A New Sensor for Temperature Measurement of Water by Laser Interferometry Technique

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Abstract

We previously developed a temperature measurement system using interferometry and used it to measure unburned gas temperature in an engine cylinder. In this study, a new sensor is proposed to determine water temperature. This sensor utilizes the difference in measurement length between two laser beams. Both are the test beams, and there is no reference beam. The two beams pass mostly through equal or closely arranged paths; therefore, the effect of mechanical vibration on the two test beams is expected to be very small. The laser beam was introduced through a selfoc micro lens (SML) into a polarization-maintaining fiber connected with a sensor part. The beam emitted from another SML was divided into two. Both beams enter a quartz block and are reflected at the corner to change direction by an angle of $\pi/4$. They then pass through the test section although the lengths of the two beams are different in the measurement region.

This sensor was installed on a side wall of a vessel. Water was poured into the vessel and stirred with a hot magnetic stirrer. The temperature near the sensor was also measured with a thermocouple as a reference. The response of the thermocouple was enough to follow the change in water temperature because the speed of change in temperature is very slow. This paper focuses on the confirmation and evaluation of this system of temperature measurement. One feature of this sensor is that it minimizes the effect of the thermal boundary layer. If the condition of the fluid near the test section is uniform, both beams have almost the same boundary layers. Then, both thermal boundary layers are expected to be cancelled because the length of the test section is the difference between both beams. The interference signals changed periodically with time as the temperature increased. The effect of the measurement length was investigated with three types of sensors. The measurement lengths were 1.0, 2.0, and 3.0 mm. When the measurement length was changed, the temperature measured with this system agreed well with that measured with a thermocouple.

It was confirmed that this sensor system is useful for detecting changes in water temperature. It is expected that this optical system is strong enough to apply to both laboratory and industrial use in future.

1. Introduction

There are several methods of determining the temperature of a gas or liquid. Thermocouples and thermistors are often used in industry and research for measuring temperatures that change slowly because of their slow response times. Some laser techniques, such as laser-induced fluorescence, are used for temperature measurement with very high response times (Eckbreth 1996). However, expensive and large facilities are required with optical windows.

On the other hand, interferometry is sometimes used for measuring temperature with a fiber as a sensor (Kilpatrick 2002, Othonos and Kalli 1999). However, these methods depend on the thermal conductivity from the outside fluid to the fiber, so that the response is limited. As for non-intrusive methods, interferometry has often been applied to the precise measurement of length under the condition of constant temperature. Conversely, temperature is measured when the length is constant without depending on thermal conductivity. Some interferometer systems, such as the Mach–Zehnder type, allow the measurement of temperature fields on a table with preventing mechanical vibrations from the surroundings. However, as long as these systems are used, local temperature cannot practicably be obtained in situations where there is mechanical vibration.

Garforth (1976) used modified Michelson interferometry to measure the transient density in the unburned gas region of a spherical combustion chamber, and obtained the transient gas temperature from the equation of state and pressure data. Hamamoto *et al*. (1989) measured the unsteady temperature change of a gas during compression and expansion using Mach–Zehnder interferometry. Achasov *et al*. (1993) used applied Michelson interferometry in a constant-volume combustion chamber. They encountered difficulties because the measurements are usually sensitive to mechanical vibration. Hamamoto *et al*. (1994) and Tomita *et al*. (1994, 2000) addressed some of these problems; they used modified Mach-Zehnder interferometry with polarization-preserving fibers and Köster prisms to measure the temperature change of a compressed unburned gas during flame propagation and to investigate the knocking phenomenon. On the other hand, heterodyne interferometry is fairly insensitive to the fluctuations in signal intensity caused by mechanical vibration, and is therefore often used to measure vibration. We previously developed a fiber-optic heterodyne interferometry system using interferometry and used it to measure the temperature of unburned gas in an engine cylinder with a small sensor installed with optics (Kawahara et al. 2001, 2002-a, b, c, 2003, 2004, 2005). The temperature of the unburned mixture in the end-gas region of a constant-volume combustion chamber was measured, and the accuracy of the measurements was discussed. The temperature history of the unburned end-gas in an engine cylinder was measured during flame propagation and the feasibility of this system was also discussed. However, mechanical vibration has still been one of the more serious problems for measurement with interferometry.

In this study, a new sensor is proposed to determine fluid temperature. At first, water temperature was measured with a new sensor using interferometry. The temperature measurement of liquid is important in industries, e.g., for controlling the temperature for the sterilization or pasteurization of milk, juice, etc. This sensor utilizes the difference in measurement length between two laser beams. Both the beams are test beams, and there is no reference beam. The two beams pass mostly through equal or closely arranged paths; therefore, the effect of mechanical vibration on the sensor is expected to be very small.

2. Measurements

When the density of water varies because of temperature changes, its refractive index also varies. The relationship between the refractive index, n, and density, ρ, is expressed by the Lorenz-Lorentz equation (Gardiner *et al*. 1980),

$$R_{\mathrm{L}} = (n^2 - 1) / \{(n^2 + 2)\rho / M\}, \tag{1}$$

where M and R_{L} denote the molecular weight and molar refractivity, respectively. There are many papers on molar refractivity of salt water, i.e., sea water. Molar refractivity without salt is almost constant for temperature, as shown in Fig.1 (Schiebener *et al*. 1990, Quan and Fry 1995). In general, molar refractivity is a function of wavelength.

Equation (1) can be rewritten as follows:

$$n = \{(1 + 2\rho R_{\mathrm{L}} / M)/(1 - \rho R_{\mathrm{L}} / M)\}^{1/2} \tag{2}$$

When the difference between the optical paths of the test and reference beams varies, the interference light intensity corresponds to changes in the refractive index of water. The interference signal changes according to

$$N = \Delta L / \lambda = d\Delta n / \lambda = d(n - n_0) / \lambda, \tag{3}$$

where N, L, λ and d denote the fringe number, optical path, wavelength of the laser used and length of the test section, respectively. Equation (3) can be used to obtain the refractive index as follows:

$$n = N\lambda / d + n_0 = N\lambda / d + \{(1 + 2\rho_0 R_L / M)/(1 - \rho_0 R_L / M\}^{1/2}. \qquad (4)$$

Equation (4) can be rewritten with n_0 obtained from Eq. (2):

$$N\lambda / d = \{(1 + 2\rho R_L / M)/(1 - \rho R_L / M)\}^{1/2} - \{(1 + 2\rho_0 R_L / M) / (1 - \rho_0 R_L / M)\}^{1/2}. \qquad (5)$$

This equation gives the relation between the number of fringe shifts and the density of the fluid. Therefore, one can obtain the temperature of the fluid from the relation between the density and temperature, as shown in Fig.2.

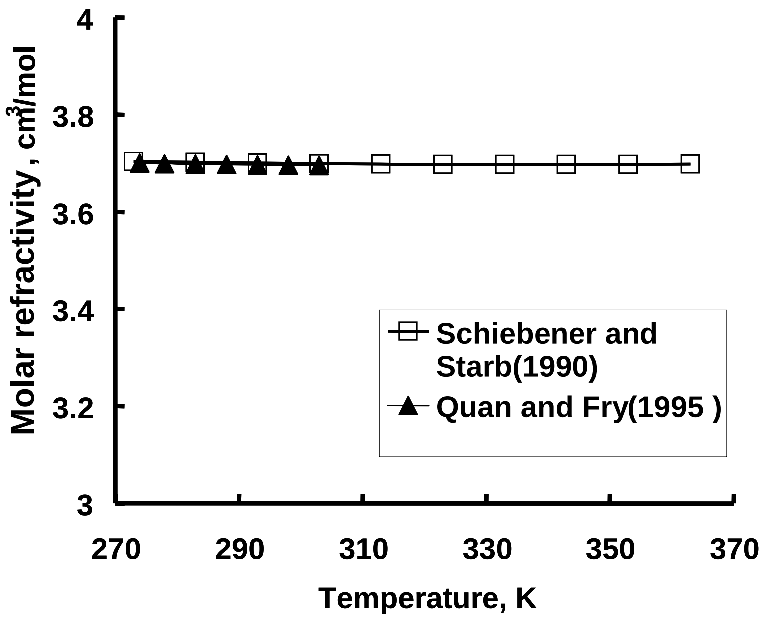

Fig. 1 Effect of temperature on molar refractivity

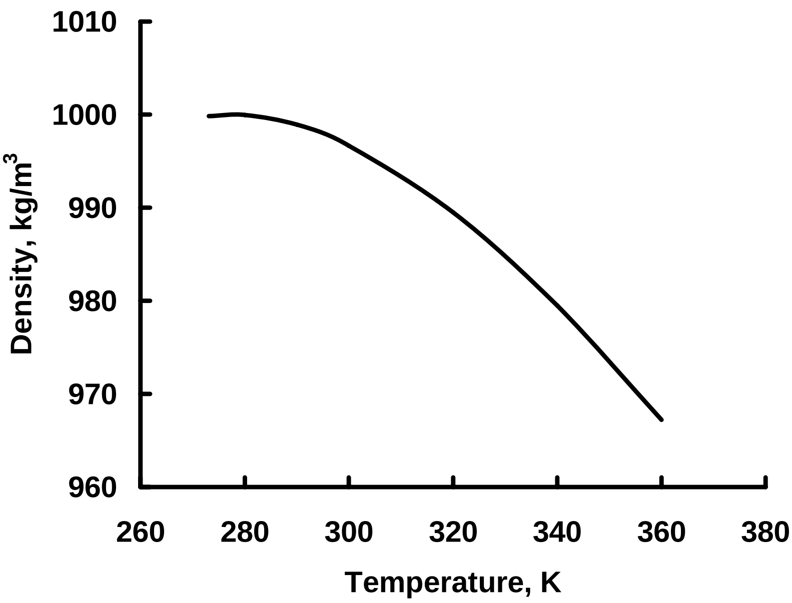

Fig. 2 Relation between density and temperature for water

3. Experimental apparatus and optical arrangement

Figure 3 shows a schematic diagram of the experimental apparatus and optical system. A helium-neon laser with a wavelength of 632.8 nm was used as a light source. The laser beam was introduced through a selfoc micro lens (SML) into a polarization-maintaining fiber connected to a sensor part. The beam emitted from another SML connected to the fiber was divided into two using a beam splitter and a mirror. The edges of a quartz block were cut at an angle of $\pi/8$ to introduce the laser beams into the test section. Both beams enter the quartz block and are reflected at the corner through an angle of $\pi/4$. They pass through the test section, although the lengths of the two beams are different. Here, the length of the test section, d, is expressed as the difference between the lengths of the two beams.

$$d = d_1 - d_2 \tag{6}$$

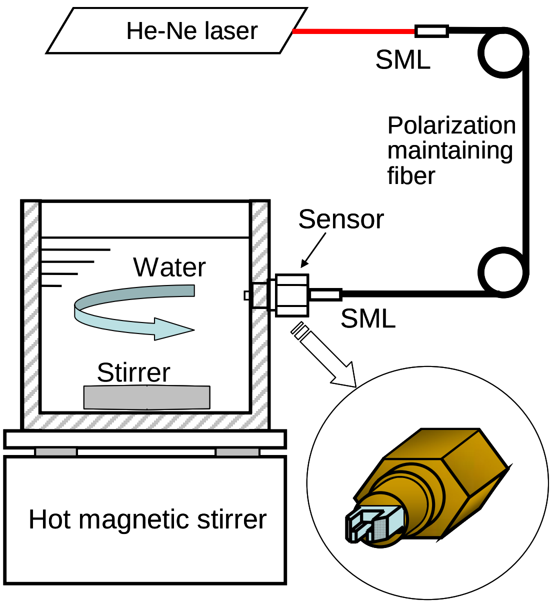

Fig. 3 Schematic diagram of experimental apparatus and optical system

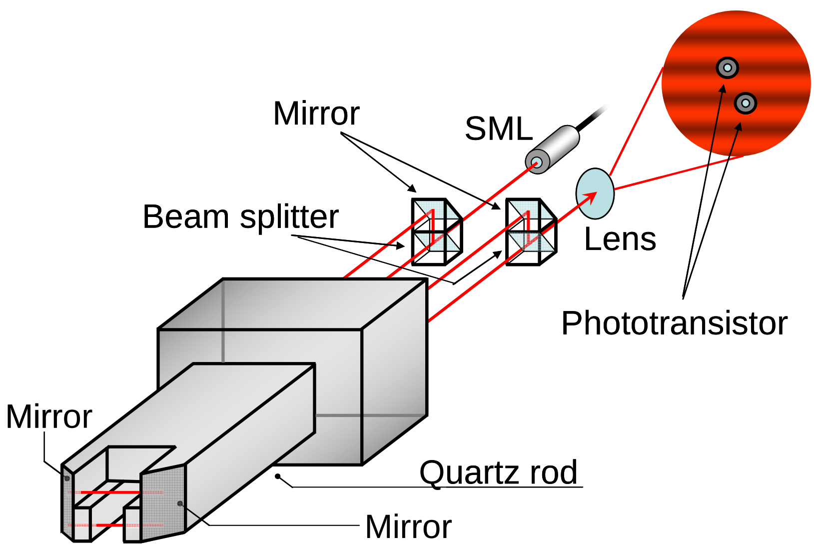

Fig. 4 Optical arrangement in the sensor and method for detecting interference fringes

Both beams enter the quartz block again and are reflected at the corner through an angle of $\pi/4$. After emerging from the quartz block, the two beams are made to interfere using a mirror and a beam splitter.

By adjusting the optical parts for the laser beams, interference fringes can be made easily. The interference fringe was expanded with a convex lens and the light intensities of the fringes were detected with two phototransistors, to obtain the interference signals. Here, two detectors were placed at a certain location, where the intensity of one light beam is $\lambda/4$ apart from the other, as shown in Fig. 4.

This sensor was installed on a side wall of a vessel. Water was poured into the vessel and stirred with a hot magnetic stirrer, as shown in Fig. 3. The water temperature was increased with a heater. The temperature near the sensor was also measured with a K-type thermocouple as a reference. In this study, the response of the thermocouple is enough to follow the change in water temperature because the rate of change in temperature is very slow. This paper focuses on the confirmation and evaluation of this system of temperature measurement.

Another feature of this sensor is that it minimizes the effect of the thermal boundary layer. If the condition of the fluid near the test section is almost the same, both beams have almost the same boundary layers. It is expected that both thermal boundary layers are cancelled out because the length of the test section is the difference between both beams.

4. Results

First, a difference of 2.05 mm for the measurement length was prepared to perform the experiment. Figure 5 shows a test result obtained from this optical system. Both interference signals changed periodically with time when the temperature increased. Data were obtained for only one experimental run. Only the top and the bottom of the interference signal were analyzed here. As shown in Fig. 6, the temperature obtained from this interferometry system presents a good agreement with the temperature determined with a thermocouple. As a result, it was confirmed that this measurement system is useful for detecting water temperature. The measurement response (of the order of microseconds) depends on the performance of the detector, although the water

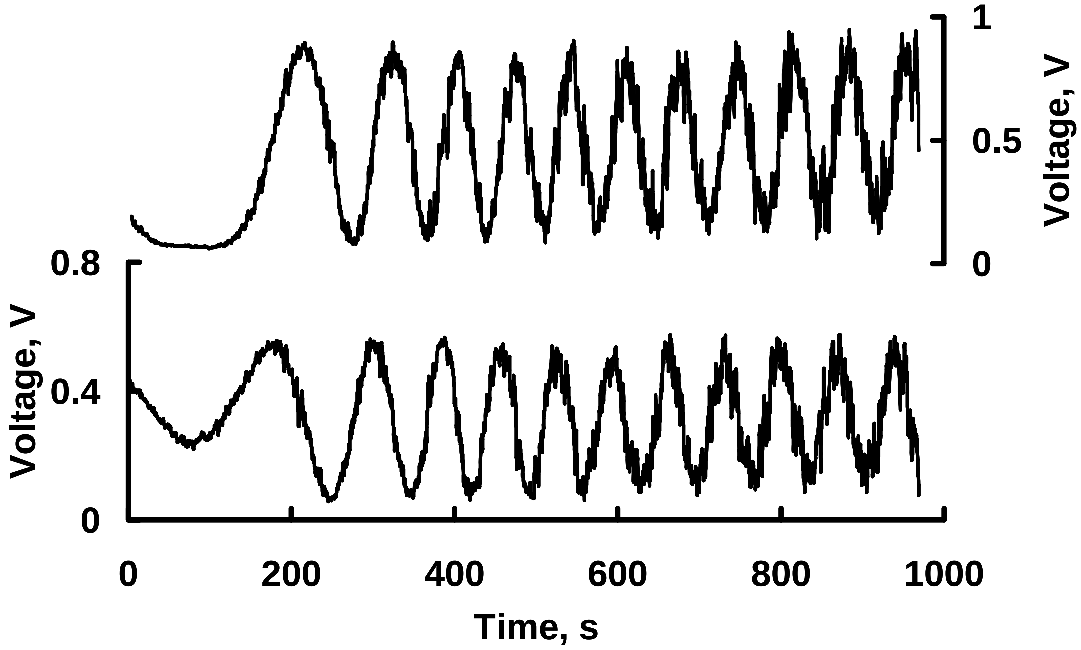

Fig. 5 Interference signals obtained from two detectors

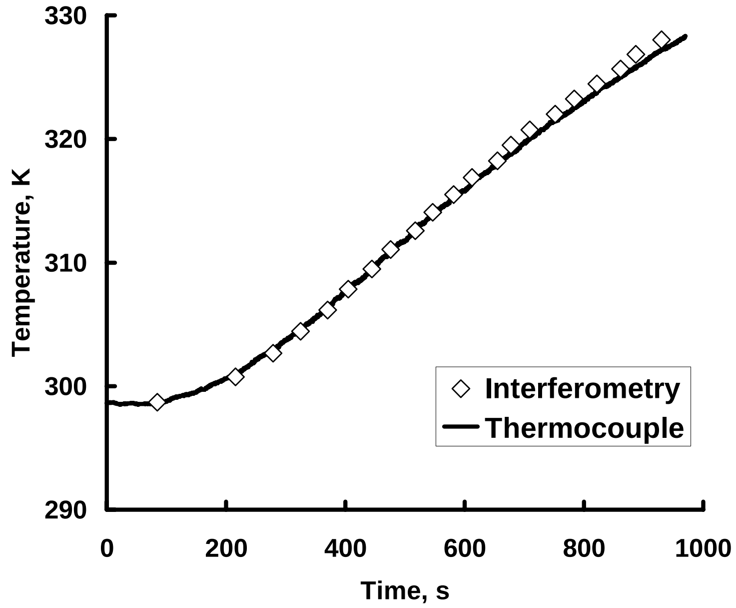

Fig. 6 Temperature determined from the interferometry system and from a thermocouple

temperature does not change rapidly in this case. Therefore, it is expected that this system can be used to detect temperature fluctuations with high response times.

When the temperature increased, the signal fluctuated gradually. The top and bottom of the signal were clearly distinguished and analyzed. Here, the signals were normalized to analyze the temperature in detail.

The intensities of the electromagnetic waves of the two beams are expressed as

$$E_1 = E_{01}\exp\{\mathrm{j}(2\pi f_1 t + k_1 L_1)\} \tag{7}$$

$$E_2 = E_{02}\exp\{\mathrm{j}(2\pi f_2 t + k_2 L_2)\} \tag{8}$$

where $\mathrm{j} = \sqrt{-1}$, and E_0, k, L, f, and t denote the wave amplitude, wave number ($=2\pi/\lambda$), optical path, frequency and time, respectively; subscripts 1 and 2 denote beams 1 and 2, respectively. When two beams interfere, the intensity of interference light is

$$\begin{aligned} I &= |E_1+E_2|^2 \\ &= E_1E_1^* + E_2E_2^* + E_1E_2^* + E_2E_1^* \\ &= E_{01}^2 + E_{02}^2 + 2E_{01}E_{02}\cos\{2\pi(f_1 - f_2)t + (k_1L_1 - k_2L_2)\} \end{aligned} \tag{9}$$

where the asterisk (*) denotes a complex conjugate. When a laser is used, f and k are the same; thus,

$$I = E_{01}^2 + E_{02}^2 + 2E_{01}E_{02}\cos\{k(L_1 - L_2)\}. \tag{10}$$

The interference signal exhibits a cosine curve because the first and the second terms are constant. Therefore, when the phase shift of the signal is determined, the successive temperature is obtained. Figure 7 shows the comparison of temperature determined from the interferometry to the temperature from thermocouple. The value of root-mean-square for its variation is presented in Fig.8. Here, the period for moving average of the data was changed from 10 s to 50 s. As the period

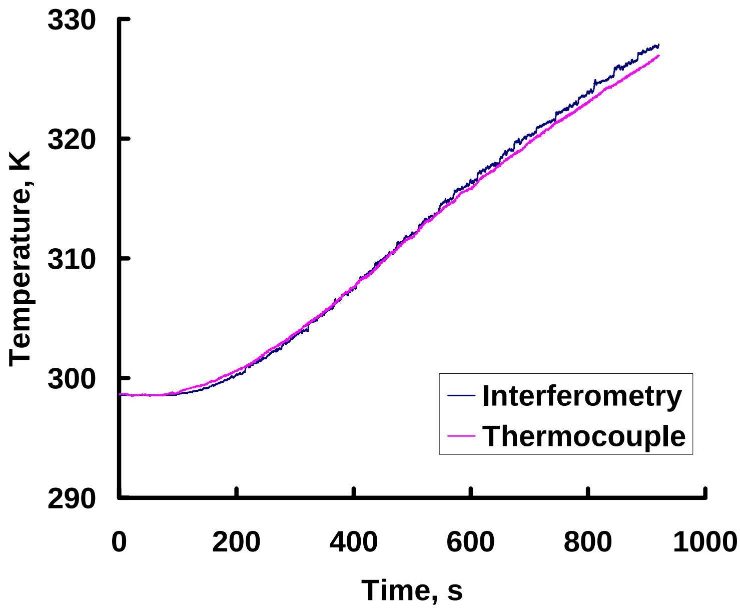

Fig. 7 Temperature determined from the interferometry system and from a thermocouple

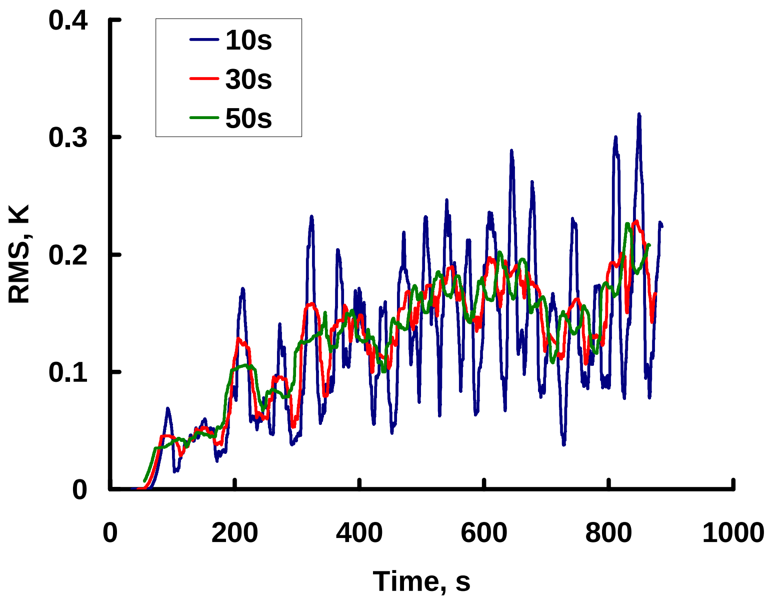

Fig. 8 Fluctuation of temperature

was long, the trend of RMS value was found more easily because the fluctuation of the RMS became small. The variation of the temperature increased at higher temperatures because the convective movement of water becomes stronger as the temperature increases. Interferometric methods give an averaged temperature along the line of sight to be measured. And two beams are used for the test beams in this study. Therefore, it is considered that the mean temperature along the test beams fluctuates and inhomogeneity of temperature along the beams and between the two beams becomes larger as the water temperature increases.

In this study, the difference length was changed to evaluate the measurement system, as shown in Fig. 9. In order to investigate the effect of the measurement length, *d*, three types of sensors were prepared as shown in Fig.9. Measurement lengths of 1.0, 2.0, and 3.0 mm were obtained by attaching one or two quartz plates of thickness 1.0 mm or 1.5 mm. Figure 10 presents the measurement results of the interference signal and the temperature obtained from this interferometry method and the thermocouple. Here, the interference signal detected from only one phototransistor was analyzed because the density changed monotonously. When the measurement length was set to 1.0 mm, the change in interference signal was slow. On the other hand, when the measurement length was set to 3.0 mm, the change in the signal became faster. The temperature determined from this interferometry system agreed very well with that determined with the thermocouple for all cases. For d = 3.0 mm, the intensity of the signal decreased gradually after 800 seconds because there were a lot of bubbles, which could be seen near the measurement region. This fact led to a decay in the laser beam intensity although the crests and troughs of the signal could be recognized. The intensity of the signal was weaker for d = 2.0 mm, when the adjustment of the optical parts was not accurate. However, the data could be read adequately.

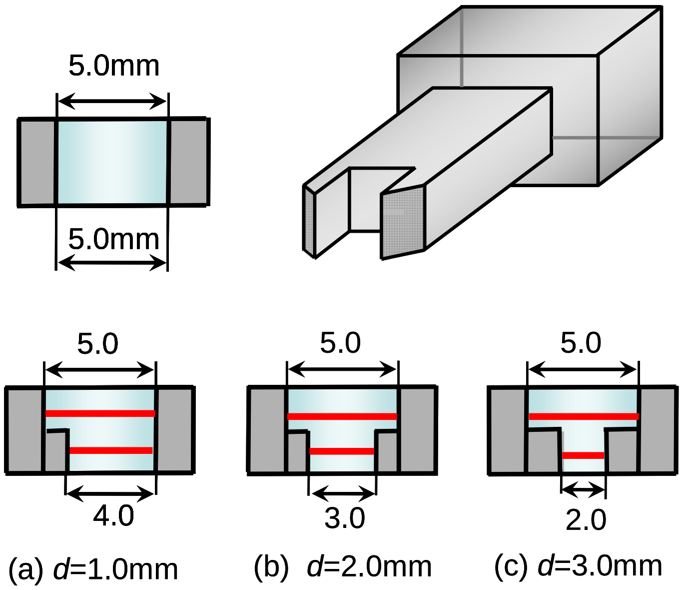

Fig. 9 Measurement length. Four different measurement lengths were tested: (a) 1.0 mm, (b) 2.0 mm, and (c) 3.0 mm.

5. Summary

A new sensor for fluid temperature measurement using interferometry was developed. Water temperature measured with this sensor agreed well with that obtained using a thermocouple. It was confirmed that this sensor system is useful in detecting changes in fluid temperature. One of the features of this sensor is that it uses almost the same paths for two beams so that the vibration of the fiber does not affect the interference signals. Another feature of this system is that it minimizes the effect of the thermal boundary layer. It is expected that this optical system is strong enough to apply not only to laboratory use but also to industrial use in future.

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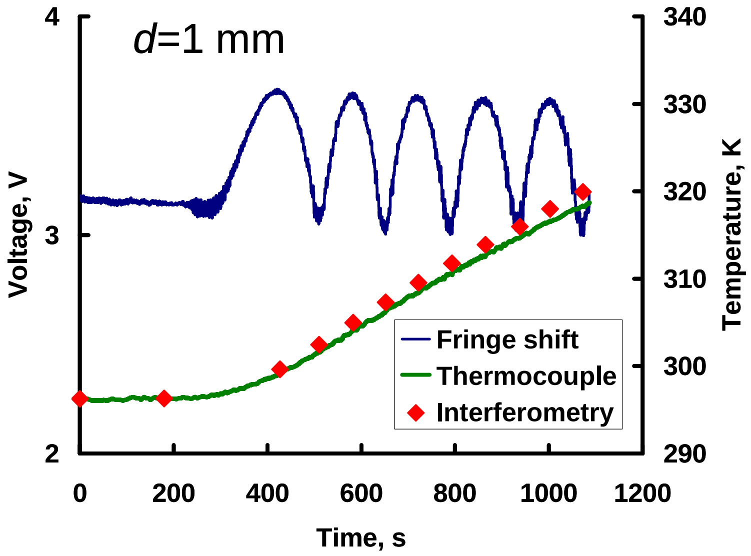
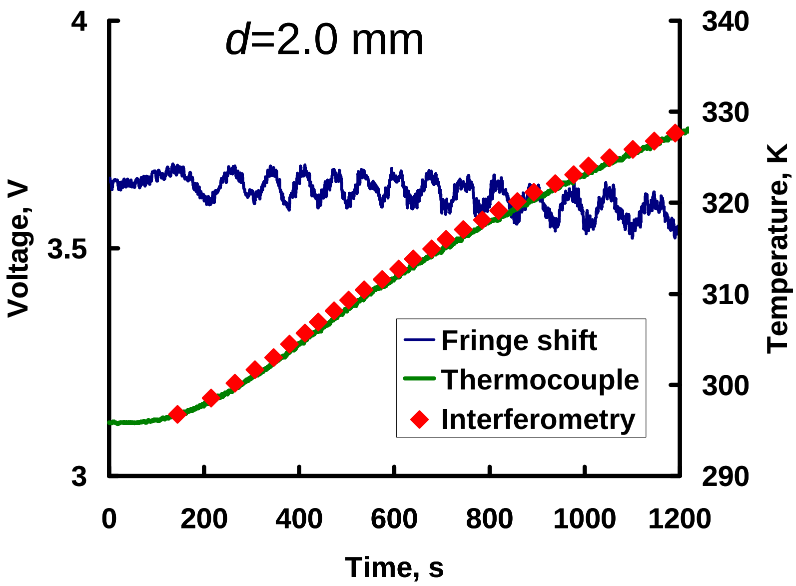
(a) *d*=1.0 mm



(b) *d*=2.0 mm



(c) *d*=3.0mm

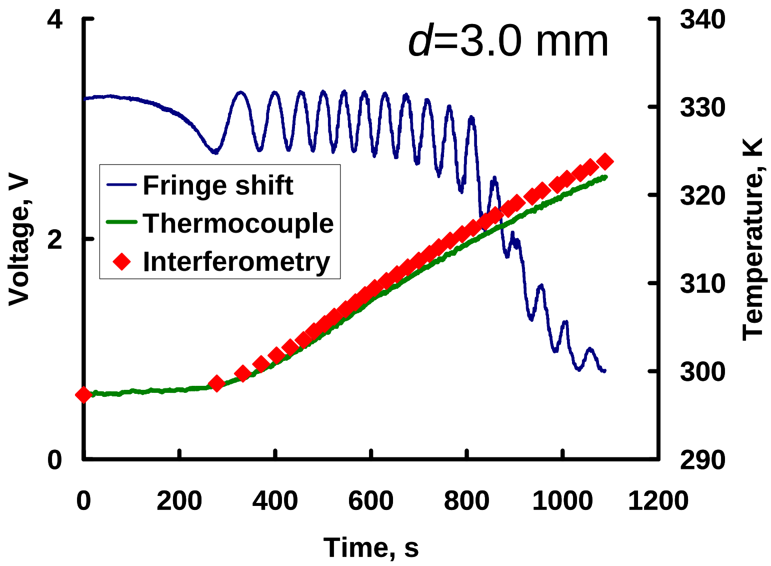


Fig. 10 Interference signal and temperature determined from the interferometry system and from a thermocouple for four different measurement lengths.

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