Karman Vortex Probe for the Detection of Molten Metal Surface Flow in Low Velocity Range

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A previously developed Karman vortex probe is equipped with a circular cylinder for the generation and detection of Karman’s vortex streets. This probe is known to be useful for the measurement of the meniscus velocity of molten steel flow in the real continuous casting mold. The detectable velocity ranges from approximately 10 to 70 cm/s. Efforts were devoted in this study to develop a Karman vortex probe capable of measuring a meniscus velocity lower than 10 cm/s. Three kinds of non-circular cylinders were selected to detect the shedding frequency of Karman’s vortex streets in this low velocity range. A triangular cylinder was found to meet this requirement provided that the direction of flow approaching the cylinder is known \textit{a priori}. Accurate measurement was possible for a minimum approaching velocity of 5 cm/s.

KEY WORDS: steelmaking; continuous casting; meniscus flow; velocimeter; Karman’s vortex streets.

1. Introduction

Many kinds of velocimeters have been developed for the measurement of molten metal flow. A hot-film anemometer,\textsuperscript{1,2) }a reaction probe,\textsuperscript{3,4) }a melting probe,\textsuperscript{5) }a Vives probe (magnet probe),\textsuperscript{6) }a non-contact electromagnetic probe,\textsuperscript{7–9) }ultrasonic Doppler velocimetry,\textsuperscript{10) }and a Karman vortex probe\textsuperscript{11–14) }are familiar with researchers and engineers in the steelmaking industries. The hot-film anemometer uses the fact that the heat transfer from a heated film is uniquely related to the velocity of flow approaching the hot-film. The measurement principle of the reaction probe is that the drag force acting on a solid body immersed in a molten metal flow is proportional to the square of the approaching flow velocity. The melting probe relies on the fact that the melting rate of a solid body immersed in a molten metal flow is mainly determined by the approaching flow velocity. The Vives probe and non-contact electromagnetic probe work based on the Faraday law. The ultrasonic Doppler velocimetry, of course, uses the Doppler effect. The Karman vortex probe uses a unique relationship between the shedding frequency of Karman’s vortex streets and the approaching flow velocity.

A reaction probe equipped with a circular cylinder is currently used in the steelmaking industries.\textsuperscript{15) }This probe gives a reliable result when the meniscus flow is steady and the fluctuation of the meniscus level is absent. Once there appears a level fluctuation, it is detected as the meniscus velocity fluctuation even if the amplitude is much less than the immersion depth of the cylinder. An electromagnetic probe developed by Julius \textit{et al.}\textsuperscript{9) }is capable of measuring the velocity of molten steel flow very near the walls of the mold. The detection unit is embedded in the mold wall, and accordingly, it is not suitable for the meniscus velocity measurement. A non-contact electromagnetic probe recently developed by Hiraga \textit{et al.}\textsuperscript{7,8) }also suffers from disturbances originating from the meniscus level fluctuations. The discrimination of the meniscus velocity signal from the output signal including the level fluctuations seems considerably difficult. The remaining hot-film anemometer, melting probe, Vives probe, and ultrasonic Doppler velocimetry are not suitable for the measurements in molten metal baths of a temperature higher than 1 600°C. Recent papers on these probes are listed in Refs. 2), 10), and 16).

At present, a Karman vortex probe seems the most adequate velocimeter for the measurement of the meniscus velocity of molten steel flow in the continuous casting mold, as this probe is hardly influenced by the fluctuation of the meniscus level, a change in the molten steel temperature, and the physical properties of molten steel.\textsuperscript{11–14) }

Previously developed Karman vortex probes are equipped with a circular cylinder for the generation and detection of the Karman’ vortex streets. This is due to the fact that Karman’s vortex streets generated behind a circular cylinder is not sensitive to the direction of flow approaching it. The Karman vortex probe thus developed was applicable to the measurement of a meniscus velocity of molten steel flow ranging from approximately 10 to 70 cm/s. Unfortunately, it could not detect the shedding frequency in a velocity range lower than approximately 10 cm/s. The circular cylinder could not oscillate in such a low velocity range due to low periodical force acting on it. The main objective of this study therefore is to develop a Karman vortex probe capable of measuring a molten metal flow velocity lower than approximately 10 cm/s.
2. Experiment

2.1. Generation and Detection System for the Shedding of Karman’s Vortex Streets

Three kinds of non-circular cylinders, i.e., triangular, semi-circular, and rectangular cylinders were selected to shed Karman’s vortex streets by referring to widely used vortex flow meters.17–19) These cylinders are expected to shed more regular and stable Karman’s vortex streets than a circular cylinder in a low velocity range because they have more than two corners. In addition, these cylinders are made of SiN, and, hence, easy to be produced. The shape, the size, and the cross section of them are shown in Fig. 1.

The length, $D (=10\text{ mm})$, indicated in the figure is used as a representative length. This 10 mm was selected by considering many factors such as the strength and stiffness of the cylinder, the spatial resolution, and erosion. Karman’s vortex streets are known to be shed regularly when the immersion depth of the cylinder is longer than approximately $6D$.11) Accordingly, the length of the vortex generation part of every cylinder was determined to be longer than 60 mm; 100 mm for the triangular cylinder and 140 mm for the semi-circular and rectangular cylinders. The immersion depth was set to be $7D$ (70 mm) in every case. The shape and size of the cylinder above the vortex generation part does not play an essential role for the generation of Karman’s vortex streets. However, they are associated with the natural frequency of the Karman vortex probe. Attention therefore was paid to avoid overlapping of the natural frequency with the shedding frequency of Karman’s vortex streets.

The cylinder was supported by a jig, as shown in Fig. 2. The shedding frequency, $f$, of Karman’s vortex streets was measured with the dynamic strain meter connected to the strain gauges. This supporting and detection system is known to be suitable for the measurement of the meniscus flow velocity of molten steel flow in the real continuous casting mold when a circular cylinder is used. The details of the measurement method are described in the previous papers.11,12)

The angle between the direction of flow approaching the cylinder and the representative orientation of the cylinder was named the attack angle and denoted by $\theta$ (see Fig. 3). In this study the relationship between $\theta$ and the shedding frequency of Karman’s vortex streets, $f$, is investigated to determine which cylinder meets the present requirement most adequately.

2.2. Experimental Apparatus and Procedure

A bird’s-eye view of the experimental apparatus is shown in Fig. 4. One of the cylinders was attached to the rotation arm and then immersed in a molten Wood’s metal bath. The immersion depth was 70 mm as mentioned above. The arm was rotated at a prescribed angular frequency, $\omega$. The bath temperature was 90°C. The density, $\rho$, the kinematic viscosity, $\nu$, and the surface tension, $\sigma$, of the Wood’s metal were 9 560 kg/m$^3$, $0.341 \times 10^{-6}$ m$^2$/s, and 460 mN/m, respectively. In this case mold powder was not placed on the surface of the molten metal. According to the previous experiments,13) the effects of mold powder on the shedding of Karman’s vortex streets is negligibly small.

It should be stressed that the relationship between $f \cdot D$ and the approaching velocity, $V$, obtained for Wood’s metal flow is directly applicable to molten steel flow.12)
3. Experimental Results and Discussion

3.1. Triangular Cylinder

The attack angle, $\theta$, was varied from 0° to 60° with equal intervals of 15°. Karman's vortex streets were shed behind the triangular cylinder for $\theta=0°$ and 15°, but the cylinder did not oscillate in phase with the shedding frequency of the Karman's vortex streets. This is because the pressure difference around the cylinder caused by the shedding of the Karman's vortex streets is not enough to oscillate the cylinder. Accordingly, the shedding frequency was not detectable. The most regular Karman's vortex streets were generated for $\theta=60°$. The relationship between $f \cdot D$ and $V$ for this attack angle (see symbol $\Delta$) was linear, as seen in Fig. 5 and an approaching velocity lower than 10 cm/s could be detected. The measured values of $f \cdot D$ were also predicted by the solid line for a stationary triangular cylinder. The term "stationary" means that the cylinder is rigidly fixed in the flow field. This line was calculated from:

$$St = 0.21 C_D^{-0.622} \quad (1)$$

$$St = f \cdot D / V \quad (2)$$

$$V = R \omega \quad (3)$$

where $St$ is the Strouhal number, $C_D$ is the drag coefficient, and $R$ is the length of the rotation arm. Equation (1) is valid in the following Reynolds number range.

$$10^3 < Re < 10^6 \quad (4)$$

$$Re = VD / \nu \quad (5)$$

where $\nu$ is the kinematic viscosity of liquid. Information on the drag coefficient is available elsewhere. Data on $St$ are available. Data on $C_D$ and $St$ for a stationary triangular cylinder for $\theta=30°$ and 45° are not available as far as the authors are aware.

Such a linear relationship for $\theta=60°$ is beneficial for the accurate detection of a low approaching velocity, $V$. However, the relationship between $f \cdot D$ and $V$ is strongly dependent on the attack angle, $\theta$, because the relationship for $\theta=30°$ is much different from that for $\theta=60°$. Consequently, a triangular cylinder is useful when the direction of flow is known a priori or it is detected simultaneously.

The minimum detectable velocity was approximately 5 cm/s. The Reynolds number is around 1 500 and falls in the applicable range of Eq. (1). The triangular cylinder almost stops oscillating at this velocity. It is difficult at present to predict the minimum detectable velocity because this velocity is a function of the size, shape, and mass of the test cylinder, the configuration of the supporting system in addition to the physical properties of fluids.

3.2. Semi-circular Cylinder

The attack angle, $\theta$, was varied from 0° to 180° with equal intervals of 30°. The semi-circular cylinder was very sensitive to the approaching flow velocity for $\theta=60°$ (see Fig. 6). In other words, the relationship between $f \cdot D$ and $V$ is linear, but the shedding of Karman's vortex streets around this attack angle is significantly influenced by the attack angle, as can be seen from the fact that the relationship for $\theta=30°$ is different from that for $\theta=90°$. The relationship between $f \cdot D$ and $V$ for $\theta=0°$ is nearly the same as that of the circular cylinder. Anyhow, an approaching velocity lower than 10 cm/s could not be detected.

The amplitude of the transverse oscillation of the cylinder became a few times as large as that of the triangular cylinder although the data are not shown here. Such a large
amplitude oscillation is caused because the semi-circular cylinder behaves as if it were an airfoil, i.e., the wing of an airplane. Under this condition, the semi-circular cylinder disturbs the molten metal flow and may be destroyed when it is used for a long time. A semi-circular cylinder therefore is not suitable for practical applications.

3.3. Rectangular Cylinder

The attack angle \( \theta \) was varied from 0° to 45° with equal intervals of 15°. Before carrying out experiments, the authors supposed that a rectangular cylinder would be superior to a circular cylinder. This is because the four corners seem to cause more regular shedding of the Karman’s vortex streets. Unexpectedly, the rectangular cylinder was not so sensitive to the approaching flow, as shown in Fig. 7. The gradient of the \( f \cdot D \) and \( V \) curves for \( \theta = 15°, 30°, \) and 45° are almost equal to that for a circular cylinder.\(^{11-13} \) The drag coefficient required for the calculation of the Strouhal number, \( St \), in Eq. (1) is available for an arbitrary attack angle in a paper by Igarashi et al.\(^{20} \)

In this study a rectangular cylinder of the square cross section was treated. Namely, the length in the longitudinal (flow) direction, \( a \), is equal to that in the transverse direction, \( b \). As the aspect ratio, \( a/b \), is increased beyond unity, the cross section of the cylinder becomes slender in the flow direction. In this case, less accurate result would be obtained because the shedding of Karman’s vortex streets becomes difficult. On the other hand, as the aspect ratio is decreased below unity, the relationship between \( f \cdot D \) and \( V \) would become similar to that of the semi-circular cylinder for \( \theta = 180° \). Anyway, superior results would not be obtained.

3.4. Relationship between \( f \cdot D \) and Attack Angle, \( \theta \)

Figure 8 shows that the relationship between \( f \cdot D \) and the attack angle, \( \theta \), for \( V = 15.3 \) cm/s. A similar relationship was obtained for other \( V \) values, although the evidence is not given here. It is evident that \( f \cdot D \) is most dependent on the attack angle, \( \theta \), for the triangular cylinder.

3.5. Sensitivity of Karman Vortex Probe

As partly described in the previous paper,\(^{12} \) the measured values of \( f \cdot D \) can be approximated by:

\[
f \cdot D = k_1 V + k_2\ 
\]

where \( k_1 \) and \( k_2 \) are constants depending on the shape and size of the cylinder, the cylinder supporting system, the attack angle, and so on. The reason why \( k_1 \) is dependent on the flow direction or the attack angle can be explained by the fact that the drag coefficient, \( C_D \), and, hence, the drag, \( F_D \), are dependent on the flow direction. The coefficient \( k_1 \) is a measure of the sensitivity of the Karman vortex probe. The \( k_1 \) and \( k_2 \) values measured at representative attack angles for the four types of cylinders are shown in Table 1. The \( k_1 \) and \( k_2 \) values for circular cylinders were reproduced from the previous papers.\(^{12,13} \) Table 1 shows that \( k_1 \) is the largest for the triangular cylinder, and, hence, the triangular cylinder is most sensitive to the approaching velocity among the four types of cylinders chosen in this study.

This is because the shedding of Karman’s vortex streets behind a triangular cylinder of an attack angle of 60° is possible even in a low velocity range and the oscillation of the triangular cylinder in the lateral direction is easy compared to another cylinder as can readily be inferred from Fig. 3(a).

3.6. Applicability of Karman Vortex Probe Equipped with Triangular Cylinder for Measurement of Meniscus Velocity of Molten Steel Flow

Figure 9 shows the relationship between \( f \cdot D \) and \( V \) for a circular cylinder of a diameter of 5.6 mm and the triangular cylinder for \( \theta = 60° \). This circular cylinder is currently used in the real continuous casting mold.\(^{14} \) The data for the triangular cylinder were reproduced from Fig. 5. The measured values of \( f \cdot D \) for the circular cylinder are approximated by a straight line which does not pass through the origin, while those for the triangular cylinder can be approximated by a straight line passing through the origin. Similar relationship was observed for other circular cylinders of different diameters.\(^{12,13} \) The gradient of the straight
line for the circular cylinder, \( i.e., k_t \) is smaller than that for the triangular cylinder for \( \theta = 60^{\circ} \). This result means that the accuracy of the velocity measurement using a triangular cylinder is superior to that using a circular cylinder, provided that the direction of flow approaching the triangular cylinder is known. Furthermore, it should be stressed that the triangular cylinder can detect a lower velocity than the circular cylinder, as already shown in Table 1. For an approaching velocity higher than approximately 20 cm/s, the circular cylinder is known. Furthermore, it should be stressed that the direction of flow approaching the triangular cylinder is superior to that using a circular cylinder, providing the accuracy of the velocity measurement using a triangular cylinder is known. The minimum detectable velocity was approximately 5 cm/s.

These findings collectively suggest that a Karman vortex probe equipped with a triangular cylinder can be effectively used in a low velocity range (5 cm/s < \( V < 20 \) cm/s) in the real continuous casting mold as long as the direction of the meniscus flow is known.

From a different point of view, a Karman vortex probe equipped with a triangular cylinder can detect the velocity vector of steady surface flow by searching the direction in which the output signal shows the highest value.

In this study the supporting system of a cylinder and the strain detection unit originally developed for the Karman vortex probe equipped with a circular cylinder were used without any modification, and only the circular cylinder was replaced by a non-circular cylinder. When the supporting system and detection unit are changed, different results may be obtained. Namely, the sensitivity of a Karman vortex probe equipped with a circular cylinder would also be improved by enhancing the supporting system, the strain detection unit, and the diameter of the cylinder. The same is true for the Karman vortex probe equipped with a triangular cylinder. Further investigations are required for the improvement of the sensitivity of the Karman vortex probe.

### 4. Conclusions

Three types of non-circular cylinders were chosen to examine whether or not they could enhance the measurement accuracy of the Karman vortex probe in a low velocity range (\( V < 10 \) cm/s) where the conventional Karman vortex probe equipped with a circular cylinder was not applicable. Among them, a triangular cylinder was found to meet this requirement most adequately as long as the direction of flow approaching the triangular cylinder was known. The minimum detectable velocity was approximately 5 cm/s.

### Nomenclature

\[ C_{Dt} : \text{Drag coefficient (–)} \]
\[ D : \text{Representative length of cylinder (mm)} \]
\[ f : \text{Shedding frequency of Karman’s vortex streets (Hz)} \]
\[ R : \text{Length of rotation arm (mm)} \]
\[ Re : \text{Reynolds number (–)} \]
\[ St : \text{Strouhal number (–)} \]
\[ V : \text{Velocity of flow approaching cylinder (cm/s)} \]
\[ \theta : \text{Attack angle (°)} \]
\[ \omega : \text{Angular frequency of arm rotation (rad/s)} \]
\[ \nu : \text{Kinematic viscosity of liquid (m}^2\text{/s)} \]
\[ \rho : \text{Density of liquid (kg/m}^3\text{)} \]
\[ \sigma : \text{Surface tension of liquid (mN/m)} \]

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