A Technique for Measuring an Unsteady Temperature Distribution in a Liquid using Holographic Interferometry*

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An application of a holographic interferometry technique was demonstrated for measuring the steady and unsteady state temperature distributions in two liquids, water and *n*-propanol. The deflection and temperature errors caused by refraction, which is the most important source of errors within a steep temperature gradient field such as the thermal boundary layer, were discussed and estimated. Estimated errors in the measured temperature of the liquid phase under spreading flame conditions for a 0.5 cm path length of *n*-propanol with 250°C/cm temperature gradient are within 2%. The technique required : (1) transparency of the liquid and (2) availability of the relation for the thermo-optic coefficient of the liquid with temperature. If these requirements are satisfied, the temperature distribution within the liquid phase can be measured with a spatial resolution of as high as 20 μm .

Key Words : Temperature Measurement, Holographic Interferometry, Liquid Phase, Refractive Index, Spatial Resolution

1. Introduction

It is often necessary to measure the temperature distribution in a liquid phase to understand the heat transfer mechanisms for various applications such as convection, boiling, condensation, multiphase flow and combustion. These measurements are commonly conducted by the use of thermocouples. Although the thermocouple is a reliable element to measure temperature, the spatial resolution of unsteady temperature measurement is generally limited by the actual number of thermocouples that can be installed. Also the insertion of thermocouples impairs some conditions of the setup. Moreover, the accuracy of the heat flux measurement in a liquid layer determined from the temperature distribution obtained with sparsely in-

stalled thermocouples is poor.

Previously, the interferometry method was used for the measurement of temperature distribution in the transparent fluid^{(1),(2)}. There are few studies that report the application of this technique to measuring temperature distributions in liquid phase. Chen and Mayinger⁽³⁾ measured the temperature distribution around a single bubble in water using a holographic interferometer. Ootsuji⁽⁴⁾ used the method to visualize the forced convective boiling. Kashiwagi et al.⁽⁵⁾ measured the concentration distribution in an aqueous solution using the same method. Recently, authors applied holographic interferometry to measure the temperature distribution in a liquid phase during capillary flow⁽⁶⁾ and during flame spread over a liquid fuel⁽⁷⁾. In a holographic interferometer, both the object and the comparison waves travel across the same object space. Therefore, high optical quality of the setup is not required. This technique required : (1) transparency of the material and (2) availability of the relation for the thermo-optic coefficient of the material with temperature. As a first step, a 1-D temperature distribution in a layer of water is reported in this study to demonstrate an application of the

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technique and to estimate the measurement accuracy. Subsequently, a 2-D unsteady state temperature distribution in an alcohol under spreading flame conditions was measured and discussed.

2. Interferogram Analysis and Possible Errors

2.1 Fringe shift interpretation

Interferogram analysis is based on refractive-index changes in the sample due to temperature variations. These changes are illustrated schematically in Fig. 1. The Pyrex tray has an inner width L , depth H and a wall thickness of l . The temperature in liquid phase is T and the initial liquid temperature is T_0 . Assuming the laser beam directed along the y -direction moves straight and the temperature variation within the sample along the y -direction is negligible, the relationship between temperature and fringe number can be expressed as :

$$\left| L \int_{T_0}^T \frac{dn_l}{dT} + 2l \int_{T_0}^T \frac{dn_s}{dT} dT \right| = N\lambda \quad (1)$$

$$\left(N = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots \text{Double-exposure method} \right),$$

$$(N = 1, 2, 3, \dots \text{Real-time method})$$

where dn/dT is the thermo-optic coefficient of the material (n_l is the refractive index of the liquid; n_s is the refractive index of Pyrex), N is the fringe number and λ is the wavelength of light.

The second term of the left-hand side in Eq. (1) represents the change in optical path length due to the different refractive index of glass plate. The magnitude of the second term in the temperature measurement is :

$$(dn_s/dT)/(dn_l/dT) \times 2l/L.$$

The thermo-optic coefficient of fused silica is one order of magnitude smaller than that of liquid. If the thickness of the glass plate is one order of magnitude smaller than the width of the tray, the magnitude of the second term of the left-hand side in Eq. (1) is less than 2%.

Fig. 1 Schematic illustration of the sample and the coordinates for interferogram analysis and temperature and refractive index distributions

2.2 Temperature error due to refraction

There are several potential sources of error in this technique, the most important of which is due to the bending of light rays caused by the temperature gradients. Refraction of the ray results in three types of error : (1) spatial error in the position of the fringes, (2) temperature error due to the variation in the temperature along the ray path caused by this deflection, and (3) temperature error due to the change in path length.

As the light ray passes through the medium, it is bent in the direction of increasing refractive index as shown in Fig. 1. Assuming a small angle of ray deviation, the differential equation⁽¹⁰⁾ describing the ray path can be expressed as :

$$\frac{d^2 z}{dy^2} \approx \frac{1}{n_l} \frac{dn_l}{dT} \cdot \frac{dT}{dz} \quad (2)$$

The thermo-optic coefficient of liquid dn_l/dT can be approximated as a linear function of the temperature:

$$\frac{dn_l}{dT} \approx a + bT, \quad (3)$$

where a and b are constants. If the temperature gradient is constant, the solution of Eq. (2) can be obtained by integration. Then the solution is expanded in a Taylor series and higher-order terms are disregarded. The shift of the actual ray from the z -coordinate, δ , is obtained as follows :

$$\sigma = \frac{AL^2}{2} \left(1 + \frac{BL^2}{12} \right) \quad (4)$$

where

$$A = dT/dz \cdot (a + bT_0)/n_l, \quad B = (dT/dz)^2 b/n_l$$

and T_0 is the temperature at $z=0$. As the ray passes through a medium having a variation in temperature causing the deflection expressed by Eq. (4), the fringe shift is proportional to the path-averaged temperature. Then the temperature error, ΔT_e , caused by the deflection as in Eq. (4) can be approximately expressed as follows :

$$\Delta T_e = \frac{AL^2}{6} \frac{dT}{dz} \left(1 + \frac{BL^2}{20} \right) \quad (5)$$

The deflection and temperature errors caused by refraction in water are plotted in Fig. 2. In this test, these errors are quite small for water with a width of 2 cm and having a maximum temperature gradient of $dT/dz = 30^\circ\text{C/cm}$. The temperature error due to the change in path length is less than ΔT_e , and is negligible.

On the other hand, the magnitude of the thermo-optic coefficient for any alcohol or hydrocarbon is 4~6 times that of water (see Table 1). In the test under spreading flame conditions for a temperature gradient of 250°C/cm , the refraction errors are not negligible as has been discussed in section 5.2.

3. Thermo-optic Coefficient

Many measurements of the refractive index of water have been reported^{(11),(12)~(13)}. Dobbins and Peck⁽¹²⁾ reported the refractive index for water at a wavelength of 632.8 nm over a range of temperature from 0 to 60°C as follows :

$$n_w = 1.33317 - (1.936T + 0.1699T^2) \times 10^{-5} \quad (6)$$

Hauf and Grigull⁽¹¹⁾ reported the thermo-optic coefficient for water at a wavelength of 632.6 nm at 25 °C as :

$$dn_w/dT = -0.985 \times 10^{-4} \quad (7)$$

Thormählen et al.⁽¹³⁾ recently arranged many refractive index data for water and suggested an experimental equation which includes the effect of wavelength, temperature and pressure on the refractive index. Their data on refractive index vs temperature were fitted in a second-degree polynomial. By differentiating this equation, we obtained the following equation :

$$dn_w/dT = -(2.26 + 0.284T) \times 10^{-5} \quad (8)$$

The value obtained from the above equation is in close agreement with that determined by our experimental data listed in Table 1.

Few data on dn/dt for any other liquid have been published. These data on dn/dT at 25°C are listed in Table 1. Unfortunately, the dependency of the temperature on dn/dT is unknown. Authors have measured the thermo-optic coefficient for various liquids by Abbe refractometer with a modified test section. Detailed discussion of this measurement will be presented elsewhere ; only the results are listed in Table 1 and have been compared with the data reported by Hauf and Grigull⁽¹¹⁾.

Table 1 Thermo-optic coefficient of liquids determined by using a wavelength of 632.8 nm

Liquid fuels	$-dn/dT \text{ } ^\circ\text{C}^{-1} \text{ } (\lambda = 632.8 \text{ nm})$	
	Hauf&Grigull(1970) At 25°C	Present work [Temperature range 2~80°C]
Water	0.985×10^{-4}	$(3.6 + 0.256T) \times 10^{-5}$
Methyl alcohol	4.0×10^{-4}	$(3.7 + 0.0105T) \times 10^{-4}^{**}$
Ethyl alcohol	4.0×10^{-4}	$(3.8 + 0.0106T) \times 10^{-4}^{**}$
n-Propyl alcohol		$(3.8 + 0.0137T) \times 10^{-4}$
Iso propyl alcohol	4.15×10^{-4}	
n-Butyl alcohol		$(4.0 + 0.0072T) \times 10^{-4}$
n-Hexane	5.4×10^{-4}	$(5.3 + 0.0122T) \times 10^{-4}$
n-Heptane		$(5.0 + 0.0075T) \times 10^{-4}$
n-Octane	$4.76 \times 10^{-4}^*$	$(4.8 + 0.0069T) \times 10^{-4}$
n-Decane	$4.48 \times 10^{-4}^*$	$(4.5 + 0.0034T) \times 10^{-4}$

(*) $\lambda = 546.1 \text{ nm}$, (**) $T = 5 \sim 80^\circ\text{C}$

Fig. 2 Deflection and temperature errors due to refraction

4. Experimental Apparatus and Procedure

4.1 Measurement of steady-state temperature distribution

A schematic illustration of the experimental apparatus for 1-D steady-state temperature distribution is shown in Fig. 3. A test sample of the liquid was held between two constant-temperature flowing water layers separated by 3 mm brass plates. The upper layer of flowing water was of higher temperature. The temperature and flow of both upper and lower layers were well regulated by a thermostatic bath. The test section of the liquid was 25 cm in length (x -direction), 2 cm wide (y -direction) and 1 cm in height (z -direction). Two long sides of the test section were made of Pyrex with 0.1 cm thickness. Fifty- μm diameter copper-constantan thermocouples were used to measure the temperature of the upper and lower surfaces, and at the middle of the layer of the test liquid.

The optical setup for the holographic interferometer is shown schematically in Fig. 4. The light source is a 5 mW He-Ne laser : the laser beam is divided into object and reference beams by a partially reflecting mirror (BS). To magnify the image, a convex lens (L) is placed in the path of the object beam between the test section (TS) and the holographic plate. Holographic plates used in this test were 10E75 of Agfa-Gevaert. Exposed plates were developed for 3 minutes in Refinal, then fixed for 10 minutes in Fujifix. A double-exposure method was used in the

measurements of steady-state temperature distribution. The first holographic exposure was made with the sample of liquid at ambient temperature. After the sample was heated and reached a steady state, the second exposure was made. Both the first and the second exposure times were 1/250 s.

4.2 Measurement of unsteady-state temperature distribution

The unsteady-state temperature distribution within liquid phase during flame spreading over alcohol was measured as a demonstrative application of the technique. A schematic illustration of the experi-

Fig. 3 Schematic illustration of the experimental apparatus for measuring the steady-state temperature distribution

Fig. 4 Optical system used for holographic interferometry

Fig. 5 Schematic illustration of the experimental apparatus for measuring the unsteady-state temperature distribution in the liquid phase under spreading flame condition

mental apparatus is shown in Fig. 5. Trays with dimensions of 40cm in length, 1cm in height and four different widths (0.5~2 cm) with a rectangular cooling unit were used. Both long sides of the tray were made of Pyrex with 0.1 cm thickness.

A real-time method was used in this test. The procedure to obtain a hologram with a fine diffraction image is not based on bleaching the hologram but on balancing the objective image with the diffractive image by splitting the main beam and allocating it to 10 % of the main intensity for the objective beam and 90 % for the reference beam. The first holographic exposure for a reference image (at ambient temperature) was for 1s, while the interferogram for spreading flame was recorded in a 0.1s interval by a motor-driven camera with 1/500 s exposure time. The test liquid was *n*-propyl alcohol maintained below the flash point temperature (25°C).

5. Results and Discussion

5.1 Steady-state temperature distribution in water

A typical result of an interferogram in water is shown in Fig. 6(a). T_h and T_0 are the temperatures of the upper and lower wall measured by thermocouples. The temperature difference between the two consecutive fringes was about 0.4°C for water with a 2 cm path length at 20°C. In this test, we could count 20 maximum fringes within 1mm for water and 30 maximum fringes within 1mm for *n*-propanol as shown later. Therefore, the temperature distribution of the material can be measured with a high spatial resolution.

The temperature distribution in the z -direction in the closed section corresponding to the thermocouple position is also shown in Fig. 6(b). The temperatures are calculated from Eq.(1) counting the number of fringes N from the colder surface temperature for reference. In this figure, the temperature distribution represented by the circles has been obtained using Eq. (8) which describes the dependence of dn/dT on temperature. The triangles are the result obtained using Eq.(6) showing the relation of n_w to temperature. The dotted line is the result obtained with a constant value of dn_w/dT represented by Eq.(7). Three squares represent the temperatures of water measured by the thermocouples. From this figure, it is noted that three calculated temperature distributions are quite similar below ~30°C. However, a dependence of the calculated temperature on the thermo-optic coefficient appears above 30°C. The upper layer temperature, which was calculated on the basis of a constant thermo-optic coefficient, is higher than the temperature measured by the thermocouple,

Although the steady-state condition is achieved, the temperature distribution shown in Fig. 6(b) is not a linear function of the z coordinate. This is due to heat loss from both sides of the glass walls. This heat loss from the edges results in variations in temperature along the ray path (y -coordinate). An average temperature for the nonisothermal temperature distribution can be calculated from the integrated temperature distribution divided by the path length. The temperature difference, ΔT_e , between the temperature at the center of the sample and the average temperature has been estimated from a heat balance equation which includes heat loss from the side wall. It was found that the maximum ΔT_e of water with 2 cm width is about 0.2% of the measured temperature.

In this test, the temperature errors caused by refraction and heat loss are negligibly small. The difference between the temperatures determined from fringes and that obtained by thermocouples mainly depends on the difference of the thermo-optic coefficient used for calculation. The result shown in Fig. 6(b) suggests that the thermo-optic coefficient for water represented by Eq.(8) is of higher accuracy. The temperature distribution calculated from Eq.(8) is in close agreement with that measured by the thermocouple and the difference is within 2% below 76°C.

5.2 Unsteady-state temperature distribution in alcohol

The unsteady-state temperature measurement is based on the steady-state measurement technique as mentioned above. Interferogram for the unsteady-state condition is photographed with a short exposure time which is fast enough to "freeze" the formed fringe pattern. The unsteady-state temperature distribution in liquid phase under spreading flame condition over alcohol was measured as a demonstrative application of the technique. The flame spread over subflash point liquid fuel is mainly controlled by the subsurface liquid convection. To understand the heat transfer mechanism through liquid phase, detailed knowledge of the instantaneous temperature field in the subsurface liquid current is essential.

A series of interferograms (a) through (c) for n -propanol with an initial temperature of 22°C are shown in Fig. 7. An illustration of the isothermal lines (d) from the interferogram of case (c) is included in this figure. The measurement was carried out with a narrow tray of 0.5 cm width (path length). The fringe density is about 30 lines/mm for the temperature gradient of 250°C/cm. As the maximum resolution was $\sim 20 \mu\text{m}$ (50 lines/mm) for this optical apparatus, it would be difficult to resolve each fringe if a wider tray was used.

The thin black layer in subsurface liquid just

Fig. 6 (a) Typical interferogram and (b) temperature distribution in water

Fig. 7 Three different interferograms (a) through (c) and the isothermal lines for condition (c) for *n*-propanol

below the flame's leading edge shown in Figs. 7 (b) and (c) seems to be the deflection of light due to the refractive index gradient. The deflection and temperature errors caused by refraction were estimated from Eqs. (4) and (5) using dn/dT represented in Table 1. The maximum errors are $\delta_{\max} = -9.1 \times 10^{-3}$ cm, $\Delta T_{\max} = 0.75^\circ\text{C}$ for *n*-propanol with a tray width of 0.5 cm. This temperature error is less than 2 % of the temperature of liquid. The error due to the temperature distribution in liquid along the light beam, which is caused by the heat loss through the wall, was estimated. Difference of temperature at the center of liquid along path length and the average temperature is less than 1 % of the temperature at the center.

To accurately resolve each fringe in the interferogram in the liquid layer having a steep temperature gradient, narrower tray width is more advantageous.

It is undeniable that a narrow tray leads to the distortion of the liquid flow near the side wall. However, the subsurface liquid convection current within a thin liquid layer of 0.05 cm was found from the interferogram shown in Fig. 7 but was impossible to measure by thermocouples. Based on the detailed temperature profiles in the liquid phase, it is possible to clarify the flame spread mechanism by examining the energy balance within the liquid phase.

6. Conclusions

(1) The equation for determining the temperature distribution in a liquid in a transparent tray from the interferogram fringe was proposed in Eq. (1). The technique requires : (1) transparency of the measured liquid and (2) availability of the relationship for the thermo-optic coefficient of the liquid with temperature. If these requirements are satisfied, the temperature distribution can be measured with a spatial resolution of about $20 \mu\text{m}$.

(2) The measured thermo-optic coefficients for water, four different alcohols and four different hydrocarbon liquids as a function of temperature between 2°C and 80°C were approximated by a quadratic expression in Table 1.

(3) The deflection and temperature errors caused by refraction were estimated by Eqs. (4) and (5). The temperature error increases in proportion to the thermo-optic coefficient and in proportion to the square of path length and temperature gradient. For example, the estimated error does not exceed 2 % of temperature of *n*-propanol with a width of 0.5 cm having a temperature gradient of $250^\circ\text{C}/\text{cm}$.

(4) The measurement technique for unsteady-state temperature distribution was discussed from the viewpoint of a quasi-steady-state interferogram in which each fringe is "frozen" in a short exposure time.

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