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The influence of a magnetic field on turbulent heat transfer of a high Prandtl number fluid

H. Nakaharai [a,*], J. Takeuchi [b], T. Yokomine [c], T. Kunugi [d], S. Satake [e], N.B. Morley [b], M.A. Abdou [b]

[a] Department of Advanced Energy Engineering Science, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga-kouen 6-1, Kasuga, Fukuoka 816-8580, Japan
[b] Mechanical and Aerospace Engineering Department, University of California, Los Angeles, CA 90095-1597, USA
[c] Faculty of Energy Engineering Science, Kyushu University, Kasuga-kouen 6-1, Kasuga, Fukuoka 816-8580, Japan
[d] Department of Nuclear Engineering, Kyoto University, Yoshida, Sakyo, Kyoto 606-8501, Japan
[e] Department of Applied Electronics, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan

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Abstract

The influence of a transverse magnetic field on the local and average heat transfer of an electrically conducting, turbulent fluid flow with high Prandtl number was studied experimentally. The mechanism of heat transfer modification due to magnetic field is considered with aid of available numerical simulation data for turbulent flow field. The influence of the transverse magnetic field on the heat transfer was to suppress the temperature fluctuation and to steepen the mean temperature gradient in near-wall region in the direction parallel to the magnetic field. The mean temperature gradient is not influenced compared to the temperature fluctuation in the direction vertical to the magnetic field.

Keywords: Magneto-hydrodynamics (MHD); Turbulent flow; Heat transfer

1. Introduction

In the long history of the study of an electrically conducting fluid flow, a great deal of effort has been made on magnetohydrodynamics (MHD) effects in liquid metals, commonly used in many engineering applications. Gardner [1] examined the influence of a transverse magnetic field on the structure of a turbulent flow of mercury and observed that the turbulence intensity decreased to a laminar level over a broad range of Reynolds numbers and magnetic fields. A similar result has been reported by Brouillette [2] and Reed [3]. As for the numerical simulation, the effects of the magnetic field on near-wall turbulence structures were investigated by Satake [4] and Lee [5]. They reported an increase in the skin friction when the strength of the wall-normal magnetic field exceeded a certain value. This increase was attributed to the drag increase due to the Hartmann effect, which was greater than the drag reduction due to turbulence suppression, that is laminarization. Gardner [6] also reported that the influence of a transverse magnetic field on the heat transfer was to inhibit the convective mechanism of heat transfer, resulting in up to 70% reductions in Nusselt number. In another paper [7], Gardner summarized his results of turbulent heat transfer calculations using a curve fit equation representing the average Nusselt number as a function of both Peclet number and Hartmann number. Recently, several studies have been made for a fusion blanket cooled by molten salt [8]. Unlike MHD effects on the flow field, as for the heat transfer the problem becomes more complicated, because the molten salt is a characteristic of a high Prandtl number

* Corresponding author. Tel.: +81 92 583 7603; fax: +81 92 583 7601.
E-mail address: nakah@aees.kyushu-u.ac.jp (H. Nakaharai).

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Nomenclature

B_0	magnetic field (T)	α	thermal diffusivity (m^2/s)
D	pipe diameter (m)	λ	heat conductivity (W/mK)
L	total heating length (m)	v	kinematic viscosity (m^2/s)
q_w	heat flux applied to the pipe surface (W/m^2)	ρ	density (kg/m^3)
R	pipe radius (m)	σ	electric conductivity (S/m)
T_b	bulk temperature (K)	Ha	Hartmann number ($=B_0R(\sigma/\rho v)^{1/2}$)
T_{in}	inlet temperature (K)	Nu	Nusselt number ($=Dq_w/\lambda(T_w-T_b)$)
T_{out}	outlet temperature (K)	Nu_0	Nusselt number without magnetic field
T_c	pipe center temperature (K)	Pr	Prandtl number ($=v/\alpha$)
T_w	wall temperature (K)	Re	Reynolds number ($=U_bD/v$)
U_b	bulk velocity (m/s)		
z	distance from the starting point of applying the magnetic field (m)		

fluid. In general, for a high Prandtl number fluid, heat transport from a heated wall into the core of the fluid flow is dominated by turbulent motion rather than thermal diffusion. Moreover, near-wall flow structures are especially important, because the thermal boundary layer is much thinner than the momentum boundary layer. In the case of where turbulence suppression due to strong magnetic field occurs, it is expected that the heat transfer performance degradation of high Prandtl number fluid is more sensitive than that of low Prandtl number fluid. Thus, investigation of the fluid mechanics, and the heat transfer of a high Prandtl number fluid is very important from the design point of view compared to low Prandtl number fluid, especially for the high heat flux cooling system such as fusion reactor. In comparison with the studies on heat transfer mechanism of liquid metal, very few attempts have been made on heat transfer mechanism of a high Prandtl number fluid for the design of MHD devices. Blum [9] conducted heat transfer experiment using an electrolyte flowing through a rectangular channel over a wide range of Reynolds number including the transition region from laminar to turbulent and presented an empirical function for the reduction of heat transfer in a turbulent MHD flow by means of an interaction parameter. It is the objective of the present study, to acquire the data for local and average heat transfer and temperature fluctuation of an electrically conducting turbulent fluid round pipe flow with high Prandtl number under the magnetic field, and to understand the interaction between the magnetic field, the fluid turbulence and the heat transfer.

2. Experiment

A Potassium hydroxide (KOH) 30 wt% water solution is used in this experiment, the KOH water solution properties are mentioned in Table 1. A schematic diagram of the experimental closed loop, named "Fli-Hy (FLiBe-simulant Hydrodynamics) loop" established at UCLA [10] is shown in Fig. 1a. The KOH water solution flow is introduced into the horizontal pipe test section by mechanical pump. The KOH temperature is monitored at both the inlet and the

Table 1
The properties of 30 wt% KOH water solution

		$T = 15$ (°C)	$T = 35$ (°C)
Thermal conductivity	λ (W/(mK))	0.693	0.729
Density	ρ (kg/m^3)	1291	1279
Kinematic viscosity	v (m^2/s)	1.778×10^{-6}	1.189×10^{-6}
Specific heat capacity	C_p (J/(kg K))	2957	2999
Electrical conductivity	σ (1/Ω*m)	51.6	75.2
Prandtl number	Pr	9.8	6.2

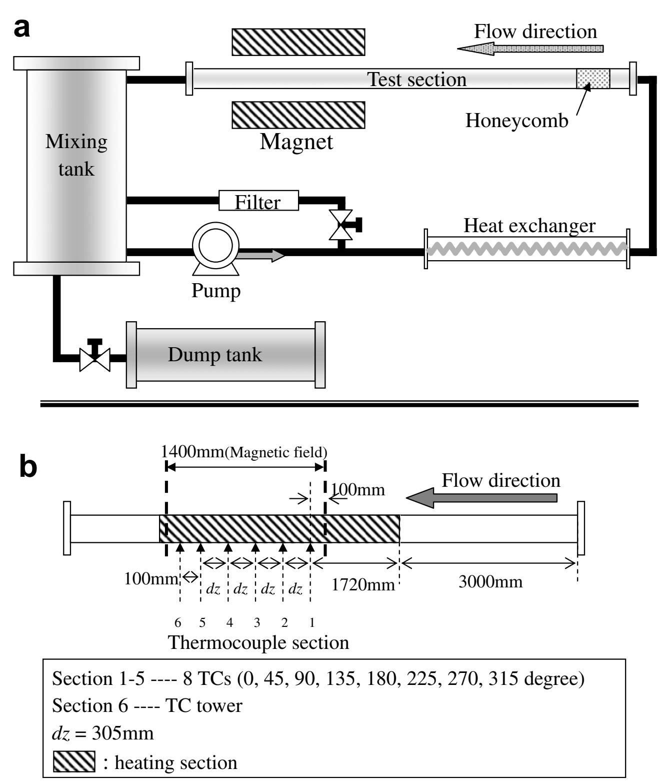

Fig. 1. Systems of Fli-Hy closed loops: (a) overall view and (b) Detail of test section.

outlet of the test section using thermocouples. The bulk mixing temperature of an arbitrary cross section T_b is estimated by the linear interpolation from the inlet temperature T_{in} and the outlet temperature T_{out} using Eq. (1) where, x is the downstream position of the measurement and L is the total heating length.

$$T_b = T_{in} + (T_{out} - T_{in})\frac{x}{L} \tag{1}$$

The details of the test section are shown in Fig. 1b. The test section of this loop is made of 8 m long SUS pipe, an inner diameter of 89 mm. A part of this test section is heated uniformly by heating tape. A constant magnetic field is applied for 1.4 m along the pipe up to 2 T. A number (40) T-type thermocouples having a diameter of 0.5 mm are fixed using high thermal conductivity grease (15 W/mK) at five axial stations and eight angles from the horizontal magnetic field. The depths of the holes and the tube wall thickness are 4 mm and 5 mm, respectively, i.e. the length from the inner tube surface to measuring point is 1 mm. The location of thermocouples for wall temperature measurement is shown in Fig. 1b. The effect of the magnetic field on the thermocouples is shown in Fig. 2, where, a significant noise signal appeared at the moment of application and removal of the magnetic field. This noise is not caused by the induction current in the SUS pipe, but due to the effect of changing the magnitude of the magnetic field on the thermoelectric power directly, because the sheathed T-type thermocouples used in this test section is insulated. However, the measured temperature was stable when the magnetic field was constant. The average difference in temperature measured with and without the magnetic field was about 0.01 K on all the thermocouples.

The radial temperature distribution of the fluid flow in the pipe is measured by means of thermocouples tower (TC tower) consisting of inconel sheathed K-type thermocouples having a diameter of 0.13 mm arranged from the inner wall surface to the centre of the pipe as shown in Fig. 3. The 63% response time of this thermocouple is 2 ms. The case when the angle between the TC tower and the magnetic field is 0° and 90° are named case A and case B, respectively.

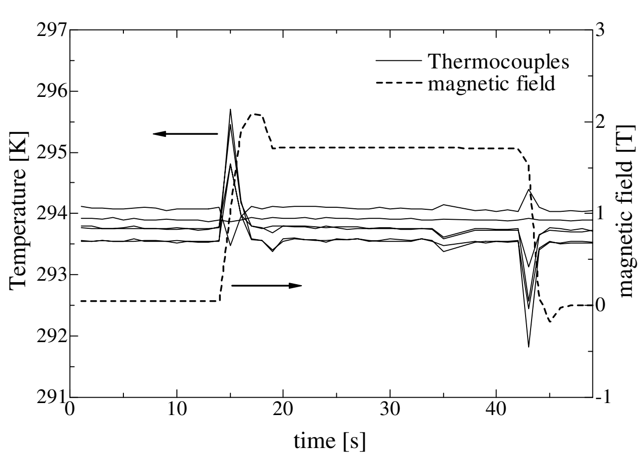

Fig. 2. Magnetic field effect on thermocouples.

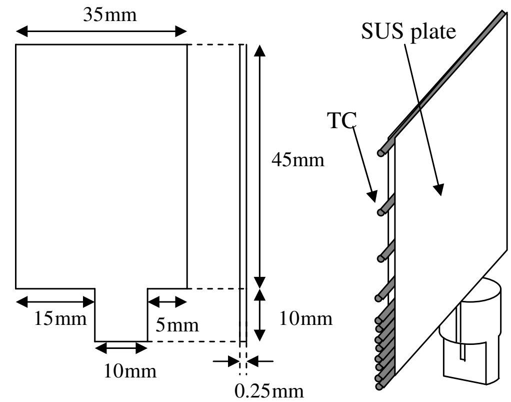

Fig. 3. Schematic view of TC tower.

Table 2
Detail of experimental condition

Pr (Temperature of KOH (°C))	*Re*	*Ha* (magnitude of magnetic field (T))
6.2 (35)	5000, 20000	0 (0), 5 (0.51), 10 (1.05), 15 (1.60)
9.8 (15)	5000, 20000	0 (0), 5 (0.75), 10 (1.6)

The Reynolds number based on bulk velocity and pipe diameter is set to 5000 and 20000 for four Hartmann numbers, $Ha = 0$, 5, 10, 15, and $Pr = 6.2$, 9.8. The bulk velocity is calculated by the flow rate and the cross section of pipe. The flow rate is measured and monitored using vortex flow sensor which measures the flow rate from the frequency of Karman vortex. Details of the experimental conditions are summarized in Table 2 below. It is to be noted that the maximum Hartman number is 15 in the case that Prandtl number is 6.2. However, in the case of Prandtl number is 9.8, maximum Hartman number is 10, because of low electrical conductivity of KOH solution at low temperature.

3. Results

Fig. 4a shows the difference in Nusselt number between $Ha = 0$ and $Ha = 5$, 10, 15 at $Re = 5000$, $Pr = 6.2$. The vertical axis, Nu–Nu_0, is defined by the difference in Nusselt number with and without magnetic field. In the horizontal axis-z and D are the distance from the starting point of applying the magnetic field and the pipe diameter, respectively. Nu is defined as the following,

$$Nu = \frac{q_w D}{(T_w - T_b)\lambda} \tag{2}$$

where q_w is the heat flux applied to the surface, which is calculated by heater power $q_w = 500\ \mathrm{W/m^2}$ at $Re = 5000$, $q_w = 3500\ \mathrm{W/m^2}$ at $Re = 20000$, where T_w and T_b are the wall temperature measured by T.C. directly and the bulk

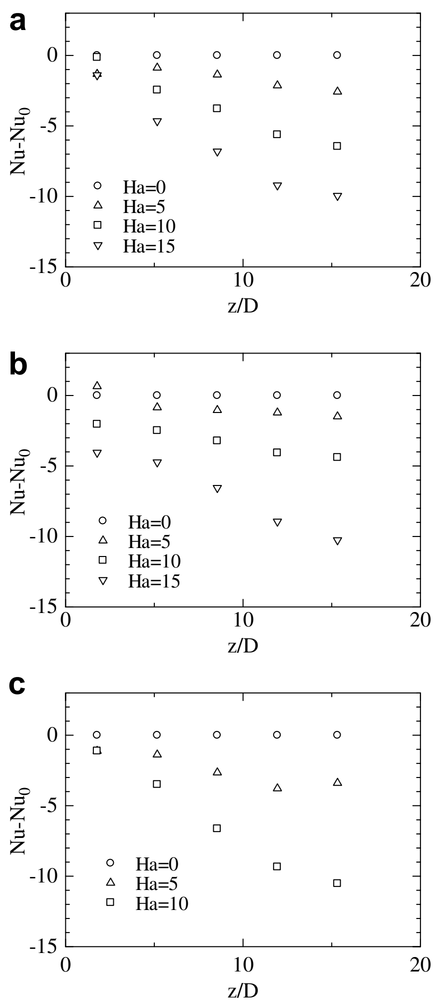

Fig. 4. Local heat transfer from magnetic field: (a) $Re = 5000$, $Pr = 6.2$, (b) $Re = 20000$, $Pr = 6.2$ and (c) $Re = 5000$, $Pr = 9.8$.

mixing temperature from Eq. (1), respectively. The Nusselt number decreased when the magnetic field was applied. It is reasonable to suppose that the turbulence suppression under the magnetic field causes the decrease in Nusselt number. Gardner [6] showed a qualitatively similar tendency in his experimental result using mercury as a working fluid in spite of its extremely low Prandtl number and high electric conductivity compared with KOH. In addition, the amount of change in Nusselt number increases toward the magnetic field end. This indicates that the turbulent is more suppressed toward downstream.

Fig. 4b shows the difference in Nusselt number between $Ha = 0$ and $Ha = 5$, 10, 15 at $Re = 20000$, $Pr = 6.2$. The tendency of this figure is the same as the case of $Re = 5000$. However, the magnetic field effect on heat transfer is smaller than that at $Re = 5000$, because of the decrease in the interaction parameter (Ha^2/Re). More definitely, a ratio of $Nu–Nu_0$ to Nu_0 at $Re = 5000$ is 0.25, while it is 0.15 at $Re = 20000$.

The change in Nusselt number at $Re = 5000$, $Pr = 9.8$ is shown in Fig. 4c. The decrease in Nusselt number is large compared with the case of $Pr = 6$ at the same Hartmann number. The heat transfer of a high Prandtl number fluid is dominated by turbulent diffusion rather than molecular diffusion. Assuming that the temperature is a passive scalar, turbulent diffusion itself is independent of Prandtl number. Therefore, it is reasonable that higher Prandtl number fluid is susceptible to turbulence suppression due to the magnetic field.

Fig. 5 shows the local Nusselt number at the top, side, and bottom of the pipe at the thermocouple Section 5 in Fig. 1b. Incidentally, the sidewall of the pipe is perpendicular to the direction of the magnetic field. In the case of $Re = 5000$, the Nusselt number at the bottom is the highest. Since this tendency of Nusselt number is similar to that under the mixed convection pipe flow, the effect of natural convection cannot be negligible at $Re = 5000$. On the other hand, local Nusselt number does not depend on the angle at $Re = 20000$. Therefore, the effect of natural convection can be negligible.

Fig. 6 shows the mean temperature distribution in the pipe measured by the TC tower at $Re = 5000$, $Pr = 6$. The TC tower is set horizontally i.e. case A. The temperature is normalized with the temperature difference between the wall T_w and the centre of the pipe T_c, where T_c is the measurement value of the T.C. tower top thermocouple. When a transverse magnetic field is applied, the temperature difference between the wall and the fluid is reduced. This means that the temperature of near-wall fluid is raised and a steeper temperature gradient is formed in the near-wall region. In this region, heat transfer mechanism is likely

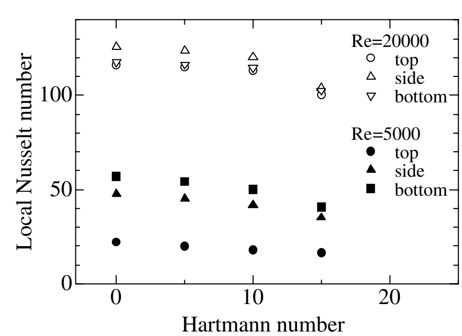

Fig. 5. Local Nusselt number $Pr = 6.2$.

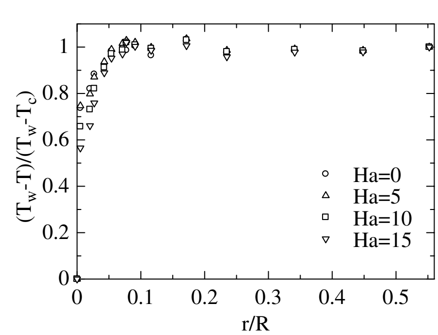

Fig. 6. Inner temperature profile $Re = 5000$, $Pr = 6.2$, case A.

dominated by mean temperature gradient and turbulent heat flux. It is clear that the turbulent intensity is suppressed in this region [4,5]. Therefore, it becomes necessary that the mean temperature gradient grow steeper to transport the constant heat flux from the wall. This tendency is similar to the Gardner's results [6] except for thermal boundary layer thickness. Since he used an extremely low Prandtl number fluid, mercury, as a working fluid, the thermal boundary layer was thicker.

Fig. 7a shows the temperature fluctuation normalized with temperature difference between the wall and the centre of the pipe at $Re = 5000$, $Pr = 6.2$. The TC tower setting was corresponding to case A. It is observed that the temperature fluctuation near the wall is damped when the magnetic field was applied. In order to explain this more exactly, we need to deeply investigate the behaviour of turbulent heat flux under the magnetic field, since the production term of temperature fluctuation consists of a turbulent heat flux in its transport equation. However, there has been no study that tried to measure the temperature and velocity simultaneously under the magnetic field with a high accuracy. Therefore, we consider the mechanism of such suppression of temperature fluctuation with the aid of some DNS [4,5] results for the velocity field. In this past work, the suppression of turbulence fluctuation of velocity due to the magnetic field is seen throughout the pipe. This suppression strengthens our conjecture for the chain of events: first, the magnetic field suppresses the turbulent velocity fluctuation, then the turbulent heat flux is decreased. Because the production term in the transport equation of turbulent heat flux includes the Reynolds

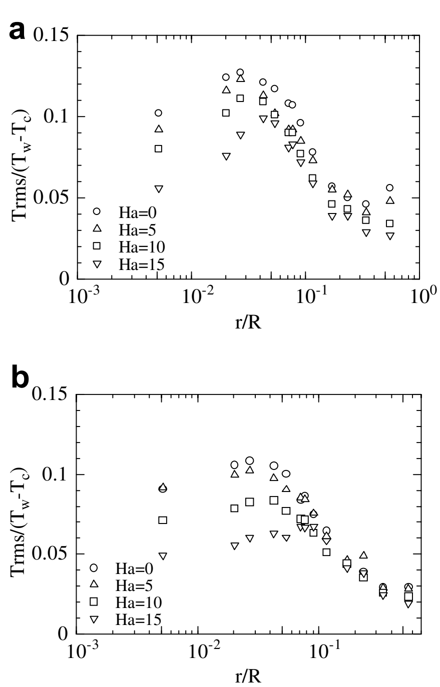

Fig. 7. Temperature fluctuation profile: (a) $Re = 5000$, $Pr = 6.2$, case A and (b) $Re = 5000$, $r = 6.2$, case B.

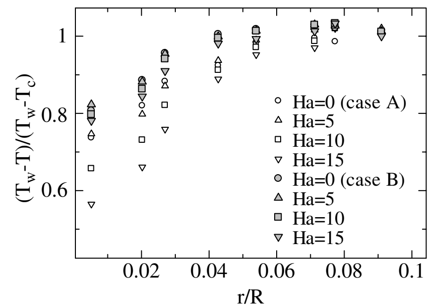

Fig. 8. The magnetic field effect on temperature distribution in the pipe ($Re = 5000$, $Pr = 6.2$).

stress, finally the production of the temperature fluctuation is decreased. Fig. 7b shows the temperature fluctuation profile of case B. When the magnetic filed was applied, damping of temperature fluctuation is observed in the near-wall region as in case A. It is reasonable to suppose that the reason of this damping can be explained by the same chain of events proposed in the discussion of case A. In order to more fully characterize the expected error, we measured the root mean square (rms) value of the temperature of an isothermal stationary fluid to estimate the fluctuation error caused by data logger noise, compensating lead wire and so on. As a result, the rms is 2.3% of the minimum rms value in the Fig. 7a.

Fig. 8 shows the temperature profile in the pipe. In case B, the magnitude of the temperature gradient change is smaller than that of case A. As mentioned above, the heat transfer mechanism is likely dominated by the mean temperature gradient and the turbulent heat flux in the near-wall region. According to Satake [4], the amount of turbulent suppression in case B is not so large compared with case A. Considering these circumstances, it is reasonable that the amount of change of mean temperature gradient is also smaller than that of case A.

4. Summary

The local and average heat transfer and temperature fluctuation of a high Prandtl number turbulent pipe flow through a uniformly heated tube are measured in this study. As a result, Nusselt number for turbulent pipe flow decreased 22% at $Ha = 15$, $Re = 5000$, $Pr = 6.2$, 24% at $Ha = 10$, $Re = 5000$, $Pr = 9.8$ and 8% at $Ha = 15$, $Re = 20000$, $Pr = 6.2$.

It is clear that the temperature fluctuation is damping under the magnetic field at $Re = 5000$. More improvement in the TC tower is needed to measure with a higher degree of accuracy. In this study, however, the errors due to the flow meter, gauss meter, and fluid properties are included in both Reynolds number and Hartman number. Therefore, it is difficult to estimate the error precisely, because the experimental data on a like-for-like basis (same Re, same Ha, and same bulk temperature) is not sufficient. This might be an important future issue.

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