z^+
2000	0,48,96	5.0	16.0h, 2h, 6.4h	2000, 2032, 1920	16.0,0.25-2.0,6.7

and heat transfer data was obtained in case of KOH solution.

Turbulent Reynolds number ($Re_\tau = u_\tau h/\nu$) was kept constant, 2000, and Hartman number ($Ha = B_y 2h(\sigma/\rho\nu)^{1/2}$) was changed from 0 to 96.

3. Performance of present DNS code

Using the program information of MPI/SX9, computational speed has been measured for the calculation of 100 time steps in the SX-9 and the ES2, respectively. This computational speed taken in initialization was included from the measurement. The corresponding numbers of nodes (CPUs) taken up in case of SX-9 at Tohoku University were 4(64), 8(128) and 16(256) used by a flat MPI, respectively. Those in case of ES2 were 96(768) and 128(1024) used by a hybrid MPI with 8 microtasking process, respectively.

Figure 4 shows the computational speed [Tflops] as a function of numbers of CPUs in the SX-9 and ES2. Maximum computational speed was 21 Tflops corresponded to 20% of the theoretical peak of ES2.

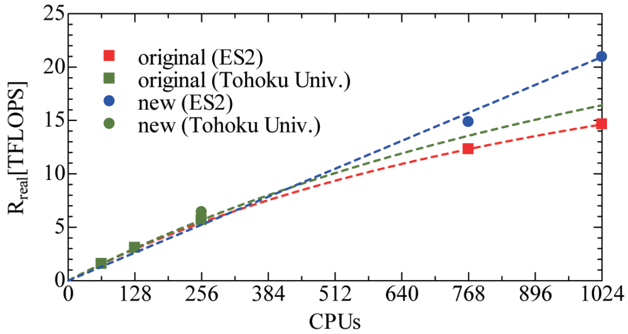

Fig. 4 Computational speed [TFLOPS] as a function of number of CPUs in SX-9 and ES2.

4. Conclusions

Using the high performance computing techniques, DNSs of MHD heat transfer in the high-Re and the high-Pr have been executed on the 128 nodes configurations on the Earth Simulator 2 (ES2).

As the results, the computational speed of our DNS code was measured up 21 Tflops, in which computational performance was attained about 20% of the theoretical peak of ES2.

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核融合炉先進ブランケットにおける MHD 熱伝達データベースの構築

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核融合炉先進ブランケットデザイン条件下での高精度 MHD 乱流熱伝達データベース構築を目的として、地球シミュレータ 2（128 ノード）を対象とした MHD 乱流場の直接数値計算手法開発を実施した。その結果、ベクトル化率 99.8%、実行効率 20%、実行演算速度 21 TFLIOPS の高速・高精度 MHD 乱流直接数値計算手法の開発に成功した。

キーワード: MHD, 高レイノルズ数, 高ハルトマン数, 高プラントル数, DNS