Variation of forced convective heat transfer in rectangular duct flow of a magnetic fluid under magnetic field

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Abstract. Variation of forced convective heat transfer in a rectangular duct flow of a magnetic fluid under a magnetic field was investigated experimentally. Experiments were performed changing the magnetic field intensity, and this magnetic field could be varied from 0 mT to 600 mT. The Reynolds number based on the hydraulic diameter was set to 960, 1900 (laminar flow), and 2830 (turbulent flow). The results of the experiments show that in the case of laminar flow of the magnetic fluid, when a magnetic field is applied to a magnetic fluid flow, heat transfer locally increases in the region where the magnetic field exists. In contrast, in the turbulent flow of the magnetic fluid, heat transfer is not enhanced but reduced. In order to better understand this heat transfer phenomenon, we measured the velocity distribution of magnetic fluid flow by the Ultrasonic Velocity Profile (UVP) method. In the case of laminar flow, the result shows that the flow velocity at the center of the rectangular duct decreases and the velocity gradient in the near-wall region increases. Moreover, we calculated the flow resistance under a magnetic field by measurement of the pressure gradient, and the relationship between heat transfer and flow resistance was discussed.

1. Introduction

Magnetic fluid [1] is a stable colloidal solution which uniformly disperses ferromagnetic particles in solvents such as water or kerosene. These ferromagnetic particles are about 10 nm in size and coated with surfactant in order to avoid aggregation. Therefore, these particles can remain suspended because of Brownian motion. In addition, magnetic fluid has enough liquidity to be treated as a Newtonian fluid under no magnetic field. However, once a magnetic field is applied to magnetic fluid, several interesting flow phenomena, which are not seen in a Newtonian fluid, have been observed [2, 3]. Since magnetic fluid was developed about 50 years ago, many studies on the physical properties [4] and interesting phenomena of magnetic fluid [5] have been performed. In recent decades, magnetic fluid has been applied in mechanical engineering [6], medical engineering [7], space engineering, and so on.

In thermal engineering, magnetic fluid also has interesting thermophysical properties such as temperature-dependent magnetization. Therefore, the thermophysical properties of magnetic fluid have also attracted attention and have been applied to many technologies recently. One of the most successful applications of the thermophysical properties of magnetic fluid is the audio speaker [8]. In audio speakers, magnetic fluid is used to fill the space around the voice coil. Because the thermal conductivity of magnetic fluid is much greater than that of air, the fluid provides a lower heat resistance between the coil and the pole plate. As a result, the operating temperature of the voice coil

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can be reduced. On the other hand, magnetic fluid is also useful for heat transport applications. Iwamoto et al. [9] developed a self-driven heat transport device using temperature-sensitive magnetic fluid. As mentioned above, because magnetic fluid contains nano-order-size ferromagnetic particles in the carrier liquid, it can be considered a kind of nanofluid. Recently, there has been intensive research on the heat transfer of nanofluids and several studies on the heat transfer characteristics of nanofluid have been performed [10]. Therefore, the study on heat transfer of the magnetic fluid can be regarded as the combination of heat transfer of the nanofluid and active control of heat transfer by a magnetic field. Moreover, if heat transfer enhancement and reduction of flow resistance can be realized simultaneously, it is very useful for many engineering techniques. As a basic study of these backgrounds, we investigate the forced convective heat transfer characteristics in rectangular duct flow of a magnetic fluid.

Several studies on the heat transfer characteristics of magnetic fluid have been carried out attracting great engineering interest [11-13]. However, the heat transfer phenomena of magnetic fluid are very complicated and there is not enough knowledge about them. In our previous study [14], we performed an experimental investigation of forced convective heat transfer in the rectangular duct flow of a magnetic fluid in a laminar flow. The result showed the heat transfer was enhanced locally in the region in which the magnetic field existed. Generally, if heat transfer is enhanced, the flow resistance will increase in the same region. Therefore, it is necessary to investigate the relationship between heat transfer and flow resistance.

Moreover, in order to better understand the characteristics of the complicated physical phenomena of magnetic fluid, the internal velocity fields should provide useful information. However, because magnetic fluid is opaque, it is impossible to apply optical methods such as Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV). To realize the measurements of the velocity profile of an opaque fluid, Takeda developed the Ultrasonic Velocity Profile (UVP) method more than 20 years ago [15]. The UVP method is a way of measuring a velocity profile along the ultrasonic beam from the ultrasonic Doppler shift frequency. After the development of UVP, Sawada et al. [16] and Kikura et al. [17] applied the UVP method to velocity profile measurement of magnetic fluid. These experimental studies have shown the efficiency of the UVP method for velocity profile measurement of magnetic fluid.

In this study, we performed an experimental investigation of variation of forced convective heat transfer in the rectangular duct flow of a magnetic fluid. The experiments were carried out in both a laminar flow and a turbulent flow. The magnetic field intensity could be varied from 0 mT to 600 mT. To discuss the heat transfer characteristics of magnetic fluid flow, we measured the velocity distribution of the rectangular duct flow of a magnetic fluid subject to magnetic fluid by UVP. In addition to this heat transfer experiment, the flow resistance of the magnetic fluid flow under a magnetic field was measured. On the basis of the results of these experiments, the effect of magnetic field on the forced convective heat transfer, and the relation between heat transfer and flow resistance in the rectangular duct flow of magnetic fluid was discussed.

2. Experiment
2.1. Experimental apparatus
Figure 1 shows a block diagram of the flow system of the experimental apparatus. The experiment was performed with a closed-circuit loop with the rectangular duct as a test section. The fluid was circulated by a pump and the flow rate could be adjusted by a bypass. An impeller type flow meter was installed downstream of the pump to measure the flow rate. Two thermocouples were set at the inlet and outlet of this duct. Therefore, we could measure the temperature of the flow liquid at inlet \( T_{in} \) and outlet \( T_{out} \). A storage tank on the flow loop was equipped with a heater and a cooler to keep \( T_{in} \) at a constant level. An electromagnet was located at the center of the test section. This electromagnet could apply a uniform magnetic field to the magnetic fluid flow and the magnetic field could be varied from 0 mT to 600 mT.
The detailed structure of the rectangular duct and the cross-section of this duct at the center position are shown in Figs. 2 and 3, respectively. This rectangular duct was made of a transparent acrylic resin except for the heater plate, and was 18 mm × 18 mm in cross-section and 950 mm in length. The hydraulic diameter $D_h$ of this duct is 18 mm. Two pressure taps were located on the top of the rectangular duct, 700 mm apart, and the static pressure gradient between the two pressure taps was measured. There was an electromagnet between these pressure taps. Therefore, we could measure the change in the flow resistance under the magnetic field. We defined the Cartesian coordinates as shown in Figs. 2 and 3 (i.e. $x$: Streamwise direction, $y$: Direction of normal to the heater plate, $z$: Spanwise direction). In this experiment, the Reynolds number based on the bulk mean velocity and hydraulic diameter was set to 960, 1900 and 2830. As a result of the measurement of the velocity distribution by the UVP method, we confirmed that the magnetic fluid flow was a laminar flow at $Re = 960$ and $Re = 1900$, but the magnetic fluid flow was a turbulent flow at $Re = 2830$.

The heater plate was attached to the bottom of the rectangular duct. This heater plate comprised the heater and a copper plate as shown in figure 3. The flow liquid in the rectangular duct could be heated by this heater plate with a uniform heat flux. The heat flux of this heater plate was 41 kW/m² in this experiment. We defined the entrance of the duct as $x = 0$. Five thermocouples were installed in the heater plate and located at $x = (a) 205$ $(x/D_h = 15.3)$, $(b) 340$ $(x/D_h = 18.9)$, $(c) 475$ $(x/D_h = 26.4)$, $(d) 610$ $(x/D_h = 33.9)$ and $(e) 745$ mm $(x/D_h = 41.4)$ downstream from the entrance of this duct. Therefore, we could estimate the wall temperature of the heater plate ($T_w$) at each position. It could be assumed that the bulk temperature ($T_b$) of the flow liquid increased linearly with the length of channel, and we were able to calculate the bulk temperature at the each position.
2.2. UVP method

2.2.1. Principle [18]. Figure 4 shows the principle of the UVP method and the relation between the ultrasonic beam and the flow. The UVP method is based on pulsed ultrasound echography. An ultrasonic pulse is emitted from the transducer along the measuring line and the same transducer receives the echo signal reflected from seeding particles in the flow. All velocity profile information, such as the instantaneous velocity and the positions from where the ultrasound is reflected, can be detected. The position \( x \) from where the ultrasound is reflected can be extracted from the time delay \( \tau \) between the start of pulse burst and reception time as follows:

\[
x = \frac{c \tau}{2}
\]

where, \( c \) is the ultrasonic propagation velocity in the flow liquid. At the same time, the velocity information is derived from the Doppler shift frequency by the following equation.

\[
V = \frac{c f_D}{2 f_0}
\]

where, \( f_D \) and \( f_0 \) are the Doppler shift frequency and original ultrasonic frequency, respectively. Thus, a velocity profile can be obtained along the ultrasonic beam by analyzing the echo signal to derive instantaneous frequencies at each instant.

2.2.2. Velocity profile measurement by UVP. A UVP probe was set on the center of the rectangular duct and at the position where the magnetic field was applied to the magnetic fluid, as shown in Figs. 2 and 3. Therefore, we could measure the velocity distribution in the x-y plane at the center of the duct. The UVP probe was fixed on the outer wall of the duct at an angle of 14°. In order to obtain the reflected echo signal, we added the poly(methylmethacrylate) particles (MBX-100 produced by Sekisui Plastics Co., Ltd.) as tracer particles. These particles were 115 \( \mu \)m in mean diameter.

2.3. Magnetic fluid. The test magnetic fluid was a water-based magnetic fluid named W-40 produced by Taiho Industries Co., Ltd. W-40 was 40 % weight concentration of fine magnetite particles (Fe₃O₄) in water. However, because W-40 is too dense for this experiment, we diluted this magnetic fluid to 70 volume % with water as a test fluid. The properties of this test fluid are listed in Table 1.
Table 1. Properties of the magnetic fluid (at 25°C).

| Test Fluid          | Water | Magnetic fluid |
|---------------------|-------|----------------|
| Particle material   | -     | Fe₃O₄          |
| Particle diameter   | -     | about 10 nm    |
| Carrier liquid      | -     | water          |
| Density kg/m³       | 997   | 1305           |
| Viscosity mPa·s     | 0.89  | 8.0            |
| Specific heat J/kg·K| 4110  | 3080           |
| Thermal conductivity W/m·K | 0.58 | 0.55         |
| Prandtl number      | 6.2   | 39.5           |

2.3.1. Thermo physical properties of test magnetic fluid. Because it is very difficult to obtain the exact values of the thermo physical properties such as specific heat and thermal conductivity, these values are estimated by the following methods:

- **Specific heat**: The specific heat of magnetic fluid \( c_{pmf} \) at constant pressure was estimated by the following equation.
  \[
  c_{pmf} = c_{pw}n_w + c_{pm}n_m
  \]
  where, \( c_{pw} \) and \( c_{pm} \) are the specific heat of water and magnetite particles, respectively. \( n_w \) and \( n_m \) are the volume fraction of water and magnetite particles, respectively. The volume fraction can be calculated by the density of magnetic fluid, water and magnetite.

- **Thermal conductivity \( k \)**: Takegoshi et al. [19] estimated the thermal conductivity of magnetic fluid \( k_{mf} \) by Kerner's coating model. The estimated thermal conductivity of magnetic fluid had good agreement with the measured thermal conductivity. Therefore, we also estimated the thermal conductivity of magnetic fluid by Kerner's coating model.

- **Prandtl number**: The Prandtl number can be calculated by the specific heat \( c_p \), thermal conductivity \( k \) and viscosity \( \mu \) by the following equation,
  \[
  Pr = \frac{c_p\mu}{k}
  \]
  The estimated values of specific heat, thermal conductivity and the Prandtl number are also listed in Table 1.

Moreover, when a magnetic field is applied to a magnetic fluid, it is possible that these thermo physical properties will change. Li et al. [20] measured the thermal conductivity of magnetic fluid under a magnetic field and they reported that the thermal conductivity of magnetic fluid changed by applying a magnetic field. However, also according to them, when the magnetic field was applied to a magnetic fluid in a direction perpendicular to the temperature gradient, which is the same situation as in our experiment, the thermal conductivity hardly changed. Therefore, in our experiment we treated these values of thermo physical properties of magnetic fluid as being constant under a magnetic field.

2.3.2. Ultrasonic velocity in test magnetic fluid. When the UVP method is applied to measure the velocity profile of the test fluid, the ultrasonic propagation velocity in the test fluid is needed as represented in equations (1) and (2). However, it is very difficult to measure the ultrasonic propagation velocity in a fluid precisely. Moreover, in the case of magnetic fluid, because the magnetic field influences the ultrasonic propagation velocity in a magnetic fluid, it is necessary to investigate the influence of the magnetic field.

In our previous study [21], we measured the ultrasonic propagation velocity in a magnetic fluid and investigated the influence of the magnetic field on the ultrasonic propagation velocity. Details of the measurement technique can be found in Motozawa et al. [21]. When a magnetic field is applied to a magnetic fluid, the ultrasonic propagation velocity increases in proportion to the length of time the
magnetic field is applied. The inner particles coagulate and form a chain-like cluster under a magnetic field. This change seems to be caused by chain-like cluster formations. However, because the change in ultrasonic propagation velocity is rather small, this change does not influence UVP measurements.

We also measured the ultrasonic propagation velocity in the test magnetic fluid by the same technique and ultrasonic propagation velocity of this was \( c = 1429 \text{ m/s} \).

3. Result and Discussion

3.1. Effect of magnetic fluid on heat transfer and velocity distribution

3.1.1. Laminar flow case. Figure 5 shows the effect of a magnetic field on the heat transfer in the rectangular duct flow of a magnetic fluid. In this experiment, the Reynolds number was set to 960, and the magnetic fluid flow was a laminar flow. The horizontal axis is the distance from the entrance of the duct, and the position of the thermocouples in the duct is also indicated. The flow is from the left to the right side.

Heat transfer coefficient \( h \) can be calculated at each position where the thermocouple is attached (i.e. position (a) - (e) in figure 2) by the following equation,

\[
h = \frac{\dot{q}}{T_b - T_s}
\]

where, \( \dot{q} \) is heat flux, \( T_b \) is the bulk temperature of magnetic fluid flow which is estimated by \( T_{in} \) and \( T_{out} \). Therefore, the Nusselt number is defined by,

\[
Nu = \frac{hD_b}{k}
\]

To compare between the Nusselt number with and without a magnetic field, we evaluated the local Nusselt number ratio defined by \( Nu_{mag}/Nu_{no\ mag} \) at each position. Here, \( Nu_{mag} \) and \( Nu_{no\ mag} \) are the local Nusselt number with and without a magnetic field at the same position, respectively.

This figure indicates that when the magnetic field is applied to a magnetic fluid flow, the heat transfer at the position (c) where the magnet field exists greatly increases compared with under no magnetic field. This increment of the Nusselt number becomes larger with increasing magnetic field. In addition, heat transfer is also enhanced just downstream of the position (c) (i.e. position (d)), but slightly smaller than that at the position (c). This seems to show that good heat transfer at position (c) remains but weakens downstream of the area where the magnetic field exists. On the other hand, the heat transfer hardly changes at the entrance and the end of the duct (i.e. position (a) and (e)). This indicates that a magnetic field locally influences the heat transfer of a magnetic fluid flow in the area where the magnetic field is applied.
In the case of magnetic fluid flow, there seems to be two prominent reasons why the forced convective heat transfer of magnetic fluid flow changes by magnetic field. One reason is the change in the thermo-physical property of magnetic fluid (e.g. specific heat, thermal conductivity etc.), and the other is the change in the velocity distribution on the basis of the change in the physical properties of magnetic fluid (e.g. apparent viscosity, local density in the region where the magnetic field exists). Regarding the change in the thermo-physical properties of magnetic fluid by magnetic field, as mentioned above, Li et al. [20] reported that when a magnetic field is applied to a magnetic fluid, thermal conductivity of a magnetic fluid changes related with the direction of magnetic field. However, if the direction of the magnetic field is perpendicular to the temperature gradient, which is the same direction as our experiment, the thermal conductivity hardly changed. Therefore, the influence of the change in the thermo-physical properties of magnetic fluid is excluded from the reason why the forced convective heat transfer changes.

On the other hand, figure 6 shows the effect of a magnetic field on the velocity distribution of a magnetic fluid flow at Re = 960 (Laminar flow). In this figure, the black plots and solid line indicate the velocity distribution of the magnetic fluid flow under no magnetic field and Newtonian fluid obtained by the theory, respectively. The horizontal axis is the distance from the bottom wall normalized by the half of the duct and the vertical axis is the mean velocity $u_m$ normalized by the bulk mean velocity $u_b$.

When a magnetic field is not applied to the magnetic fluid, magnetic fluid can be treated as a Newtonian fluid. However, the configuration of the measured velocity distribution is different from that of the Newtonian fluid. The mean velocity of magnetic fluid under no magnetic field near the center of the duct is smaller than that of Newtonian fluid. This is due to a problem in the experimental system. In this experiment, we measured the velocity distribution at the developing region. Therefore, the magnetic fluid flow was not developed enough and the velocity distribution of magnetic fluid under no magnetic field was different from that of the Newtonian fluid.

When the magnetic field is applied to magnetic fluid, this figure indicates that the mean velocity at the center of the duct decreases but the velocity gradient increases near the wall. The increment of velocity gradient gradually becomes larger with increasing magnetic field. In this study, because a uniform magnetic field is applied to magnetic fluid flow, magnetic body force $M \cdot VH$ equals to zero. This means that the velocity distribution does not change by magnetic field. However, because apparent viscosity of magnetic fluid increases by magnetic field and the length of magnetic field region is very short, the velocity distribution changes in the entrance of magnetic field region and magnetic fluid flow is not developed enough. Therefore, the velocity gradient increases in the region where the magnetic field exists.

![Figure 7](image1.png)  ![Figure 8](image2.png)

**Figure 7.** Effect of magnetic field on heat transfer in a turbulent flow at Re=2830.

**Figure 8.** Effect of magnetic field on streamwise velocity fluctuation in a turbulent flow at Re = 2830.
In addition, when a magnetic field is applied to a magnetic fluid, magnetic particles form a micro-scale chain-like structure in the direction of magnetic field [22]. It is a possibility that this clustering structure could inhibit the axial velocity of the flow [23]. This inhibition also leads to the increment of the velocity gradient in the near-wall region because the flow rate is constant when magnetic field is applied to magnetic fluid flow in this experiment. For these reasons, velocity gradient near the heater plate increases in the region where the magnetic field exists and this increment of velocity gradient cause local heat transfer enhancement. However, the increment of velocity gradient indicates the increment of the shear stress. Therefore, it is important to investigate the relationship between heat transfer and flow resistance.

3.1.2. Turbulent flow case. In contrast to the above, figure 7 shows the effect of a magnetic field on the heat transfer for a turbulent flow. In this case, the Reynolds number was set to 2830. This figure indicates that the heat transfer is not enhanced but suppressed. In addition, heat transfer decreases gradually with the distance from the entrance of the duct. Moreover, figure 8 shows the distribution of the streamwise velocity fluctuation normalized by the bulk mean velocity. This figure indicates that when the magnetic field is applied to turbulent magnetic fluid flow, the streamwise velocity fluctuation was largely suppressed. This is because apparent viscosity of magnetic fluid increases by applying magnetic field. This suppression of velocity fluctuation means the suppression of turbulent diffusion. Therefore, heat transfer was also suppressed in the region where the magnetic field exists.

On the other hand, figure 9 shows the results of the measurement of the velocity distribution at the same Reynolds number. This figure indicates that the velocity gradient in the near-wall region greatly increases with increasing magnetic field. As mentioned above, the increment of the velocity gradient leads to the heat transfer enhancement. However, the influence of the suppression of the turbulent diffusion is stronger than the effect of the increment of the velocity gradient. As a result, heat transfer was suppressed in the region where the magnetic field exists.

In addition, regarding the velocity distribution as shown in figure 9, characteristic results were obtained. When the magnetic field is applied to a magnetic fluid, not only the velocity gradient near the wall but also the mean velocity near the center of the duct increases with increasing magnetic field intensity. In this study, experiments were carried out under a constant flow rate when the magnetic field was applied to the magnetic fluid. Therefore, the increment of both velocity gradient and mean velocity near the center of the duct indicates that the velocity distribution in the x-y plane is different from that in the x-z plane, and characteristic anisotropy of the velocity distribution exists in the velocity profile related to the magnetic field direction. In the future, in order to investigate this characteristic velocity distribution, we will measure the velocity distribution in the x-z plane.
3.2. Reynolds number dependence of heat transfer and pipe frictional coefficient

Figure 10 shows the Reynolds number dependence of the heat transfer at position (c) where the magnetic field exists. The horizontal axis represents the magnetic field intensity. As mentioned above, in the cases of laminar flow for Re = 960 and 1900, heat transfer is enhanced with a magnetic field. However, in a flow with a larger Reynolds number, it is necessary for heat transfer enhancement to apply a strong magnetic field. In contrast, heat transfer is not enhanced in a turbulent flow, even if the strong magnetic field is applied.

On the other hand, figure 11 shows the Reynolds number dependence on the increment of the pipe frictional coefficient. To compare between the pipe frictional coefficient \( \lambda \) with and without a magnetic field, we evaluated the increment ratio of the pipe frictional coefficient defined by \( \lambda_{\text{mag}}/\lambda_{\text{no mag}} \). This figure indicates that the flow resistance of a magnetic fluid greatly increases with increasing magnetic field in the laminar flow. It is well known that the apparent viscosity increases when applying a magnetic field to a magnetic fluid. As a result of the increase of apparent viscosity, the flow resistance increases with increasing magnetic field intensity. However, the effect of a magnetic field is small in a turbulent flow. Kamiyama et al. [24] investigated flow resistance in a circular pipe by experiment, and almost the same result was reported.

3.3. Relationship between heat transfer and flow resistance

As mentioned above, when a magnetic field is applied to a magnetic fluid, heat transfer is greatly enhanced in the laminar flow of the magnetic fluid. However, if heat transfer is enhanced, the flow resistance would generally increases in the same region. Therefore, it is necessary to investigate the relationship between heat transfer and flow resistance. We evaluated the relationship between heat transfer and flow resistance by the following method.

The Stanton number is defined by,

\[
St = \frac{Nu}{Re \cdot Pr}
\]  

(7)

In this study, the Stanton number was evaluated at position (c) where a magnetic field exists. Using the Chilton-Colburn analogy, which can be applied to a wide range of Prandtl numbera, Colburn's J-factor is defined by the following equation,

\[
J = \frac{St \cdot Pr^{1/3}}{(C_f / 2)}
\]  

(8)

To compare between the value of \( J \) with and without a magnetic field, we evaluated the increment ratio of \( J \) defined by \( J_{\text{mag}}/J_{\text{no mag}} \). The value of \( J \) would be 1 in a water flow theoretically. In this experiment, we obtained about 0.8 of the value of \( J \).

Figure 12 shows magnetic field dependence on the increment ratio of \( J \). This figure indicates that when the magnetic field is applied to a magnetic fluid, \( J_{\text{mag}}/J_{\text{no mag}} \) decreases with increasing magnetic

![Figure 11. Reynolds number dependence of flow resistance.](image1)

![Figure 12. Evaluation of the relation between heat transfer and flow resistance by Colburn's J-factor.](image2)
field intensity in both the laminar flow case and the turbulent flow case. In the case of a turbulent flow, heat transfer decreases and flow resistance slightly increases when applying a magnetic field. Therefore, it goes without saying that $J$ decreases under a magnetic field. On the other hand, in the case of the laminar flow, this result means that the increment of flow resistance is relatively larger than the heat transfer enhancement. Therefore, although the heat transfer was greatly enhanced in a laminar flow as shown in figure 5, this is unfavorable case in the heat transfer with considering the flow resistance. We will continue to experiment changing in the situation of applying magnetic field in the future.

4. Conclusions
Variation of heat transfer in a rectangular duct flow of a magnetic fluid under a magnetic field was investigated experimentally. Moreover, in order to better understand the heat transfer characteristics of the magnetic fluid flow, we measured the velocity distribution of magnetic fluid flow by the UVP method. We performed experiments on both the laminar flow and the turbulent flow of a magnetic fluid. A magnetic field can be varied from 0 mT to 600 mT. As a result of this study, the following results were obtained.

1. In the case of laminar flow, when the magnetic field is applied to a magnetic fluid, heat transfer is locally enhanced at the region where the magnet field exists. This heat transfer becomes larger with increasing magnetic field but saturated under a strong magnetic field. In addition, the mean velocity at the center of the duct decreases with increasing magnetic field intensity but the velocity gradient increases near the wall.
2. In the case of a turbulent flow, heat transfer is suppressed by the magnetic field. The mean velocity near the center of the duct and velocity gradient near the wall increase with increasing magnetic field intensity. This fact indicates that characteristic anisotropy exists in the velocity profile related to the magnetic field direction.
3. When the magnetic field is applied to a magnetic fluid flow, the flow resistance increases in both laminar flow and turbulent flow. To evaluate the relation between heat transfer enhancement and increment of flow resistance, we calculate Colburn's $J$-factor. In the case of a laminar flow, increment ratio of $J$ decreases with increasing magnetic field intensity. This means the flow resistance increases more compared with the heat transfer.

Acknowledgements
This study was partly supported by a Grant-in-Aid for Young Scientists (B) of the Japan Society for Promotion of Science.

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