Measurement of the Temperature and Concentration Fields in Fuel Film Evaporation Process

Z.B.Liu, J.W.Zhou and Y.S.Li

Institute of Internal Combustion Engine
Dalian University of Technology
Dalian 116024
P.R.China

ABSTRACT

The coupled temperature and concentration fields formed over the surface of the fuel film on a wall have been measured in the fuel film evaporation process by means of an optical set-up using the real-time double wavelength laser holographic interferometric technique. The optical set-up consists of two lasers with different optical wavelengths used as light sources and a holographic arrangement. By making use of this optical set-up, two independent interferograms produced from different optical waves of two different lasers in an experimental device at any instant can be recorded simultaneously. Through the two interferograms and two evaluation equations, the temperature and concentration fields formed over the surface of the fuel film on a wall in an experimental device can be calculated quantitatively. The research work done in this paper provides, the authors hope, a solid foundation for further investigation of the rules of both the evaporation of the fuel film on and the formation of the mixture of the air fuel-vapor over the combustion chamber walls.

INTRODUCTION

The combustion chamber's dimensions and high injection pressure cause part of the fuel to press against the combustion chamber walls in direct injection diesel engines under the condition of high load. In film type combustion engines, most of the fuel is sprayed directly on the combustion chamber walls. As a result, a fuel film forms on these walls. Therefore, researching the mechanisms of the fuel film evaporation process is critical in hopes of improving the performance of the diesel engines.

The measurement techniques of the thickness of the fuel film on the combustion chamber wall of the piston crown can make the researchers investigate the fuel film formation, distribution and thickness variation process [1,2,3]*. However, these techniques fall far short of examining the temperature and concentration fields over the surface of the fuel film. In this paper, the authors have succesfully measured the coupled temperature and concentration fields over the surface of the fuel film formed on a wall during the period of the fuel film evaporation by using a real-time double wavelength laser holographic interferometric technique. The basic principle and optical set-up design of the real-time double wavelength laser holographic interferometric measurement are discussed. The evaluation equations are derived. A satisfactory experimental result is presented and analyzed.

MEASUREMENT PRINCIPLE OF REAL-TIME DOUBLE WAVELENGTH LASER HOLOGRAPHIC INTERFEROMETRY

A schematic diagram of the measurement principle of the real-time laser holographic interferometry is shown in Figure 1. The real-time laser holographic interferometric measurement uses a laser holographic system. After the first exposure by which the comparison wave of the initial state in an experimental device is recorded on an interferogram, the interferogram is taken away from its place and is developed. Then, it is repositioned accurately at its original place, remaining all other optical elements and their positions in the holographic system at the same time. The comparison wave is reconstructed continuously by illuminating the interferogram with the original reference wave. If the experimental device is still illuminated with the original object wave, this reconstructed wave can now be superposed onto the momentary object wave. After the refractive index field in the experimental device is varied due to the heat/mass transfer process, there is a difference in optical path length between the reconstructed wave and the object wave passed through the experimental device. At any measurement instant, the object wave is usually called the measurement wave. Behind the interferogram both waves interfer with each other and the interference fringes will be seen. Thus the refractive index field which is continuously changing in the experimental device is visualized in the manner of the changes of the interference fringes. If the refractive index field changes slowly, the change process of the interference pattern can be continuously observed or recorded with a camera. If the refractive index field changes fast, the change process of the interference pattern can be

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* Numbers in brackets designate references at end of paper.

continuously recorded with a high speed movie film.

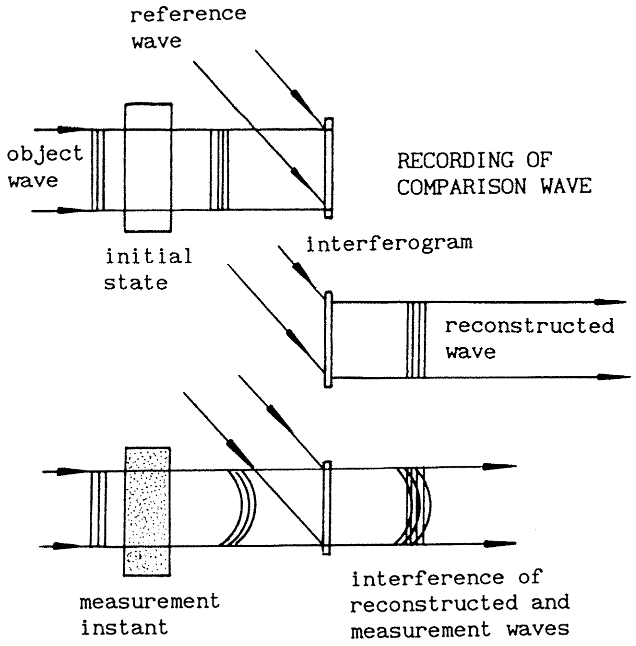

Fig. 1 Principle of the real-time holographic interferometric measurement

The measurement technique with the real-time double wavelength laser holographic interferometry is similar to that with the real-time single wavelength laser holographic interferometry in fundamental principles. The only unique feature of the real-time double wavelength laser holographic interferometric measurement technique is that the physical property that the refractive index changes with the optical wavelength is used [4,5]. We can simultaneously record two independent interferograms produced from two different optical waves of two different lasers in an experimental device at any instant. Through the two interferograms and two evaluation equations, the fields of two coupled parameters which cause the changes of the refractive index in an experimental device can be calculated quantitatively. In our example, when the coupled heat and mass transfer processes take place in the experimental device, through a set of interferograms recorded and evaluation equations derived, the temperature and concentration fields in the experimental device at the measurement instant can be obtained.

EXPERIMENTAL DEVICE

A one-dimensional experimental device is used in our measurement of the temperature and concentration fields formed over the fuel film surface during the period of the fuel film evaporation. The advantage to do so is that it is convenient to design and adjust the optical set-up, more complicated optical elements are not needed, and the experiment cost is low. At the same time, the multi-dimensional experimental device is removed, because the basic demand is adequately met with a one-dimensional experimental device, taking account of the investigation of the evaporation mechanism of the fuel film.

In order to increase the measurement precision and reduce the measurement error, an experimental device with a large size is used, in which the test flat wall is 310 mm long along the direction of optical waves and 150 mm wide, and is made of aluminium alloy material, the heat conductivity of which is very good. A uniform fuel film is put on the wall. The experimental fuel is hexadecane. The wall is evenly heated by the heat wire under it. The wall temperature is adjusted by controlling the voltage, and measured by thermocouples.

OPTICAL ARRANGEMENT

Figure 2 shows the measurement set-up of the real-time double wavelength laser holographic interferometry. In this optical set-up two lasers are used as light sources. Laser A is a He-Ne laser with a wavelength λ_1 of 632.8 nm. Laser B is an argon laser with a wavelength λ_2 of 488 nm.

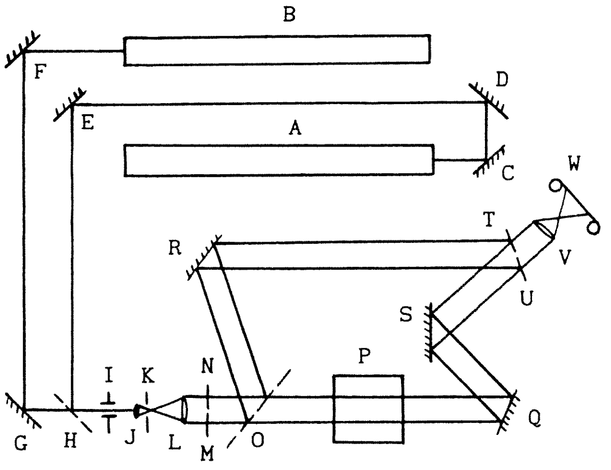

Fig.2 Optical set-up for the real-time double wavelength holographic interferometric measurement

In Figure 2, C, D, E, F, G, Q, R and S are deflective mirrors. The beam of the He-Ne laser and that of the argon laser are superimposed through a beam splitter H. Therefore, only one shutter I is needed, and equal exposure times at both wavelengths are guaranteed. Both beams are then expand to parallel waves by a telescope which consists of a microscope objective lens and a collimating lens. K is a wave filter. M and N are color filters. In half optical beam, only the optical wave with a wavelength λ_1 can pass through the filter M and the optical wave with a wavelength λ_2 cannot pass through the filter M. In another half optical beam, only the optical wave with a wavelength λ_2 can pass through the filter N and the optical wave with a wavelength λ_1 cannot pass through the filter N. By means of another beam splitter O, the two laser beams are divided into two object and two reference beams at different wavelengths. The object waves pass through the experimental device P, in which the temperature and concentration fields are to be examined, whereas the reference waves directly fall onto interferograms T and U. The interferogram T is suitable to recording the the optical wave with a wavelength λ_2, whereas the interferogram U is suitable to recording the optical wave with a wavelength λ_1. V is a lens and W is a camera.

The real-time method requires an accurate reconstruction of the comparison wave, therefore the interferograms must be repositioned precisely at its original place. This can be done by using a precise reposition interferogram holder. In our test, interferograms T and U are fixed in one precise reposition interferogram holder side by side.

EVALUATION OF THE INTERFEROGRAMS

The evaluation of the holographic interferograms, made in an optical set-up with parallel object waves, is very similar to the evaluation of the interference patterns recorded in a Mach-Zehnder interferometer [6]. Therefore only the basic equations will be given. In real-time holography, the object waves passing through the experimental device at different times are superposed, and therefore reveal the changes in optical path length between the exposures on the interferograms.

During the recording of the comparison waves, only air exists in the experimental device. The temperature of air is uniform in the experimental device, which is T_o. The refractive index is also uniform, which is n_o. In second exposure, the temperature distribution and the concentration distribution of the fuel vapor in the experimental device are not uniform due to the fuel film evaporation after heated. Since the experimental device is a one-dimensional model, the changes of the temperature and concentration are only in the direction of the coordinate y, and the isolines of the temperature and concentration are perpendicular to the coordinate y. Thus, the differences in optical path length between the two exposures can be expressed as

$$\Delta\overline{PL}_1(y) = L[n_{o1}-n_1(y)] \tag{1}$$

and

$$\Delta\overline{PL}_2(y) = L[n_{o2}-n_2(y)] \tag{2}$$

where L is the length of the wall in the experimental device, in which the refractive index is varied because of the temperature and concentration changes, n(y) is the refractive index of the mixture of air and fuel vapor at an arbitrary point (y) over the fuel film during the recording of the measurement waves. Subscript 1 corresponds to the parameters with a wavelength λ_1, subscript 2 corresponds to the parameters with a wavelength λ_2. The interference fringe shift produced by the optical wave with a wavelength λ_1 is calculated from the following equation.

$$\varepsilon_1(y) = \frac{\Delta\overline{PL}_1(y)}{\lambda_1} = \frac{L}{\lambda_1}[n_{o1} - n_1(y)] \tag{3}$$

In a similar manner, we have

$$\varepsilon_2(y) = \frac{L}{\lambda_2}[n_{o2} - n_2(y)] \tag{4}$$

Equations (3) and (4) relate the fringe shifts to the refractive index field. The obtained refractive index field can be converted into a density field by means of the Gladstone-Dale equation

$$\frac{n-1}{\rho} = K \tag{5}$$

where ρ is the density and K is the Gladstone-Dale constant. Substituting equation (5) into equations (3) and (4), we have

$$\varepsilon_1(y) = \frac{L}{\lambda_1}[\rho_o K_{a1} - \rho(y)K_1(y)] \tag{6}$$

and

$$\varepsilon_2(y) = \frac{L}{\lambda_2}[\rho_o K_{a2} - \rho(y)K_2(y)] \tag{7}$$

where ρ_o is the density of the air with a temperature T_o, $\rho(y)$ is the density of the mixture of air and fuel vapor at the point (y), K_a is the Gladstone-Dale constant of the air. If the pressure is kept constant, the density variations can only be caused by temperautre and concentration changes. Because the fluid is a gas, we can use the equation of state.

$$\rho = \frac{MP}{RT} \tag{8}$$

In equation (8), P is the pressure, M is the molecular weight, and R is the universal gas constant. Substitution for the density yields

$$\frac{\varepsilon_1(y)\lambda_1 R}{PL} = \frac{M_a K_a}{T_o} - \frac{M(y)K_1(y)}{T(y)} \tag{9}$$

and

$$\frac{\varepsilon_2(y)\lambda_2 R}{PL} = \frac{M_a K_a}{T_o} - \frac{M(y)K_2(y)}{T(y)} \tag{10}$$

where M_a is the molecular weight of the air, M(y) is the molecular weight of the mixture of air and fuel vapor at the point (y), T(y) is the temperature of the mixture at the point (y).

Taking C(y) as the molar absolute concentration at the point (y) and X(y) as its corresponding molar relative concentration, and expressing the parameters corresponding to the air with the subscript a and the parameters corresponding to the fuel vapor with the subscript b, the following relations exist.

$$X_a(y) + X_b(y) = 1 \tag{11}$$

$$M(y) = M_aX_a(y) + M_bX_b(y) \tag{12}$$

$$\begin{aligned} K(y) &= K_a \frac{\rho_a(y)}{\rho_a(y)+\rho_b(y)} + K_b \frac{\rho_b(y)}{\rho_a(y)+\rho_b(y)} \\ &= K_a \frac{M_aC_a(y)}{M_aC_a(y)+M_bC_b(y)} + K_b \frac{M_bC_b(y)}{M_aC_a(y)+M_bC_b(y)} \\ &= \frac{K_aM_aX_a(y)+K_bM_bX_b(y)}{M_aX_a(y)+M_bX_b(y)} \end{aligned} \tag{13}$$

Utilizing equations (11), (12) and (13), we can obtain the following formulas, which relate the fringe shifts to the temperature and concentration.

$$\frac{\varepsilon_1(y)\lambda_1 R}{PL} = \frac{M_aK_{a1}}{T_o} - \frac{M_aK_{a1}+X_b(y)(M_bK_{b1}-M_aK_{a1})}{T(y)} \tag{14}$$

and

$$\frac{\varepsilon_2(y)\lambda_2 R}{PL} = \frac{M_aK_{a2}}{T_o} - \frac{M_aK_{a2}+X_b(y)(M_bK_{b2}-M_aK_{a2})}{T(y)} \tag{15}$$

From inspection of the coupled equations (14) and (15), it is evident that there are only two unknowns in the two coupled equations. Thus, the coupled temperature and concentration fields over the surface of the fuel film during its evaporation at any instant can be obtained through the two coupled equations and two independent interferograms.

The equations (14) and (15) show that it is the difference between the phase shifts that is used for the measurement of the temperature and concentration fields. This difference is usually very small. Therefore the two wavelengths used should be as far apart as possible.

MEASUREMENT RESULT AND ANALYSIS

The measurement result of the coupled heat and mass transfer during the fuel film evaporation is shown in Figure 3. This figure reveals the temperature and fuel vapor concentration boundary layer formed over the fuel film at natural convection. In Figure 3, the left half is the interferogram recorded by the optical waves with awavelength λ_1, and the right half is the interferogram recorded by the optical waves with a wavelength λ_2.

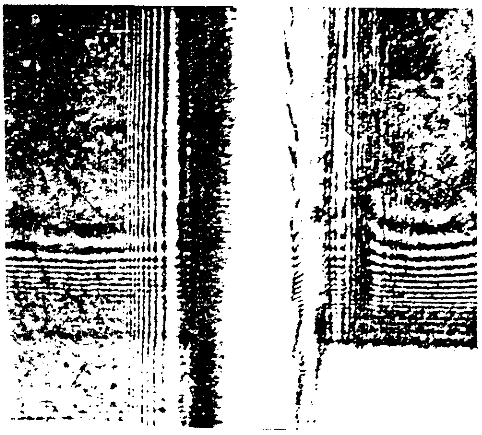

Fig.3 Dual interferograms of the fuel film evaporation

The temperature and concentration fields over the fuel film can be solved by using the two coupled equations (14) and (15), and the two independent interferograms shown in Figure 3. Figure 4 shows the curves of the temperature and fuel vapor concentration distribution over the fuel film. From Figure 4, the thicknesses of the heat and concentration boundary layers over the fuel film can be determined.

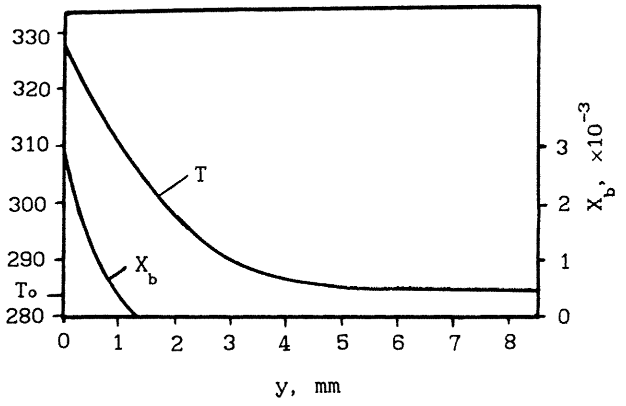

Fig. 4 Temperature and concentration fields over the surface of fuel film during its evaporation

Further measurement results show that as the wall temperature rises, the boundary layer thickness of the fuel vapor concentration increases, and the fuel vapor concentration gradient increases either [7]. However, the concentration level on the fuel film surface has an effect on the fuel film evaporation and diffusion. Therefore, it is believed that the temperature of the combustion chamber wall has some control function on the velocity of the fuel film evaporation. Although the high temperature of the gas in the combustion chamber space has a strong effect on the fuel film evaporation, the control function of the wall temperature cannot be neglected.

Figure 4 displays the measurement result during the period of the steady fuel film evaporation. From inspection of Figure 4, it is evident that the fuel vapor concentration is largest at the fuel film surface, which is its saturation vapor concentration. The concentration gradually decreases away from the fuel film surface. It is known that only after part of the fuel vapor on the fuel film surface is blown off by the air stream brushed the fuel film surface or burnt away by the flame in the combustion chamber space, the fuel vapor can be released from the fuel film, and diffuses outwards to maintain the concentration equilibrium. Although the situation in the combustion chamber space in diesel engines is very complicated, and the temperatures of combustion chamber wall and gas in the combustion chamber space are much higher than in simulation device investigation, as well as part of the fuel vapor is blown off or burnt away without reaching the steady state, the tendency that, only after part of the fuel vapor over the fuel film surface is blown off or burnt away, the fuel vapor can be released from the fuel film and diffuses outwards, will not be varied. Therefore it is believed that the fuel film on the combuston chamber wall in diesel engines evaporates and burns layer by layer.

CONCLUSIONS

The following conclusions can be drawn from this paper.

1) The experimental result shows that the real-time double wavelength laser holographic interferometric measurement technique is applicable for measuring the couplecd heat and mass transfer of the fuel film evaporation. The measurement result is satisfactory.

2) After the temperature and concentration fields formed over the surface of the fuel film during the period of the fuel film evaporation are measured, a good foundation will be provided for further investigation of the formation and combustion of the mixture of fuel vapor and air.

3) The fuel film on the combustion chamber wall evaporates and burns layer by layer, and the wall temperature has some control function on the evaporation and diffusion of the fuel film. Therefore these characteristcs should be considered in the design of new combustion systems in diesel engines.

NOMENCLATURE

$\Delta\overline{PL}$ = difference in optical path length
L = model length
n = refractive index
y = coordinate
ε = interference order
λ = wavelength
ρ = density
K = Gladstone-Dale constant
P = pressure
R = universal gas constant
M = molecular weight
T = temperature
C = absolute concentration
X = relative concentration

Subscripts

a = air
b = fuel vapor
o = initial state
1 = parameters at a wavelength of 632.8 nm
2 = parameters at a wavelength of 488 nm

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