EXPERIMENTAL STUDY ON FORCED CONVECTIVE HEAT TRANSFER AND FLOW RESISTANCE OF MAGNETIC FLUID FLOW UNDER NON-UNIFORM MAGNETIC FIELD

MOTOZAWA*[1] M., TATSUNO[2] S., SAWADA[3] T., KAWAGUCHI[2] Y., FUKUTA[1] M.
[1]Shizuoka University, 3-5-1 Johoku Naka-ku Hamamatsu 432-8561, Japan,
[2]Tokyo University of Science, 2641 Yamazaki, Noda 278-8510, Japan,
[3]Keio University, 3-14-1 Hiyoshi Kohoku-ku Yokohama 223-8522, Japan
*E-mail address of corresponding author: tmmotoz@ipc.shizuoka.ac.jp

Abstract : Forced convective heat transfer and flow resistance of rectangular duct flow of a magnetic fluid by applying non-uniform magnetic field was investigated experimentally. One characteristic result shows that heat transfer is largely enhanced by applying non-uniform magnetic field in the laminar flow regime. Comparing with the result with applying uniform magnetic field, heat transfer enhancement is larger than that with applying uniform magnetic field. This seems that thermal convection excited by applying non-uniform magnetic field strongly affects the heat transfer.

1. Introduction

A magnetic fluid is a kind of typical magnetic functional fluid which has the function of changing physical properties by applying magnetic field. This fluid is a colloidal suspension which is composed of surfactant-coated ultrafine ferromagnetic particles and liquid carrier such as water. The diameter of inner magnetic particles of mangnetic fluid are about 10 nm and these particles are well dispersed due to the effect of surfactant. On the other hand, a nanofluid, which is the fluid conteains nano-order size pirticles in a liquid carrier, has been attracted attentions in the last two decades [1]. Because of its composition, magnetic fluid can be consieded a kind of nanofluid. Actually, magnetic nanofluid which has similar feature and composition to matnetic fluid was developed by nanofluid researchers [2]. In the recent, several studies of heat transfer characteristics of magnetic fluid have been performed by not only magnetic fluid researchers but also nanofluid researchers. Particularly, some of them including our previous study [3] reported enhancement of forced convective heat transfer by the effect of magnetic field in laminar flow regime [4, 5]. However, it still remains unclear why and how much heat transfer is enhanced by applying magnetic field.

In our previous studies [6], we investigated the forced convective heat transfer of magnetic fluid flow in a rectangular duct by applying uniform magnetic field. Furthermore, in order to discuss this heat transfer characteristics, we measured the velocity distribution by ultrasonic velocity profiling (UVP) method. However, since magnetic field gradient does not exist in the case of uniform magnetic field, it is also important to investigate heat transfer characteristics by applying non-uniform magnetic field and compare with the results with applying uniform magnetic field for discussion of the effect of magnetic field gradient. Based on this background, we investigated the forced convective heat transfer of magnetic fluid flow in same rectangular duct by applying non-uniform magnetic field, and also measured velocity distribution by UVP and flow resistance in this study.

2. Experiment

The schematic diagram of the experimental apparatus used in this study is shown in Fig. 1. The upper figure shows the flow system. The flow system consists of storage tank, pump and rectangular duct which is the test section. Two thermocouples are set at inlet and outlet of the test section. The lower figure in Fig.1 shows the structure of the rectangular duct. The heater

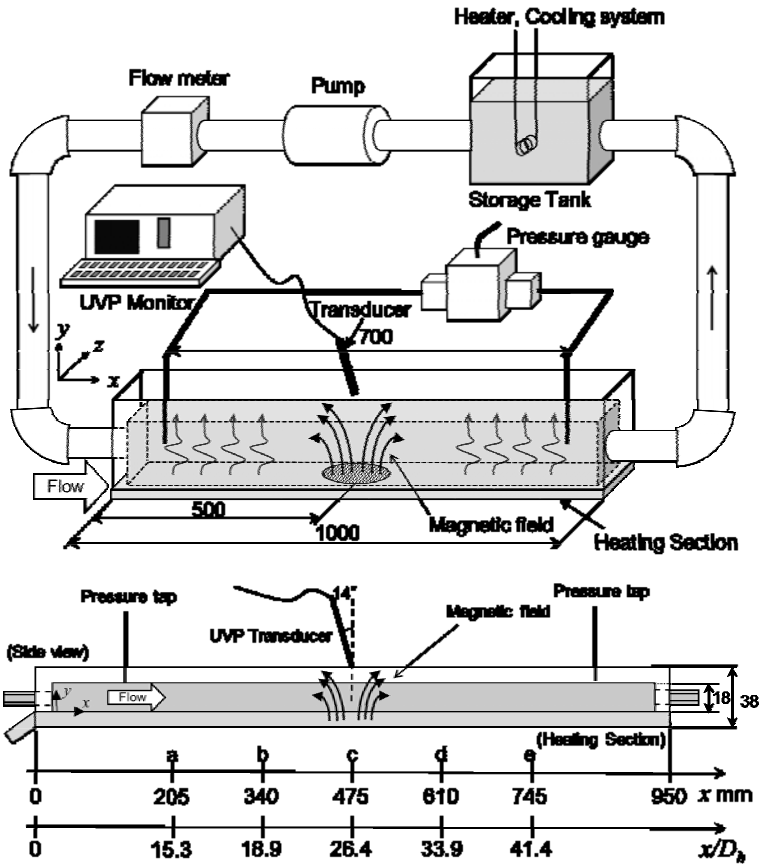
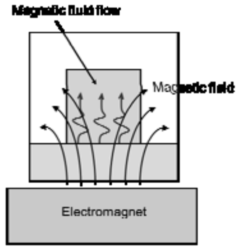
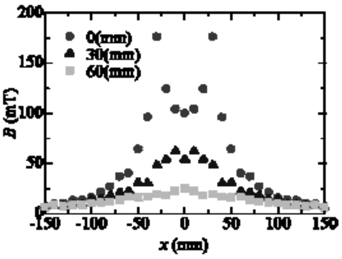


Figure 1 : Experimental apparatus.



(a) Magnetic field situation



(b)Magnetic field distribution

Figure 2 : Non-uniform magnetic field

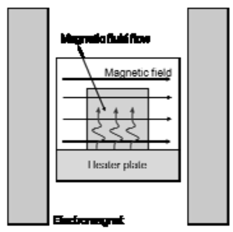


Figure 3 Uniform magnetic field

plate which is made of copper plate and heater attached to one-side of rectangular duct. The cross sectional area and the length of this duct are 18 mm×18 mm and 950 mm, respectively. Five thermocouples are installed in this heater plate and the position of these thermocouples are shown in the lower figure of Fig. 1. UVP transducer was set on the test section at the position (c) and we can measure the streamwise velocity distribution normal to the heater plate. We reported previously the measurement details and results of the velocity distribution of magnetic fluid flow by applying non-uniform magnetic field in [7].

Magnetic field is applied at the center of the rectangular duct, that is, at position (c). The electromagnet which is composed of a solenoid and an iron core was installed under the test section as shown in Fig. 2 (a) and the diameter of this iron core was 60 mm. The magnetic field distribution in a radial direction at each height from the top surface of iron core is also shown in Fig. 2(b). This figure is the magnetic field distribution when the magnetic field intensity is 100 mT near the center of the top surface of the iron core. In this study, magnetic field intensity was varied from 50 mT to 100 mT. In order to compare with our previous study in which was applied uniform magnetic field [6], Fig. 3 shows the situation of applying uniform magnetic field. The diameter of electromagnet was 150 mm.

Magnetic fluid used in this study is water-based magnetic fluid named as W-40 produced by Taiho Industries Co., Ltd. We diluted this magnetic fluid with water. The density and viscosity of this magnetic fluid without magnetic field are 1.3×10^3 kg/m^3 and 8.0 mPa·s, respectively. Experiments were carried out in both laminar flow and turbulent flow. Reynolds number based on the hydraulic diameter and bulk mean velocity are around 950 in the laminar flow case and around 2800 in the turbulent flow case. Moreover, we measured heat transfer and flow resistance with applying uniform magnetic field again for comparison in this study and almost similar results were obtained.

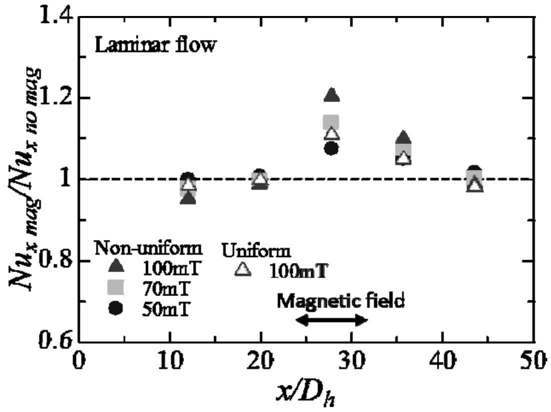


Figure 4 : Heat transfer result in laminar flow.

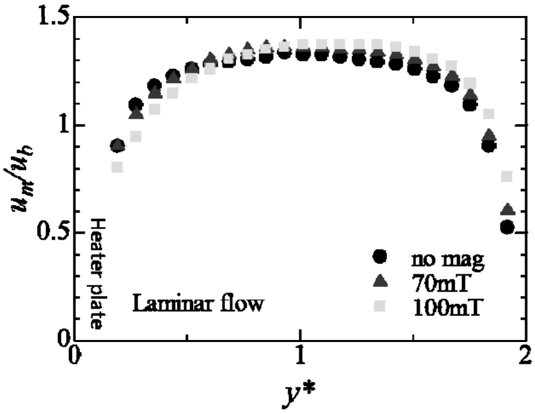


Figure 5 : Velocity distribution in laminar flow.

3. Results and discussion

3.1. Laminar flow case. Figure 4 shows the changes in heat transfer of a rectangular duct flow of a magnetic fluid with applying non-uniform magnetic field in a laminar flow. For comparison, the heat transfer characteristic by applying uniform magnetic field at 100 mT is also shown in this figure. This figure indicates that heat transfer increases with increasing magnetic field intensity at the position of applying magnetic field. This tendency is the same as the heat transfer by applying uniform magnetic field. Furthermore, the increment level of heat transfer by applying non-uniform magnetic field is much larger than that by applying uniform magnetic field. We discuss this difference of heat transfer enhancement. In the case of laminar flow, the following three changes by applying magnetic field affect the heat transfer; (1) change in thermal conductivity of magnetic fluid, (2) change in the velocity distribution and (3) convection occurs by the effect of magnetic field.

Regarding (1), some researchers reported that the increment of thermal conductivity of magnetic fluid in the direction of magnetic field [8, 9]. The increment of thermal conductivity should lead to the heat transfer enhancement. When the magnetic field is applied to magnetic fluid, the inner particles coagulate and form chain-like structure along the magnetic field. This clustering structure seems to have close relationship with thermal conductivity of magnetic fluid. However, in accordance of previous study [10], it takes time to grow the chain-like cluster. Considering this study, because the region where magnetic field exists is short, it is difficult to form the clustering structure and it seems that thermal conductivity of magnetic fluid hardly changes in this short region. Therefore, we consider that the change in the thermal conductivity hardly affects this heat transfer.

Next, we consider the change in the velocity distribution by applying magnetic field. Figure 5 shows the velocity distribution of a laminar rectangular duct flow with and without non-uniform magnetic field. In this figure, the vertical axis is the velocity at each *y*-position u_m normalized by the bulk mean velocity u_b. The heater plate is $y^*=0$. This figure indicates that the velocity of magnetic fluid flow decreases near the heater plate and velocity gradient also decreases. In contrast, the flow velocity in the upper side from the duct center (i.e. y^* is around 1.5) increases to follow the continuity equation. The decrement of velocity gradient does not lead to heat transfer enhancement. Therefore, we think that the change in the velocity distribution also hardly affects heat transfer. The detailed results of the velocity distribution by applying non-uniform magnetic field and discussion can be found in [7]. On the contrary, in the situation of applying uniform magnetic field [6], the velocity gradient increases near the heater plate by applying magnetic field and this increment of velocity gradient leads to heat transfer enhancement.

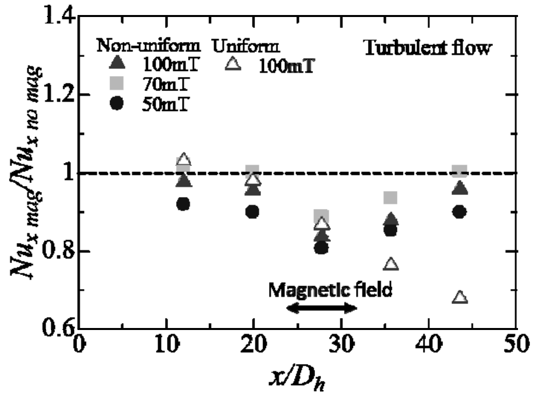


Figure 6 : Heat transfer result in turbulet flow.

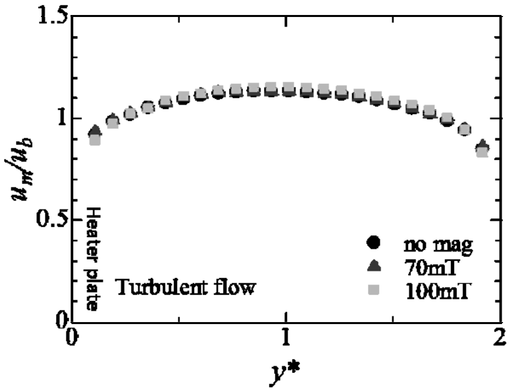


Figure 7 : Velocity distribution in turbulent flow.

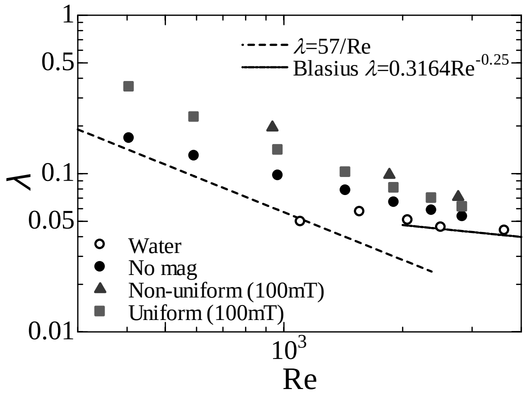


Figure 8 : Pipe frictional coefficient.

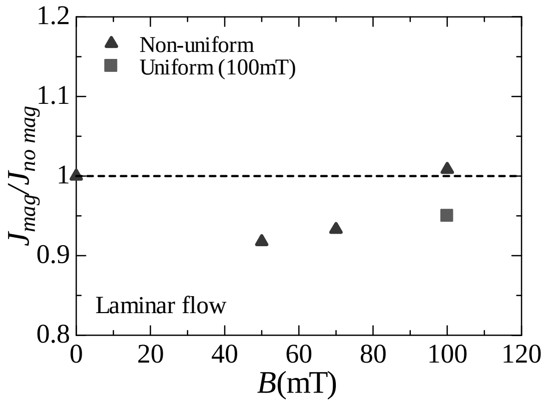


Figure 9 : Evaluation of flow resistance and heat transfer.

Finally, when the non-uniform magnetic field is applied to magnetic fluid flow, thermomagnetic convection occurs by the effect of magnetic body force. This convection strongly affects the forced convective heat transfer. Ganguly et al. [11] investigated the influence of thermomagnetic convection on forced convective heat transfer of magnetic fluid flow by numerical simulation, and reported forced convective heat transfer was largely enhanced by the effect of the thermal convection induced by the non-uniform magnetic field. Therefore, the heat transfer enhancement by applying non-uniform magnetic field in this study is caused by the convection induced by the magnetic body force. However, in the case of applying uniform magnetic field, because magnetic gradient does not exist, magnetic body force is zero theoretically. Therefore, the effect of convection is weak, and the enhancement level is smaller than that by applying non-uniform magnetic field.

3.2. Turbulent flow case. Figure 6 shows the effect of magnetic field on forced convective heat transfer of magnetic fluid flow in turbulent flow regime. This figure indicates that the heat transfer was suppressed at the position where magnetic field exists and this is the similar tendency by applying uniform magnetic field. However, considering the tendency of suppression of heat transfer, the result by applying 50 mT is relatively strange and so we need to check again in the future. The suppression level of heat transfer by applying non-uniform magnetic field is similar value by applying uniform magnetic field. As already discussed in our previous study [6], this suppression of heat transfer is caused by suppression of turbulent diffusion. Although the result is not shown in this paper, we also measured velocity fluctuation by UVP method and we confirmed streamwise velocity fluctuation is also suppressed by applying non-uniform magnetic field.

The velocity distribution in turbulent flow is shown in Fig. 7. This figure indicates that velocity near the heater plate slightly decreases but the velocity at the center of the duct increases. However, because this change in the velocity distribution is very small, the change in the velocity distribution hardly affect the heat transfer suppression. Moreover, in our previous study [7], we obtained characteristic change in the velocity distribution by applying stronger uniform magnetic field. Therefore, it seems that magnetic field is not so strong that the velocity distribution changes.

3.3. Relationship between flow resistance and heat transfer. Figure 8 shows the Reynolds number dependence of pipe frictional coefficient (λ).When the magnetic field is applied to magnetic fluid flow, flow resistance increases in both laminar flow and turbulent flow. The increment of flow resistance by applying magnetic field is relatively larger in the laminar flow. However, comparing applying non-uniform magnetic field with uniform magnetic field, the increment level is comparable in both flow cases.

As mentioned above, when a non-uniform magnetic field is applied to magnetic fluid flow, heat transfer is largely enhanced in laminar flow regime but flow resistance also increased. Same as our previous study [6], we evaluate this relationship by using Colburn's *J*-factor which is defined by $J = \mathrm{St} \cdot \mathrm{Pr}^{2/3} / (C_f / 2)$. Figure 9 shows the magnetic field dependence of the change ratio of *J* by applying magnetic field. This figure indicates that when 100 mT of non-uniform magnetic field is applied to magnetic fluid flow, the change ratio slightly exceeds 1. This means that heat transfer enhancement relatively exceeds the increase of flow resistance. In the case of applying uniform magnetic field, this ratio did not exceed 1. Therefore, thermal convection induced by magnetic field gradient by applying non-uniform magnetic field works effectively. However, as the exceeded value is just a small, we will continue to consider the way for how heat transfer enhances without increasing flow resistance in the future.

4. Conclusion

We investigated the forced convective heat transfer and flow resistance of rectangular duct flow of a magnetic fluid by applying non-uniform magnetic field in this study. Experiment was performed in both laminar flow and turbulent flow. In the case of laminar flow, heat transfer is largely enhanced in the region where magnetic field exists. Comparing with the results with applying uniform magnetic field, the enhancement level is larger. This is because of the effect of convection induced by non-uniform magnetic field. In contrast, heat transfer is suppressed by applying non-uniform magnetic field in turbulent flow. The suppression level is similar to that with applying uniform magnetic field.

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