Temperature Measurement of Water with a Sensor by Laser Interferometry Technique

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Abstract

This sensor utilizes the difference in measurement length between two laser beams in the fluid. Both are the test beams, and there is no reference beam. If the condition of the fluid near the test section is uniform, both beams have almost the same boundary layers on the sensor surface. The two beams pass mostly through equal or closely arranged paths; therefore, the effect of thermal boundary layer on the sensor surface is expected to be cancelled because the length of the test section is the difference between both beams. 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. In this study, the water temperature was decreased at first and increased. After that the temperature was decreased again. And the interference signal was compensated, so that successive change of the temperature was determined. When the measurement length was changed, the temperature measured with this system agreed well with that measured with a thermocouple. Consequently, 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

Temperature measurement of fluid is required in the field of thermal fluid flow. 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 (LIF), Raman scattering or coherent anti-Stokes Raman spectroscopy (CARS), 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 well as a thermocouple and a thermistor. As for non-intrusive methods, interferometry has often been applied to the precise measurement of length under the condition of constant temperature. Conversely, fluid temperature is measured when the length is constant. 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.

At first, 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 unburned 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. The gas temperature was discussed in a homogeneous charge compression ignition (HCCI) engine (Lee et al. 2007). However, mechanical vibration has still been one of the serious problems for measurement with interferometry.

The temperature measurement of liquid is important in industries, e.g., for controlling the temperature for the sterilization or pasteurization of milk, juice and for chemical plant, etc. In previous study, a new sensor was proposed to determine fluid temperature. At first, water temperature was measured with a new sensor using interferometry (Tomita 2006, 2007). 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 thermal boundary layer on the sensor surface is expected to be negligible. In the previous papers, the temperature was not obtained successively because only the peaks of the signal were read out. In this study, the method for determining successive temperature is explained. This sensor is just a concept one because the two beams are 2mm apart from each other. So if the two beams are very close, it would be a new sensor for temperature measurement for fluid flow of gas and liquid with fast response.

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, \( \rho \), is expressed by the Lorenz-Lorentz equation (Gardiner et al. 1980),

\[
R_L = \frac{(n^2 - 1)}{(n^2 + 2)\rho / M},
\]

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:

\[ n = \frac{1}{2} \frac{(1 + 2\rho R_L / M)}{(1 - \rho R_L / M)} \]

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

\[ N = \frac{\Delta L}{\lambda} = d \Delta n / \lambda = d(n - n_0) / \lambda, \]  

(3)

where \( N, L, \lambda \) 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:

\[ n = \frac{N \lambda}{d} + n_0. \]  

(4)

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

\[ \frac{N \lambda}{d} = \left( \frac{1 + 2 \rho R L/M}{1 - \rho R L/M} \right)^{1/2} - \left( \frac{1 + 2 \rho_0 R L/M}{1 - \rho_0 R L/M} \right)^{1/2}. \]  

(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.

3. Experimental apparatus and optical arrangement

The schematic of experimental apparatus and the procedure were described in the reference (Tomita 2006, 2007). Therefore, these are stated briefly in this chapter. 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. 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
Figure 2 Relation between density and temperature for water

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.

Figure 3 Schematic diagram of experimental apparatus

Figure 4 shows schematic diagram of optical arrangement in the sensor. The beam emitted from another SML connected to the fiber was divided into two using a beam splitter and a mirror. Both beams enter the quartz block and are reflected at the corner through an angle of $\pi/4$ radian. They
pass through the test section, although the lengths of the two beams are different. Here, the length of the test section in Eq.(3), \( d \), is expressed as the difference between the lengths of the two beams. Both beams enter the quartz block again and are reflected at the corner through an angle of \( \pi/4 \) radian. After emerging from the quartz block, the two beams are made to interfere using a mirror and a beam splitter. The interference fringe was expanded with a lens and the light intensities of the fringes were detected with two phototransistors, to obtain the interference signals. Here, one detector was placed at the location, where the intensity of one light beam is \( \lambda/4 \) apart from the other, as shown in Fig. 4.

4. Results

At first, hot water was poured into the vessel. The water temperature decreased with time due to heat loss when the water was stirred with a magnetic stick. In this study, after the water temperature was decreased, the temperature was increased with a heater. And the temperature was decreased again by put off the heater. Figure 5 shows a set of two interference signals. At first, the phase of blue signal of detector 1 is \( \lambda/4 \) earlier than that of green one of detector 2. This phenomenon indicates that the density increases. Therefore the temperature decreased according to the relation as shown in Fig.2. However, after the heater is switched on, the phase changes at 1100 s. Then the interference fringe moves in reversal direction. The temperature increases gradually till 2100 s. After the heater was switched off around 2100 s, the temperature decreased again with reversal direction of fringe movement.

As shown in Fig. 6, when the peaks of maximum and minimum value of interference signal were read out, the temperature presented with red diamond symbols. The temperature determined from this interferometry agreed very well with the temperature obtained from the thermocouple. In this study, a successive temperature is estimated from the following procedure. For example, the blue signal of the interference shown in Fig.5 is normalized so that the minimum and maximum values are converted to 0 and 1 as shown in Fig.7. The signal was fitted using cosine curve because the
intensity of the interference signal is expressed as follows (Tomita 2006):

\[ I = E_{01}^2 + E_{02}^2 + 2E_{01}E_{02}\cos\{k(L_1 - L_2)\}. \]  

(6)

Where, \( E_0, \) \( k \) and \( L \) denote the wave amplitude, wave number (=\( 2\pi/\lambda \)) and optical path, respectively; subscripts 1 and 2 denote beams 1 and 2, respectively. And measurement length, \( d \), is expressed as Eq.(7).

\[ d = L_1 - L_2 \]  

(7)

As shown in Fig.5, the useful data was limited because only the minimum and maximum values of the signal were read out. However, when the method stated above was adopted, the temperature determined from interferometry method agreed very well with that obtained from the thermocouple as shown in Fig.8.

When the resolution in analyzing the signal is supposed to correspond to the wavelength divided by 100, the temperature resolution is from 24 to 40 mK. And if the resolution correspond to the wavelength divided by 1000, the temperature resolution becomes very fine from 2.4 to 4.0 mK. When only the peaks (maximum and minimum) were read out, the resolution was just the wavelength divided by 2. Therefore, the temperature resolution becomes 50 or 500 times finer than ever.

![Figure 5 A set of signals of interference fringes](image-url)
Figure 6 Comparison of temperature determined from interferometry to that obtained from a thermocouple

Figure 7 Compensated value of one interference signal (Fringe 1)
An example of the performance of the sensor was presented. Of course, there should be some assumptions to determine the temperature. In this study, the two beams are 2 mm apart from each other. And the measurement lengths along the two beams are 5 mm and 3 mm. The condition of the fluid should be the same near the beam. If there are some temperature gradients along a beam, the temperature determined from the beam presents the mean temperature along the beam. But if there are some temperature gradients between two beams, the accuracy of the temperature measurement should be discussed. When the length is too small to be the gradient, there is no temperature gradient between the two beams. This means that the sensor should be small enough to eliminate this effect or the temperature gradient is small enough to determine the temperature with this sensor.

5. Summary

A method for developing accuracy and resolution of the sensor was described. Water temperature measured with this sensor agreed well with that obtained using a thermocouple when the temperature decreased and increased. 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 it minimizes the effect of the thermal boundary layer. This optical system will strong enough to apply not only to laboratory use but also to industrial use in future when the optics becomes smaller than now.

References


Tomita E, Hamamoto Y, Jiang D (1994) Temperature and Pressure Histories of End Gas under

