EXPERIMENTAL INVESTIGATION OF TURBULENT HEAT TRANSFER OF HIGH PRANDTL NUMBER FLUID FLOW UNDER STRONG MAGNETIC FIELD

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An investigation of MHD effects on Flibe simulant fluid (aqueous potassium hydroxide solution) flows has been conducted under the U.S.-Japan JUPITER-II collaboration program using "FLIHY" pipe flow facility at UCLA. Mean and fluctuating temperature profiles in a conducting wall pipe were measured for low Reynolds number turbulent flows using a thermocouples probe at constant heat flux condition. It is suggested that the temperature profiles are characterized by interaction between turbulence production, turbulence suppression due to magnetic field and thermal stratification occurred even under the situation where quite small temperature difference exists in the pipe cross-section.

I. INTRODUCTION

Flibe is one of the possible candidates for coolant/breeding materials for fusion applications. It has very low activation, low tritium solubility, low chemical reactivity, and low electrical conductivity, which relieve the problems associated with MHD pressure drop. In recent research, several design concepts utilizing Flibe have been proposed. Some of the examples are HYLIFE-II,[1] the APEX thick/thin liquid walls[2] and FFHR.[3] Furthermore, Flibe has a crucial difference from liquid metals with respect to the heat transfer characteristic: Flibe is a high Prandtl number fluid. For high Prandtl number fluid, in general, heat transport from a heated wall into the core of the fluid flow is dominated by turbulent motion rather than thermal diffusion. Near-wall flow structures are especially important because thermal boundary layer is much thinner than the momentum boundary layer. In the fusion blanket application of Flibe, there is a severe limitation of temperature window due to its high melting point. The turbulent heat transfer is, therefore, decisive in designing Flibe-based blanket. On the other hand, it is well known that the strong magnetic fields suppress the turbulence even for the flows of low conducting fluids. In the case of occurrence of turbulence suppression, it is concerned that the degradation of the heat transfer performance for high Prandtl number fluid becomes more severe than that for low Prandtl number fluid.

MHD turbulent flows have been extensively studied using liquid metals as working fluids. As far as the MHD effects on the heat transfer characteristics are concerned, Gardner[4] reported that the influence of the transverse magnetic field on the heat transfer was to inhibit the convective mechanism of heat transfer, resulting in reduction of Nusselt number up to 70%. In another paper,[5] Gardner summarized his results of turbulent heat transfer calculations using a curve fit equation representing the average Nusselt number as function of Peclet number and Hartmann number (Ha). However, the MHD turbulent heat transfer characteristics for high Prandtl number fluids are not well understood. Blum[6] conducted heat transfer experiment using an electrolyte flowing through a rectangular channel over a wide range of Reynolds number (Re) including the transition region from laminar to turbulent and presented an empirical correlation for degradation of heat transfer in a turbulent MHD flow as a function of interaction parameter ($N = Ha^2/Re$). Since his correlation was constructed from two different experimental data with completely different experimental conditions and parameter range, more reliable data will be required.

From FY2001, JUPITER-II (Japan-US Program for Irradiation Test of Fusion Materials) collaboration is in progress. As one on the important task of this collaborative program, a series of experiments on fluid mechanics and heat transfer of Flibe-simulants have been performed by means of an experimental MHD flow facility called "FLIHY" (FLIbe HYdrodynamics) at UCLA. Turbulent flow field measurements using PIV[7] and heat transfer measurements[8] have so far been carried out without magnetic field to establish the experimental techniques and verify the performance of the facility by comparing an existing experimental results[9] and DNS data.[10] The objective of the present investigation is to improve understandings of MHD effects on turbulent heat transfer on high Prandtl number fluid by acquiring experimental data for local and average heat transfer and mean and fluctuation fluid temperature distributions for turbulent flow of electrically conducting fluid in a electrically conducting wall pipe under magnetic fields using high Prandtl number fluid as a Flibe simulant.

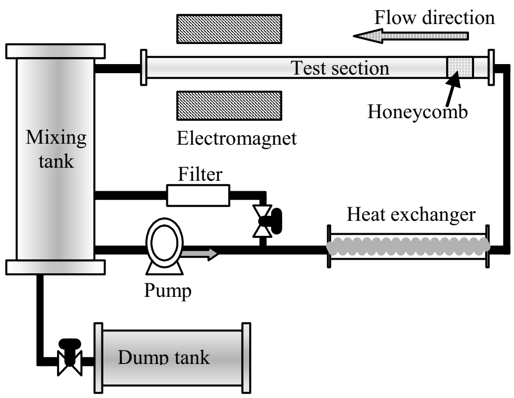


Fig.1. Schematic drawing of the pipe flow facility

II. EXPERIMENTAL SETUP

Figure 1 shows a schematic drawing of the experimental pipe flow loop "FLIHY" in UCLA. The 30%wt aqueous potassium hydroxide (KOH) solution is used as a Flibe-simulant fluid having the same interaction factor as high temperature Flibe. The fluid flow is introduced into a horizontal pipe test section by a centrifugal pump. The inlet and outlet temperature is monitored by thermocouples. The bulk mixing temperature of arbitrary cross section T_b is estimated by linear interpolation from the inlet temperature T_{in} and the outlet temperature T_{out} using equation (1), where x is the length of the heated section at the measurement position and L is the total length of the heated section.

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

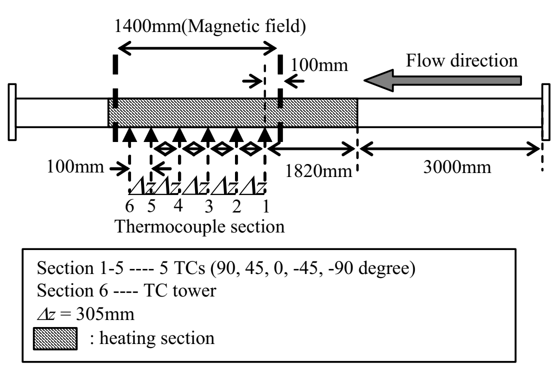


Fig.2. Details of Test Section

The magnet used for the present experiments produces maximum 2.0 Tesla magnetic fields in a narrow gap of the iron core at 3000 A of applied electric current. The test section was placed in the gap which is 1400 mm length in the streamwise direction, 250 mm in height, and 150 mm in width. The generated B field has uniform horizontal distribution within 5% variation for 1000 mm in the streamwise direction.

Figure 2 gives details of the test section. The test section is an 8000 mm long stainless steel pipe with 50 mm inner diameter. A part of the pipe is heated uniformly by heating tapes. The magnetic field is applied for 1400 mm along the pipe. Twenty-five T-type sheathed thermocouples with 0.5 mm diameter are installed in drilled holes with 1 mm diameter on the outer surface of the pipe and affixed with high thermal conductivity (15W/mK) and high electrical resistivity adhesive at five axial positions and five angles from the horizontal magnetic field. The distance from the pipe inner surface to the thermocouple junctions is 1mm.

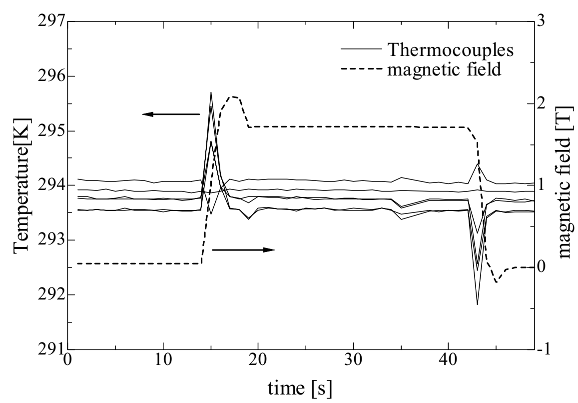


Fig.3. Magnetic field effect on thermocouples

The effect of the magnetic field on the output signals of the wall thermocouples is shown in Fig.3. Large spikes in the thermocouple output signals were observed when the magnitude of the magnetic field was changed; however, the output signals were stable when the magnetic field was kept constant. Since the thermocouples are sheathed and insulated from the test pipe, the effect of induction current in the stainless steel pipe should be negligible, and the spikes are caused by EMF induced in the thermocouple wires. The temperature difference between with and without magnetic field is less than 0.01K for all the thermocouples. Therefore, the effect of the magnetic field on the thermocouple measurements is negligible for steady state.

The radial temperature distributions of the fluid flow in the pipe are measured by means of thermocouples (TC) probe, which consists of six Inconel-sheathed K-type thermocouples with 0.13 mm diameter. The schematic view of TC probe is shown in Fig.4. The TC probe can be moved by a micrometer with the spatial resolution of 0.02mm. Measurable minimum distance from the inner pipe wall is 0.05mm. The 63% response time of these thermocouples is 2ms. It is confirmed that the effect of TC probe on the upstream temperature field and the effect of vibration of TC probe on the temperature measurement are both negligible. Although the angle of the TC probe to the B field can be changed freely, the angle is fixed in the horizontal plane which is parallel to the B field in present study.

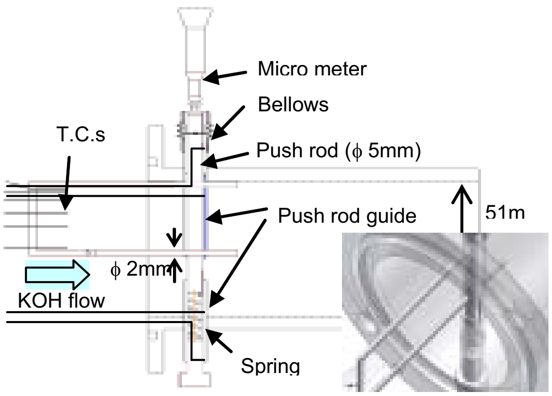


Fig.4. Schematic view of TC probe

The Reynolds number based on the bulk mean velocity and the pipe diameter is varied from 7400 to 20000 for three Hartmann numbers based on a pipe diameter, Ha=0, 10, 20. The bulk mean velocity is calculated from the flow rate. The flow rate is measured and monitored by vortex flow sensor which measures flow rate from frequency of Karman vortex. Table I shows the property of KOH solution in the present experimental conditions.

TABLE I. Properties of KOH solution

Temperature [℃]	40.0	42.5	44.0
Density[kg/m^3]	1275.6	1274.0	1272.8
Thermal conductivity[W/(m K)]	0.737	0.741	0.743
Viscosity[10^{-3}Pa*s]	1.280	1.231	1.193
Specific Heat Capacity [J/(kg K)]	3010	3014	3018
Electrical conductivity[1/ohm*m]	81.7	84.7	87.1
Prandtl number	5.23	5.01	4.85

III. EXPERIMENTAL RESULTS

Figure 5 shows the mean temperature distributions. St is Stuart number defined as Ha2/Re. The non-dimensional temperature T^+ is defined as below.

$$T^+ = \frac{T_w - T}{T^*}, \quad T^* = \frac{q_w}{\rho c_p u_\tau} \tag{2}$$

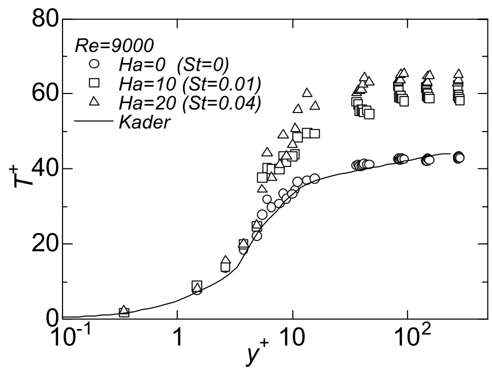
Here T^* is the friction temperature determined by the wall heat flux q_w, fluid density ρ, heat capacity c_p, and the friction velocity u_τ. The wall temperature T_w is measured by thermocouple installed in the pipe wall at the probe location. In each figure, the equation of temperature profiles in fully developed turbulent boundary layer proposed by Kader[11] shown in Eqs. (3) and (4) are plotted along with the experimental data.

$$\begin{aligned} T^+ &= \Pr y^+ \exp(-\Gamma) \\ &+ \left\{ 2.12 \ln\left[\left(1+y^+\right) \frac{1.5\left(2-y/R\right)}{1+2\left(1-y/R\right)^2} \right] + \beta(\Pr) \right\} \\ &\quad \times \exp(-1/\Gamma) \end{aligned} \tag{3}$$

$$\left.\begin{aligned} \beta(\Pr) &= \left(3.85\Pr^{1/3} - 1.3\right)^2 + 2.12\ln\Pr \\ \Gamma &= \frac{10^{-2}\left(\Pr y^+\right)^4}{1+5\Pr^3 y^+} \end{aligned}\right\} \tag{4}$$

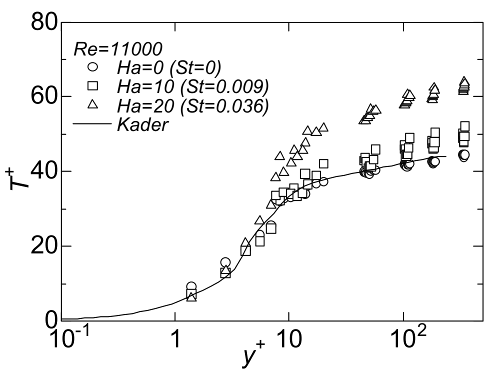
Here y is the coordinate normal to the wall, y^+ dimensionless coordinate defined by friction velocity, and R the pipe radius. In all cases, the temperature profiles without magnetic field give close agreement with Kader's equation. From the agreement, it is confirmed that the effect of natural convection is not significant. Indeed, the typical feature of natural convection appeared up to Re=5000. Common trend among these profiles is that the temperature difference between wall and fluid becomes larger in the near-wall region with increase of Ha. Heat transfer to the non-MHD turbulent flows is generally dominated by turbulent transport. For MHD flows, however, it is well known that the turbulence is significantly suppressed especially for the flows in conducting wall ducts. This results in prohibiting the turbulent transport mechanism. Therefore, the increase of the temperature difference can be explained by degradation of heat transfer due to the prohibition of turbulent transport mechanism. It is noted that for Ha = 10, the increase of the temperature difference is obvious only for Re = 9000, and no noticeable change is observed for higher Reynolds number cases. Although Gardner et al.[4] reported that significant natural convection was observed in their experiments, no evidence for natural convection was obtained in this experiments. Meanwhile, large temperature difference between top and bottom (large temperature rise in the top) of the pipe suggests that the thermal stratification occurs in the flow. This is observed even when the temperature difference between wall and bulk fluid is as small as 0.5 K at Re = 11000.

As shown above, the MHD effects on turbulent heat transfer for low Reynolds number flows are characterized by competition between turbulence production, turbulence suppression and thermal stratification. Therefore, the MHD effects are more prominent for lower Reynolds number cases in which turbulence production is weaker.

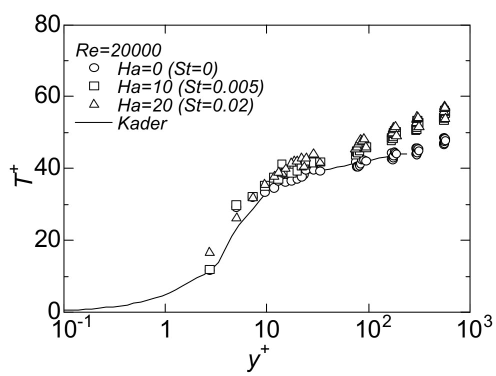


(a)

Re=9000



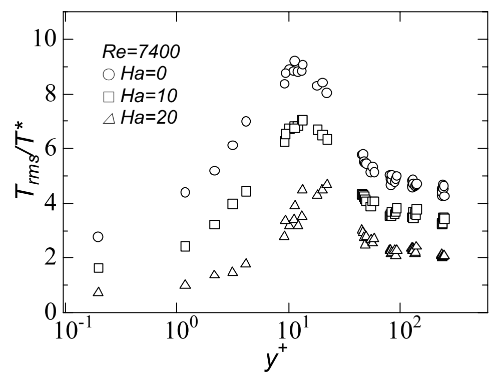
(b) Re=11000



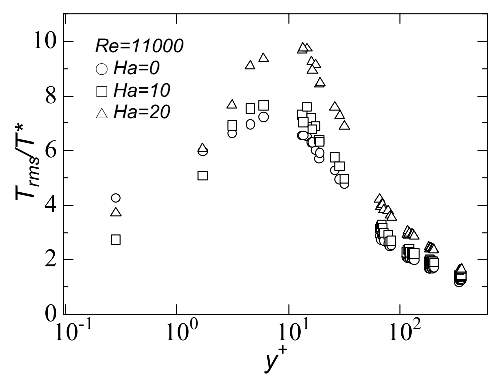
(c)

Re=20000

Fig.5. Temperature profile under magnetic field



(a) Re=7400



(b) Re=11000

Fig.6. Change of temperature fluctuation profile under magnetic field

The temperature fluctuation profiles are shown in Fig.6. The r.m.s. (root-mean-square) value of the fluid temperature is normalized by the friction temperature T^*. In the case of Re=7400, the temperature fluctuation is declined with increase of Ha in the entire region, which is rather straightforward consequence of the turbulence suppression. On the other hand, the contradictory result can be seen for Re=11000. The same tendency appears in higher Reynolds number cases. As mentioned above, the mean temperature field is governed by synergetic interaction between turbulence production, turbulence suppression and thermal stratification; therefore, it is conjectured that the fluctuating temperature profiles also depend on the balance between these effects. There is no numerical result as well as experimental investigation about the effect of magnetic field on the temperature field where the thermal stratification is significant, so the additional experiments and DNS are underway to clarify the complicated interaction.

Figure 7 shows the decrease in Nusselt number as a function of interaction parameter. The longitudinal axis is the ratio of Nusselt number with magnetic field (Nu_M) to the one at the same flow condition without magnetic field (*Nu*). The correlation proposed by Blum[3] and Garder[1] is also plotted on the same figure even though the flow configuration and Prandtl number are quite different from present experiment. The MHD effect on the degradation of heat transfer is much larger than Blums' correlation, which is based on a non-conducting wall duct experiment. Furthermore, it seems that there are two trend lines on reaching value of the interaction parameter 0.01 for present data. As underlaying premise, the original experimental data used to reduce Blum's equation is quite scattered at the small interaction parameter range in his paper. So that, the reason of difference between present data and Blum's one is not cleared yet. In the region above the interaction parameter 0.01, it can be expected that the bulk temperature field is more susceptible to the thermal stratification effect from the above explanation. Therefore, it is suggested that the balance of laminarization and thermal stratification is changed around the value of interaction parameter.

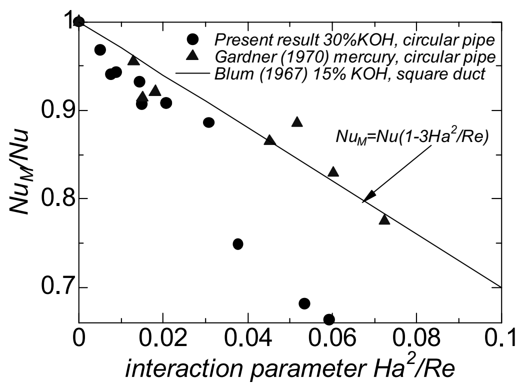


Fig.7. Degradation of heat transfer as a function of interaction parameter

IV. CONCLUDING REMARKS

The mean and fluctuating temperature profiles in the conducting wall pipe were measured for low Reynolds region with variable Hartmann numbers. It is suggested that the shift in the mean temperature profile is a result of interaction between turbulence suppression due to MHD effect and thermal stratification occurred with the temperature difference between wall and bulk fluid as small as 0.5 °C.

According to present investigation, it can be concluded that treatment of temperature field as a passive scalar in traditional numerical simulation becomes unreasonable assumption under magnetic field.

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