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Modeling of MHD turbulent heat transfer in channel flows imposed wall-normal magnetic fields under the various Prandtl number fluids

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HIGHLIGHTS

- We show the applicability to predict the heat transfer imposed on a uniform wall-normal magnetic field by means of the zero-equation heat transfer model.
- Quasi-theoretical turbulent Prandtl numbers with various molecular Prandtl number fluids were obtained.
- Improvements of the prediction accuracy in turbulent kinetic energy and turbulent dissipation rate under the magnetic fields were accomplished.

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ABSTRACT

Zero-equation heat transfer models based on the constant turbulent Prandtl number are evaluated using direct numerical simulation (DNS) data for fully developed channel flows imposed on a uniform wall-normal magnetic field. Quasi-theoretical turbulent Prandtl numbers are estimated by DNS data of various molecular Prandtl number fluids. From the viewpoint of highly-accurate magneto-hydrodynamic (MHD) heat transfer prediction, the parameters of the turbulent eddy viscosity of the k–ε model are optimized under the magnetic fields. Consequently, we use the zero-equation model based on a constant turbulent Prandtl number to demonstrate MHD heat transfer, and show the applicability of using this model to predict the heat transfer.

1. Introduction

Estimation of heat transfer degradation due to magneto-hydrodynamics (MHD) forces is one of the key issues facing the design of fusion reactors that utilize molten salt coolants [1,2] such as FLiBe, which is a molten salt mixture of LiF and BeF. To predict heat transfer degradation during the design process, we attach much value to Reynolds-averaged Navier–Stokes simulation (RANS) [3–5]. From this viewpoint, high accuracy models [6,7] of MHD source terms appearing in both the transport equations of turbulent kinetic energy and the turbulent energy dissipation rate have been proposed and passive scalar transport in MHD channel flows of low-Prandtl (*Pr*) number fluids have been investigated [8,9] by means of Direct numerical simulation (DNS). However, a turbulent heat transfer model under the MHD effects for the high-*Pr* fluid such as FLiBe has been an unexamined issue until now.

In this study, we discuss heat transfer modeling under the MHD effects by means of the DNS database [10,11]. In this DNS database, equivalent conditions [12,13], such as Reynolds number, Hartmann number, and molecular Prandtl number are selected. To begin heat transfer modeling under magnetic fields, we show the applicability of the zero-equation turbulent heat transfer model [14,15] based on a constant turbulent Prandtl number, and estimate the quasi-theoretical values of turbulent Prandtl numbers under the effects of MHD with the aid of DNS database. As an a posteriori test of heat transfer modeling, we conduct the MHD heat transfer under the same conditions as selected from the DNS database using the zero-equation model coupled with the low-Reynolds number k–ε model [16] including MHD effects.

2. DNS database

The data used in this study were taken from a fully developed turbulent channel flow imposed on a wall-normal constant

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Table 1
DNS database.

Case	Re_τ	Ha	Pr	Grid number N_x, N_y, N_z	Resolution Δx^+, Δy^+, Δz^+
1 [11]	400	0, 20, 28	25	2048, 870, 1024	2.5, 0.05–1.0, 2.5
2 [10]	400	0, 20, 28	5.25	288, 432, 288	17.8, 0.5–2.0, 8.9
3 [10]	400	0, 20, 28	0.025	288, 432, 288	17.8, 0.5–2.0, 8.9

$Re_\tau = u_\tau h/\nu$: friction Reynolds number. u_τ: friction velocity, h: channel half depth(=d/2), ν: kinematic viscosity; $Ha = B_0 d(\sigma/\rho\nu)^{1/2}$: B_0: wall-normal magnetic flux density, σ: electric conductivity; $Pr = \nu/\alpha$: Prandtl number; α: thermal diffusivity; N_x (Δx), N_y (Δy), N_z (Δz,): grid number (resolution) for stream (x), vertical (y), and spanwise (z) directions, respectively.

magnetic field [10,11]. In the DNS database, constant temperatures at the top and bottom boundaries ($\theta_{top} > \theta_{bed}$; θ_{top}: top wall temperature and θ_{bed}: bottom wall temperature) were imposed under the assumption of a passive scalar field. The numerical conditions of the DNS database are shown in Table 1, where the superscript + denotes the nondimensional quantities normalized by friction velocity (u_τ) and kinematic viscosity (ν). In the computations, the thermal properties of FLiBe were used [11], the friction Reynolds number ($Re_\tau = u_\tau h/\nu$) was kept constant at 400, the molecular Prandtl number ($Pr = \nu/\alpha$, α: thermal diffusivity) was set to 25 (FLiBe), and the Hartman number ($Ha = B_0 2h(\sigma/\rho\nu)^{1/2}$, B_0: wall-normal magnetic field, σ: electrical conductivity, and ρ: density) was changed from 0 to 28. In the DNS database, the bulk Reynolds numbers ($Re_b = U_b 2h/\nu$, U_b: bulk velocity) were approximately 14,000. These numerical conditions correspond to the equivalent design parameters for molten salt blankets in the side channel: Ha = 20, Re_b = 12,000 [12,13]. On the other hands, Smolentsev et al. [17] reviewed MHD thermofluid conditions in liquid–metal blankets, and design parameters for the Molten salt self-cooled is summarized as Re_b = 40,000 and Ha = 40. Compared with this condition, present DNS database is almost one-half of it, but flow regime is the same as three-dimensional turbulent flows.

To investigate the effects of the molecular Prandtl number, the DNS database [10] for KOH solution (Pr = 5.25) and lithium (Pr = 0.025) under the same Re_τ and Ha conditions [11] were also used. The KOH solution was used as the FLiBe simulant fluid, as described by Takeuchi et al. [13]. The heat transfer data [18] were obtained for the KOH solution.

3. Zero-equation turbulent heat transfer model

Using the turbulent eddy viscosity, the governing equations for mean velocity and temperature in a fully developed turbulent channel flow imposed on a wall-normal constant magnetic field [10,11], are described as follows:

$$0 = \frac{u_\tau^2}{h} + \frac{d}{dy}\left[(\nu + \nu_T)\frac{dU}{dy}\right] + \frac{\sigma B_0^2}{\rho}(U_b - U), \tag{1}$$

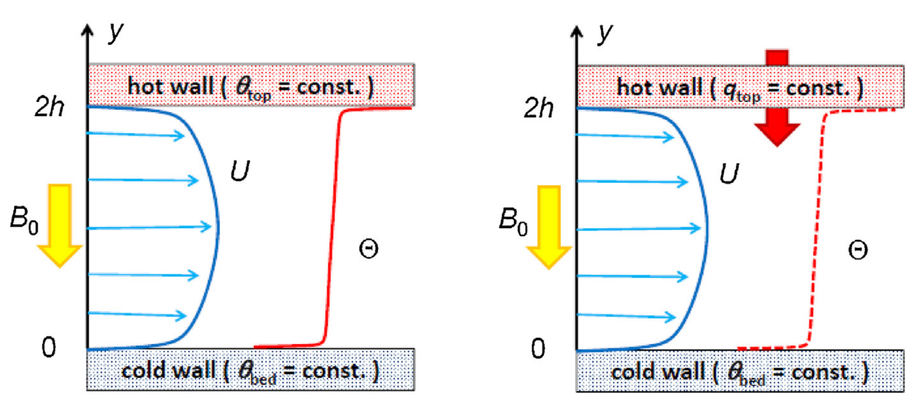
$$0 = \frac{d}{dy}\left[(\alpha + \alpha_T)\frac{d\Theta}{dy}\right]. \tag{2}$$

Here, the first term of the right-hand side of Eq. (1) denotes the streamwise mean pressure gradient, y is the wall-normal direction, ν_T is the turbulent eddy viscosity, and U is the streamwise mean velocity, the third term of the right-hand side of Eq. (1) denotes the Lorenz force, α_T is the temperature-turbulent eddy viscosity, and Θ is the mean temperature. Flow geometry and heating conditions are illustrated in Fig. 1(1).

To predict the mean velocity and temperature profiles from Eqs. (1) and (2), we must know the turbulent eddy viscosities of ν_T and α_T. The former is given by a low-Reynolds number k–ε turbulence model, such as those of Myong & Kasagi [19] or Nagano & Shimada [16]. The latter is obtained from the former with the assumption of a turbulent Prandtl number (Pr_T), i.e., through a zero-equation turbulent heat transfer model as follows:

$$\alpha_T = \frac{\nu_T}{Pr_T}. \tag{3}$$

The above simple approach has been extensively used for numerical predictions of heat transfer. In fact, Smolentsev et al. [3] investigated heat transfer degradation in closed channel flows using a turbulent Prandtl number, focusing on self-cooled molten salts such as FLiBe. However, the applicability of the zero-equation turbulent heat transfer model under the magnetic fields is still uncertain. From this viewpoint, we give first priority to investigating the applicability of the zero-equation turbulent heat transfer model under magnetic fields with the aid of the DNS database.



(1) Constant temperature ($\theta_{top} > \theta_{bed}$) (2) Constant heat flux (q_{top}) and temperature (θ_{bed})

Fig. 1. Flow geometry and heating condition.

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