Shielded Hot-wire Viscosity Sensor On-line for a Flowing System Using a Shield of High Thermal Conductivity

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Application of a hot-wire viscosity sensor, which measures the intensity of the natural convection around a hot wire, have been limited to the stagnant systems. For the adaptation of the hot-wire viscosity sensor to flowing systems, the hot-wire viscosity sensor was protected from the effects of the flow by using a stainless steel shield. The shield was normally left open, and was closed only when the measurement was done. Although the hot-wire sensor response was influenced by the flow outside the shield through the high thermal conductivity of the shield material, this effect could be eliminated when the sensor was used at a sufficiently high flow rate outside the shield. The shielded hot-wire sensor responded well to changes in the viscosity of the test fluid in a wide range of viscosity. The effects of the size of the shield and the heat-flux applied on the sensor response were investigated. The shielded hot-wire viscosity sensor was used for the monitoring of the hydrolysis of starch by α-amylase.

Development of on-line viscosity sensors is very important for factory automation in the food and fermentation industries. For the measurement of viscosity, the coaxial dual cylinder viscometer, the capillary viscometer, and the falling-ball viscometer are frequently used. These viscometers basically analyze the stress-strain relationship so that these inevitably have complicated structures with moving part, which makes these meters inconvenient as on-line sensors.

Compared with these viscometers, the hot-wire viscosity sensor has no moving parts and operates in a completely different manner. The hot-wire viscosity sensor, placed vertically in a stagnant fluid, generates a heat flux to induce natural convection around the hot wire, the intensity of which depends on the viscosity of the fluid. As the surface temperature of the hot wire depends on the intensity of the natural convection, the viscosity of the fluid is estimated from the surface temperature of the hot wire provided that the physical properties of the test fluid other than viscosity are kept constant.

The hot-wire viscosity sensor is useful for the viscosity monitoring of dilute polymer solutions with changes in the concentration or the viscosity monitoring of the solution system accompanying processes such as hydrolysis or polymerization because major changes in the physical properties occur only in viscosity in these cases.

The hot-wire viscosity sensor was first proposed by Hori1) and now it is used in the control of the milk-clotting step in cheese-making. Our group3) analyzed the basic principle of the hot-wire viscosity sensor theoretically by applying the stagnant layer analysis3) around a vertical cylinder combined with the heat-transfer theory of natural convection from a vertical plate.4,5)

Although the hot-wire viscosity sensor is convenient for the measurement of the viscosity of a stagnant fluid, it cannot be applied to flowing systems because the temperature of the hot-wire sensor is influenced both by the natural convection and by the forced convection in the flowing system. In an earlier paper,6) we used a hot-wire viscosity sensor in a nonbaffled, agitated vessel. In this case, the flow in the vessel was described well by the compound vortex model.7) Kramers’ equation8) could be used to describe the formed-convection heat-transfer from the hot wire and to relate the sensor response to the viscosity of the fluid in the vessel.

Although this is an effective attempt for the adaptation of the hot-wire sensor to the flowing system, this approach is limited to systems with known flow properties. For the general adaptation of the hot-wire viscosity sensor to flowing systems, we used a shield with a low thermal conductivity to protect the sensor response from the effects of the flow, in our preceding paper.9) In this case, the sensor behavior was completely protected from the effects of the flow outside the shield as the shield functioned as an adiabatic wall in the heat conduction process from the hot wire to the flowing system. In this case, however, no thermal steady state was obtained in the sensor response because of the accumulation of the heat generated in the space surrounded by the shield so that a special technique was necessary to relate the sensor response to the change in the viscosity of the test fluid.

In this paper, the hot-wire viscosity sensor shielded with a material of high thermal conductivity is proposed for the adaptation of hot-wire viscosity sensor to the flowing system. Because of the high thermal conductivity of the shield material, a steady-state sensor-response is expected so that the interpretation of the sensor response to the viscosity will be much easier than when using a shield of low thermal conductivity. The operating conditions necessary for the elimination of the effects of the flow outside
the shield will be investigated. The shielded hot-wire viscosity sensor is used for the measurement of the viscosity of a test solution containing carboxymethyl cellulose sodium (CMC) and also for viscosity monitoring in starch hydrolysis by α-amylase.

Materials and Methods

Materials. CMC (n=500) was purchased from Tokyo Kasei Kogyo. Potato starch was obtained from Kanto Chemical. α-Amylase was from Nagase Biochemicals.

Hot-wire viscosity sensor with a stainless steel shield. A platinum hot-wire viscosity sensor sheathed by stainless steel, 170 mm long, 3.5 mm in diameter, with the length of heating section of 30 mm was used combined with a cylindrical stainless steel shield as shown in Fig. 1. The length of the shield was 120 mm and the heater section was at the center in the shield. The inner diameter of the shield used was 11, 21, or 29 mm. The shield was composed of two coaxial half-cylinders so that the control of the state of the shield, open or closed, was easily done. The shielded hot-wire viscosity sensor was immersed in an agitator vessel 200 mm deep, 220 mm in diameter, which was placed in a temperature-controlled water bath. A flat blade paddle was used for agitation, the speed of which was controlled (Heidon 1200R). The shield was normally open and was closed only when the measurement was being done.

Measuring system. The measuring system was composed of a computer (Hewlett Packard 9112), a power source (Hewlett Packard 6634A), a data logger (Hewlett Packard 3852A), the hot-wire sensor, and a standard resistance (Yokogawa Type 2792; 0.1Ω) connected to the hot wire in series.

A hot-wire viscosity sensor measures the temperature difference between the hot wire and the ambient fluid. Because the platinum hot wire functions as a resistance thermometer, temperature measurement was done from the electric resistance of the hot wire itself. For the measurement of the temperature of the ambient fluid (Ta), a current at a weak level (1 mA) was applied. In this case, the thermal energy generated from the hot wire was negligible so that the temperature of the sensor was expected to be equal to Ta. Then, a higher current (typically about 1A) for the generation of heat was applied to the hot-wire. The exact level of the current was controlled by the computer to keep a constant level of heat flux. The change in the hot-wire temperature (ΔT) was measured and the temperature difference (ΔT) between Ta and Tc was calculated and recorded by the computer.

Test fluid and measurement of viscosity. A solution of CMC was used as the test fluid of the shielded hot-wire viscosity sensor. Measurement of the viscosity was done by a cone-plate viscometer (Tokimec Inc., type EL). Newtonianity of the test fluid was examined from the measurement of the viscosity under various shear rates in the range of this investigation.

Monitoring of the hydrolysis of potato starch. A potato starch suspension of 1.25 wt% in 6 liters vessel was heated up to 70°C for gelatination then cooled down to 40°C. To this, 1.2 mg of α-amylase was added to start the hydrolysis reaction, which was monitored by the shielded hot-wire viscosity sensor with agitation at 600 rpm. The shield was repeatedly opened and closed at intervals of about two minutes.

Results and Discussion

Figure 2 shows the dependence of the sensor response on the state of the shield, opened or closed, with water as a test fluid. When the shield was opened, the thermal steady state in the sensor response was reached in a minute. The sensor response, however, was strongly dependent on the speed of agitation because of the direct effect of the forced convection by the flow on the heat transfer around the hot wire. On the contrary, the effects of the agitation on the sensor response were very weak when the shield was closed.

The effects of the agitation on the steady state of the sensor response with shield closed are shown in Fig. 3. When the speed of agitation is higher than 300 rpm, the effects of the agitation disappeared. This suggests that the heat-transfer resistance outside the shield can be negligible compared with that inside the shield when the speed of the agitation is high enough. Thus, the effects of the flow outside the shield were eliminated so that the hot-wire sensor is expected to be usable in flowing systems.

Before testing the shielded hot-wire viscosity sensor, the flowing properties of CMC solution were measured as shown in Fig. 4. In a wide range in concentration, the shear stress was proportional to the shear rate for the CMC solution, showing that the solution is a Newtonian fluid. Figure 5 shows the dependence of the viscosity on the concentration of CMC.

A typical response of the shielded hot-wire viscosity
sensor is shown in Fig. 6 with CMC solution as a test fluid using a 21 mmφ shield. The response time of the sensor was less than three minutes and the sensor response was dependent on the viscosity of the test fluid. Figure 7 shows the dependence of the steady-state sensor response on the viscosity of the test fluid. In a wide range in viscosity between 1 to 1600 mPa·s, the shielded hot-wire viscosity sensor responded well to the change in the viscosity of the test fluid. The sensor response to viscosity was described well by the following equation with a correlation coefficient of 0.997.

\[ \Delta T = a + b(\log \mu) \]  

(1)

In Fig. 7, the response of the shielded sensor in a flow system is compared with that of the non-shielded sensor used in a stagnant system (broken line). The difference between the two is not large, showing that the space surrounded by the shield was wide enough to make the wall effect of the shield not serious in this case. For the stagnant case without shield, the response of the hot-wire viscosity sensor has been described theoretically by the following equations.\(^2\)

\[ N_u = \frac{L/r_0}{\log\left(1 + \frac{L/r_0}{N_u_p}\right)} \]  

(2)

\[ N_u_p = 0.638 Gr^{1/4} Pr^{1/4} \left(\frac{Pr}{0.861 + Pr}\right)^{1/4} \]  

(3)

where \( N_u \) and \( N_u_p \) are Nusselt numbers for a vertical cylinder and a vertical plate, respectively, \( Gr \) is the Grashof number, \( Pr \) is the Prandtl number, \( L \) is the length of the hot wire, and \( r_0 \) is the radius of the hot wire. Thus, the response of the hot-wire viscosity sensor without shield in a stagnant system is dependent on the viscosity, density, heat capacity, thermal conductivity, and volumetric expansion coefficient of the test fluid. Fortunately, the changes in the physical properties other than viscosity were not substantial compared with that of viscosity in many food processes where the control of viscosity is important. In this case, the response of the hot-wire viscosity sensor is practically dependent only on viscosity. The same principle is expected to be applicable to the shielded hot-wire viscosity sensor.

The effects of the size of the shield were studied with the inner diameter varied from 11 mm to 29 mm. With an 11 mmφ shield, the viscosity range of the sensor response became very narrow, typically from 1 to 100 mPa·s, because the wall effect through the narrow space surrounded by the shield strongly inhibited the free convection flow inside the shield. With a 29 mmφ shield, the response time for the steady state became very long because of the large heat capacity of the fluid in the space surrounded by the shield. Thus, the hot-wire sensor with a 21 mm shield gave
Fig. 8. Monitoring of the Starch Hydrolysis Process with α-Amylase by Using the Shielded Hot-wire Viscosity Sensor.

the best results with a wide response range in the viscosity along with a short response time.

The effects of the heat flux from the hot wire on the sensor response were examined. The higher heat flux gave a higher sensitivity with a short response time. The higher heat flux, however, gave a higher surface temperature to the hot wire so that the measured viscosity of the test fluid might to affected by the temperature of the hot-wire itself. Therefore, a heat flux of 5W was used.

The shielded hot-wire viscosity sensor was used to monitor the hydrolysis of potato starch by α-amylase. The results are shown in Fig. 8. With the shielded hot-wire sensor immersed in the gelatinized starch solution, the shield was repeatedly closed and opened to monitor the hydrolysis process of starch by α-amylase in a stirred vessel. Before the addition of α-amylase, the steady state sensor response was about 90°C. Immediately after the addition of α-amylase, the steady state sensor response began to decrease until the whole process of hydrolysis ended about 5000 sec after the start of the hydrolysis.

The major drawback of the hot-wire viscosity sensor has been its limited applicability, only to stagnant systems. In this paper, the hot-wire viscosity sensor was equipped with a shield of high thermal conductivity so that the hot-wire sensor could be adapted to the flowing system. Compared with the case with a shield of low thermal conductivity, a thermal steady state was obtained in the sensor response. Because of this, this method with a shield of high thermal conductivity was easier to use than the case with a shield of low thermal conductivity.

A hot-wire viscosity sensor has strong points in its simple structure with no moving parts and a wide coverage in the viscosity range with a single sensor element. The shielded hot-wire viscosity sensor, described in this paper, extended the applicability of the hot-wire viscosity sensor from stagnant to flowing systems. Thus, this technique is expected to be widely used as an on-line sensor in the food and fermentation industries.

References