Local Velocity Measurement of Magnetic Fluid Flow Using Semiconductor Laser and Optical Fiber*

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A new method is developed, using a semiconductor laser and optical fiber, to measure the local velocity of magnetic fluid flow. In this method, the local flow velocity is obtained by measuring the time taken for a tracer particle to pass between two sets of optical fiber probes. After this method is calibrated with a rotational flow in a rotating channel, it is applied to magnetic fluid flows in an open channel under the influence of a traveling magnetic field which is produced with a stator of a single-sided linear induction motor. As a result, it is clarified that the flows are mainly induced opposite to the traveling direction of the magnetic field and the magnitude of induced velocity is almost proportional to the frequency of the magnetic field, increasing especially near the free surface. The velocity distributions are quite different from those of nonmagnetic fluid flow in an open channel.

Key Words: Fluid Dynamics, Magnetic Fluid, Velocity Distribution LDV, Semiconductor Laser, Optical Fiber, Velocity Measurement, Traveling Magnetic Field

1. Introduction

Magnetic fluid was developed as new artificial material exhibiting ferromagnetic properties in a liquid state, and many investigators in various research fields have been attracted to the research on the clarification of its peculiar physical properties and mechanical behavior and the development of application devices. However, experimental studies on the basic flow characteristics of magnetic fluids have been limited to problems concerned with pipe flow resistance and increase in apparent viscosity under magnetic fields, and experimental results on velocity distributions of internal flows of magnetic fluid are few.

It is very important that velocity distributions are clarified, not only in the practical application of magnetic fluid, but also in basic fluid engineering. However, it is fairly difficult to measure because of the effect of the magnetic field on the velocity sensor and the opaqueness of magnetic fluid⁽¹⁾. Laser Doppler velocimeters (LDV), hot wire and hot film velocimeters, which have been widely used in measuring the local velocity of liquid flows, cannot be used by themselves. Fluid velocity is usually so small that dynamic pressure-type measurement, i.e., the method of using a Pitot tube, also cannot be adopted. On the other hand, it is possible to measure the velocity of a semi-opaque liquid flow, such as blood flow, using a laser Doppler velocimeter with optical fiber sensors⁽²⁾⁻⁽⁴⁾. However, it is considered that this method is inapplicable to the velocity measurement of black, very opaque magnetic fluid because the scattered light from a tracer particle is usually so weak that it is easily attenuated and absorbed.

To overcome these difficulties, we have tried to establish a new optical method by which to measure the local flow velocity of magnetic fluid⁽⁵⁾. In our method, a laser beam supplied directly from a laser

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diode is split into two beams and introduced to a measuring point via two optical fibers. The local flow velocity of magnetic fluid is obtained by measuring the velocity of a tracer particle traveling between the two beams. This idea originated from the principle of measurement using two focusing laser velocimeters. In the previous paper⁽⁶⁾, this method was applied to an open channel flow of magnetic fluid in a region where magnetic field was not applied, using a He-Ne laser supply (wavelength about 630 nm, power 50 mW) as a source of light. Although velocity measurement in the region where the traveling magnetic field is applied is the subject of interest, we could not conduct experiments on this because of the problems related to the poor transparency of magnetic fluid to the He-Ne laser beam and the floating of tracer particles in the magnetic field.

In the present paper, we report the result of the flow velocity measurement under the influence of a traveling magnetic field using an AlGaAs semiconductor laser beam as a source of light. As the semiconductor laser beam has longer wavelength and stronger intensity, it passes through magnetic fluid more easily than does the He-Ne laser beam. Moreover, we improved the method of supplying tracer particles into the magnetic fluid in order to cope with these difficult problems.

2. Semiconductor Laser Optical Fiber Velocimeter System

Figure 1 shows the layout of the semiconductor laser optical fiber velocimeter system. The semicon-

Fig. 1 Layout of semiconductor laser velocimeter with optical fiber

ductor laser beam (wavelength 804.5 nm, 15°C) is produced with an AlGaAs laser diode and a DC power supply (150 mW). After the laser beam emitted from the laser diode is introduced directly into a plastic optical fiber (outer diameter 1 mm and core diameter 0.5 mm), it is divided into two beams of the same intensity by an optical distributor, which each reach an emitting optical fiber. The probe consists of two pairs of an emitting and a detecting optical fiber (channels 1 and 2), which are set transversely to the flow direction, as shown in Fig. 2. The spacing between the emitting and the detecting optical fiber of each pair is 1.35 mm. In order to avoid a laser beam from the emitting optical fiber of one pair entering the detecting fiber of the other pair, the two laser beams from the two emitting optical fibers travel in the opposite direction. When transparent tracer particles enter the region between the two pairs of fibers, the beams from emitting optical fibers reach the detecting ones in each channel in turn. The detected light signals are transformed into analog electric signals by an optical-electric transducer using phototransistors. The waveforms of the electric signals are recorded as digital data by a transient digital recorder (wave memory, the total number of samples is 32 000 and the time interval of sampling 4 μ s–50 ms) which is automatically controlled through the GP-IB interface by a microcomputer. The signals in both channels are transferred through the interface and recorded in a magnetic disk of the computer. After the transfer and recording of 32 000 data are completed, the next collection of the measured data starts again. We continue to collect the measured data for about one hour at a measuring point. After the collections are finished, the recorded signals are transformed into the two-valued signals based on a threshold value of the voltage, as described later. The local flow velocity at the measuring point is obtained by statistically averaging the time intervals of the many collected data

Fig. 2 Details of optical fiber probe

between the two digitized pulse signals in both channels. During these operations, the system is automatically and continuously controlled by a microcomputer which we program for control, signal processing and statistical calculations. The tested magnetic fluid is water-based Ferricolloid W-35 (Taiho Industry Co.) which is diluted with distilled water to a density of $1\,050\text{ kg/m}^3$ (10°C). The penetration length of the semiconductor laser beam within the magnetic fluid is about 1.10 mm which is about twice that of the 50 mW He-Ne laser beam used in the previous experiment⁽⁶⁾. Transparent polystyrene spherical particles, which have nearly the same density as the tested magnetic fluid and the mean diameter of which is about $0.45\text{ }\mu\text{m}$, are adopted as tracer particles. Furthermore, equipment for supplying the tracer particles is prepared to cope with the problem of the floating of particles. The magnetic fluid including tracer particles with a volume concentration of about $0.086/\text{mm}^3$ is released from a nozzle into the channel. When the flow volume of the magnetic fluid into the channel reaches 50 mL during the measurement, an identical volume is discharged from the channel so as to maintain a constant depth of the liquid.

3. Calibration of Velocimeter with Rotating Channel

3.1 Experimental apparatus and method

Next, we describe a method for calibrating the velocimeter. Figure 3 shows a concentric circular acrylic open channel for the calibration of the velocimeter. A magnetic fluid flow of a constant speed is obtained by rotating the channel at a low speed using a DC variable speed motor and a gear box. The diluted magnetic fluid is poured into the channel to a depth of 10 mm . The optical fiber probe is set transversely to the flow direction at the position 180 mm from the center of the channel in the radial direction and 5 mm below the free surface in the vertical direction. After the channel is rotated at a rotational speed of

Fig. 3 Rotating open channel for calibration of velocimeter system

$0.3\text{--}2.0\text{ rpm}$ and induced flow becomes steady, the magnetic fluid including tracer particles is ejected at a constant speed of 16 mm/s from the nozzle which is located in the upstream position about 26 mm from the probe. The velocity measurement is made using the velocimeter system, as explained in section 2. The mean value of the tracers is compared with the real velocity of the induced flow. The velocity of the induced flow is obtained by measuring the time taken for the channel to turn one around, with a stopwatch.

In this experiment, the tracer particles have a tendency to float toward the surface because, by the present method, it takes so long to conduct the measurement that the density of magnetic fluid increases slightly due to the evaporation of the solvent, making it different from that of the tracer particle. As a result, the particles gradually float toward the surface and the rate of detecting the signals gradually decreases. When the rate becomes extremely low, a small amount of distilled water is poured into the channel so as to keep the density of the magnetic fluid constant. The temperature of the magnetic fluid is kept at $8\text{--}12^\circ\text{C}$ during the measurement.

3.2 Experimental results and discussion

Figure 4(a) shows a typical example of the recorded signal obtained from the experiment in the rotating open channel, where the horizontal axis expresses time and the vertical axis the output voltage corresponding to the penetration intensity. Although

(a) Measured signals

(b) Digitized signals

Fig. 4 Example of measured and digitized signals

the pulse signal is obtained in both channels in this example, sometimes they cannot be obtained in one channel. Figure 4(b) shows the two-valued signals based on a threshold value of the voltage, which are obtained from the measured signal in Fig. 4(a). In the figure, the pulse rise times and fall times are labelled T_1 , T_2 , T_3 and T_4 . It is judged from the following empirical law, by a computer program for signal processing, whether both digitized pulse signals are caused by an identical tracer particle or not.

$$T_2 - 0.5(T_2 - T_1) < T_3 \quad (1)$$

$$T_3 < T_2 + (T_2 - T_1) \quad (2)$$

Figure 5 shows an example of a relatively long time series of the two-valued signals. In the figure, the circled data satisfy conditions (1) and (2) simultaneously. These data are adopted in order to calculate the velocity of each tracer particle. The rate of adoption is about 60-70%.

Then, the velocity of each tracer particle V_T is calculated from

$$V_T = L / (T_3 - T_1), \quad (3)$$

where $L (=0.57 \text{ mm})$ is the spacing between the fibers of the two channels. The velocity of each tracer particle is collected and statistically processed. The measurement is conducted under the condition that the range of the induced flow velocity of magnetic

Fig. 5 Example of time series of two-valued signals

Fig. 6 Example of velocity histogram of tracer particles

fluid V is about 5-45 mm/s and the total number of samples n for a single value of the flow velocity is at least 100 and 260 on average. Figure 6 shows an example of a velocity histogram of tracer particles when the flow velocity V is equal to 27.56 mm/s (where s is the number of samples and n the total number of samples). In the figure, a normal distribution curve is drawn as a solid curve determined from the averaged value V_{TM} and the standard deviation σ in the samples of velocity V_T . It can be said that the distribution of V_T almost follows the normal distribution. Many histograms in a wide range of the magnitude of velocity were obtained, and consequently, it was established that almost all of them exhibit normal distributions. The relationship between the averaged velocity of tracers V_{TM} (horizontal axis) and the flow velocity of magnetic fluid V (vertical axis) is shown in Fig. 7 by dots. Although the velocity V_{TM} is almost equal to V when it is low, V_{TM} becomes greater than V in the range of high velocity. It is supposed that this is due to the effect of a contracted flow between the two fibers of the probe. Figure 8 expresses the relationship between the dimensionless standard deviation

Fig. 7 Relationship between flow velocity of magnetic fluid and averaged velocity of tracers

Fig. 8 Relationship between flow velocity of magnetic fluid and dimensionless standard deviation in velocity histogram of tracer particles

σ/V_{TM} and the flow velocity V . It is seen in the figure that the standard deviation σ is almost proportional to the velocity V_{TM} , and the equation

$$\sigma/V_{TM}=0.159 \quad (4)$$

is obtained. The relationship between V_{TM} and V is approximated based on Eq.(4) using a weighted least squares method. The result is shown in Fig. 7 as a solid curve, and is expressed by

$$V=10.61\sqrt{V_{TM}+16.06}-42.53 \quad (5)$$

The exact local velocity of magnetic fluid V can be calculated from Eq.(5). Additionally, the broken curve in Fig. 7 expresses the calibration curve proposed in the previous report⁽⁶⁾. The calibration curve given by Eq.(5) is more similar to the ideal line $V=V_{TM}$. This is due to the fact that the effects of a contracted flow between the two fibers and impingement of particles to the probe become smaller because the spacing between the fibers can be expanded by using a semiconductor laser which has longer wavelength and stronger intensity.

4. Measurement of Magnetic Fluid Flow Induced by a Traveling Magnetic Field

4.1 Experimental apparatus and method

Next, we explain the measurement of magnetic fluid flows induced by a traveling magnetic field, based on the result of the calibration in the previous section. A layout of an experimental apparatus for flow induction is shown in Fig. 9. A stator of a three-phase single-sided linear induction motor (total length 385 mm, width of iron core 64 mm, wavelength 150 mm and traveling velocity (phase velocity) 7.5 m/s (50 Hz)) is located under a straight region of an open circulation channel made of an acrylic plate, the width of which is 30 mm, the depth 30 mm and the total length 1 997 mm. The distance from the surface of the stator to the

Fig. 9 Layout of experimental apparatus

bottom of the fluid is 20 mm. Three-phase alternating current which has variable intensity and frequency supplied by a power source of 200 volts is provided for the coil of the stator. Consequently, a traveling magnetic field is produced so that a circulating flow of the magnetic field is induced in the channel. The stator is cooled with water to maintain almost constant temperature of the fluid (about 10°C) during the experiment. The measured distribution of magnetic flux density averaged over a half-period at the center of the stator is shown in Fig. 10 for the case of $I_a=5A$, where Y is the distance in the vertical upward direction from the linear motor, B_y the vertical component of averaged magnetic flux density and B_z the averaged horizontal component. It was confirmed that the magnitude of the magnetic flux density in the air is proportional to the excitation current I_a , irrespective of the frequency f .

The diluted magnetic fluid is poured into test channel until the mean depth reaches 10 mm, and the probe is placed at the center of the region inside the fluid where the magnetic field is applied. The nozzle for providing tracer particles is set about 26 mm upstream of the probe, and the vertical position is adjusted so as to detect the signal. After a steady circulation flow of magnetic fluid is induced by applying the traveling magnetic field, the distribution of the local velocity is measured along the vertical y -direction by moving the probe and the nozzle under several conditions of strength and frequency of the excitation current.

In the region where the magnetic field is applied, the circulating tracer particles tend to float toward the surface because the apparent density of the magnetic fluid increases due to the gradient of the magnetic field strength in the vertical direction. Thus, when the measurement in an applied magnetic field is conducted, a magnetic fluid slightly more diluted than that in the experiment for the calibration, the density of which is about 1 040 kg/m³, is used in order to avoid the floating of particles. Even so, it was difficult to

Fig. 10 Distribution of magnetic flux density averaged over half-period of signal

make the measurement with applied magnetic field and we could not avoid reducing the number of samples at one measuring point (50 samples at least). In particular, in the case that the gradient of applied magnetic field was strong or near the bottom of the channel, particles had such a strong tendency to float toward the surface that, ultimately, we could not make the measurement.

Moreover, in order to verify the exactness of the internal flow velocity, the surface velocity within the magnetic field is measured using a surface floating method. A small amount of aluminum powder (300 mesh) is distributed on the surface of magnetic fluid and pictures of their movement are taken through a gauge slit with a charge coupled device (CCD) camera over the channel. After the pictures are recorded in a video recorder, they are replayed frame by frame. The surface velocity is obtained by counting the number of frames during which the powder passes between a scale of the slit.

4.2 Experimental results and discussion

Through observation of the visualized surface of the induced flow, the direction of the flow was found to be opposite to that of the traveling magnetic field. Moreover, in the region where the magnetic field was applied, a small elevation of the surface was observed and the surface velocity was much faster than that in the nonmagnetic field region. It is considered that this flow corresponds to inverse flow near the center of the cylindrical vessel, which was observed in the experiment of the rotational flow of magnetic fluid induced by a rotating magnetic field⁽⁶⁾. This inverse flow is caused because the inverse body force based on the spins of particles is greater than the forward body force based on the gradient of the magnetic field strength.

Figure 11 shows the result of measuring the surface velocity at the center of the region where the magnetic field is applied. It is seen in Fig. 11 that the surface velocity increases with increase in the

Fig. 11 Result of measurement on surface velocity

strength of the magnetic field and is almost proportional to the frequency f or the phase velocity v_p of the traveling magnetic field. Next, the result of measuring the distributions of the local flow velocity is shown in Fig. 12 with the measured surface velocities. In the figure, the velocity V is on the horizontal axis and the distance from the bottom of the channel y , on the vertical axis. Figure 12(a) shows the result of varying the frequency f with fixed induction current $I_0=3\text{ A}$, and Fig. 12(b), of varying the current with fixed frequency. In all cases, the velocity distributions show convex shape, obviously different from the parabolic shapes of the velocity distributions generally observed in laminar nonmagnetic open channel flow. The magnitude of the velocity, in particular, increases greatly with increase in the current near the surface. For stronger magnetic field than in Fig. 12, it was difficult to obtain satisfactory data because of the problem concerning the floating of tracer particles. Figure 13 shows the dimensionless velocity profile, where the velocity V and the distance from the bottom of the channel y are made dimensionless using the traveling velocity of the magnetic field V_p and the depth of the liquid $h(=10\text{ mm})$, respectively. If the experimental uncertainty on each value of the measured data are taken into consideration, each datum almost fits a single curve. Therefore, it can be said that the magnitude of the induced velocity is almost

(a) Effect of magnetic field frequency f

(b) Effect of induction current I_0

Fig. 12 Result of measurement on the distribution of flow velocity

Fig. 13 Distribution of dimensionless velocity

proportional to the frequency or the traveling velocity of the magnetic field at each measuring point.

4.3 Improvement of the measurement technique

In the measurement described in this paper, a semiconductor laser beam, which has longer wavelength and stronger intensity than the He-Ne laser beam, is used. As a result, the penetration length of the beam into magnetic fluid becomes about twice longer than that of the He-Ne laser beam. Therefore it is possible to extend the spacing between the fibers. In the experiment on the calibration of the velocimeter, the velocity of a tracer particle is nearly the same as the flow velocity and the performance of the velocimeter is clearly more improved than that in the previous report. Furthermore, equipment for supplying tracer particles is prepared to cope with the problem of floating tracer particles due to the gradient of magnetic field strength. We have thus succeeded, for the first time, in measuring the distribution of the local flow velocity under the influence of magnetic field. Using this equipment, it is possible to measure the local flow velocity with a smaller amount of tracer particles.

However, in the measurement at the region where the magnetic field is applied, the ratio of the standard deviation of the distribution of measured velocities to the reliable value is about 18% on average and therefore, it is still difficult to pronounce with certainty the establishment of a completely reliable method of measuring the local flow velocity of magnetic fluid in a magnetic field. In particular, the velocity in a stronger magnetic field and near the bottom of the channel could not be obtained. The most difficult problem concerns the floating of particles due to the magnetic field gradient. If smaller tracer particles or bubbles can be used as tracer particles, we may be able to overcome this problem. Furthermore, it takes about one hour or more to conduct the measurement at one measuring point. This is another problem which should be addressed in future research.

5. Conclusions

A new method of determining the local flow velocity of black, opaque magnetic fluid by measuring the velocity of small particles dispersed in the magnetic fluid using a semiconductor laser beam and optical fibers is developed. Improvement and calibration of the measurement system are carried out and it is applied to an open channel flow of magnetic fluid induced by a traveling magnetic field. As a result, we succeed, for the first time, in measuring the velocity distribution of magnetic fluid flow in a magnetic field, and clarifying the shape of the distribution in the region. At the same time, the surface velocity is measured using a surface floating method to verify the measured velocity by means of a velocimeter. The direction of the induced flow is opposite to the traveling direction of the magnetic field. The velocity distribution has a convex shape, and the velocity near the free surface becomes fairly large. The shape of the distribution is quite different from the parabolic shape which is generally observed in the laminar viscous open channel flow. The magnitude of the velocity increases with increase in the strength of the magnetic field and is almost proportional to the frequency of the magnetic field. In the case of stronger magnetic field and near the free surface, the quantitative experimental result cannot be obtained because tracer particles have a strong tendency to float toward the surface due to the increase in apparent density of magnetic fluid. In order to improve this method, it will be important to choose the proper tracer particle and reduce the time needed for measurement.

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