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Measurement of Cylinder Gas Temperature of Internal Combustion Engines*

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All the techniques that have been previously developed for unsteady-state determination of cylinder gas temperature are used exclusively for measuring comparatively higher gas temperature with spatial variation existing in a cylinder such as flame or combustion gas temperature.

This paper introduces a new method for the determination of average gas temperature in a cylinder during compression and expansion strokes. The principle is as follows: At the maximum or minimum point of the fluctuating temperature of a thin metallic wire exposed to gas, the wire temperature agrees with gas temperature, thus giving a basic temperature to determine gas temperature at the other points using the equation of state in conjunction with an indicator diagram, in so far as the maximum or minimum temperature is representative of the temperature of the whole gas in a cylinder. The temperature data taken on a two-stroke diesel engine by employing a platinum resistance thermometer are presented. The principle of this method is verified by the test results obtained in motoring. The results of the firing tests show that the minimum temperature appearing in a compression stroke indicates average gas temperature, which is applicable as the basic temperature, while the maximum temperature occurring in an expansion stroke scarcely represents average temperature.

1. Introduction

Cylinder gas temperature is considered as one of the fundamental variables in an engine. Engine researches on such problems as combustion phenomena, startability, thermal load, and cycle analysis need the accurate knowledge of cylinder gas temperature in an operating engine. To meet the requirement, various methods for the temperature measurement have been developed. The radiation method⁽¹⁾, the light absorption method⁽²⁾, and the velocity-of-sound technique⁽³⁾ are considered satisfactory in regard to the time rate of response. However, their use is limited to measuring comparatively higher gas temperature such as flame or combustion gas temperature. Resistance thermometers and thermocouples have been often used because of their experimental simplicity, but obviously they are not adequate to instantaneous measurements. The use of high-frequency current for resistance thermometers⁽⁴⁾ might

be effective to reduce the time lag in some degree. The mathematical compensation method for the time lag⁽⁵⁾ would be helpful in thermocouple or resistance thermometer measurements, but it is very laborious.

One great difficulty with these methods is the problem of the nonhomogeneity of the cylinder charge, which has made it almost impossible to measure the spatial average temperature in a cylinder. The only knowledge of the average gas temperature has been obtained theoretically, assuming the gas temperature at the beginning of compression and applying the equation of state for perfect gas.

This paper introduces a new technique for the determination of average gas temperature in a cylinder during compression and expansion strokes. It works on the principle that at the maximum or minimum point of the fluctuating temperature of a thin metallic wire exposed to gas, the wire temperature agrees with gas temperature, thus giving a basic temperature to determine gas temperature at the other points using the equation of state in conjunction with an indicator diagram, in so far as the maximum or minimum temperature is representative of the temperature of the whole gas in a cylinder.

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2. Principle of the measurement

The metallic wire under consideration is so fine that the temperature difference in its cross-section may be practically neglected. Let us consider the unsteady heat transfer in a wire illustrated in Fig. 1, where the wire is exposed to ambient gas, temperature of which is T °K. The wire is supported between much larger diameter rods which are made of the same material as the wire, and it carries the measuring current in it. We have the equation for wire temperature T_w °K at the distance of x from one end⁽⁶⁾ considering the thermal change in resistance:

$$\xi(\partial T_w / \partial t) = \eta^2 (\partial^2 T_w / \partial x^2) + T - T_w + \zeta \{1 + \beta(T_w - 273)\} \quad (1)$$

where

$$\xi = (c_w \gamma_w d_w^2) / (4 N_u \lambda_g) \quad \text{sec}$$

$$\eta^2 = (\lambda_w d_w^2) / (4 N_u \lambda_g) \quad \text{cm}^2$$

$$\zeta = (I^2 r_0) / (J N_u \lambda_g \pi) \quad \text{deg}$$

$$N_u = \alpha d_w / \lambda_g$$

$$c_w: \text{specific heat of wire} \quad \text{cal/g deg}$$

$$\gamma_w: \text{specific weight of wire} \quad \text{g/cm}^3$$

$$d_w: \text{diameter of wire} \quad \text{cm}$$

$$\lambda_w: \text{heat conductivity of wire} \quad \text{cal/sec cm deg}$$

$$\lambda_g: \text{heat conductivity of gas} \quad \text{cal/sec cm deg}$$

$$\alpha: \text{heat transfer coefficient between wire and gas} \quad \text{cal/sec cm}^2 \text{ deg}$$

$$I: \text{measuring current} \quad \text{A}$$

$$r_0: \text{resistance per unit length of wire at } 0^\circ \text{C} \quad \Omega/\text{cm}$$

$$\beta: \text{temperature coefficient of resistance of wire} \quad \text{deg}^{-1}$$

$$t: \text{time} \quad \text{sec}$$

$$J = 4.1855 \quad \text{J/cal}$$

In examining Eq. (1), the first and fourth terms on the right-hand side, which represent the influence of temperature distribution along the wire and Joule's heat, respectively, are small enough to be safely neglected for the ratio of diameter to length of the wire and for the measuring current ordinarily used in experiments. Then, Eq. (1) becomes

Fig. 1 Heat transfer model of thin metallic wire exposed to gas

$$\xi(dT_w/dt) = T - T_w$$

At the minimum or maximum point of the fluctuating temperature of the wire, the rate of change of T_w with time is zero: $dT_w/dt = 0$

Accordingly, $T_w = T (\equiv T_M)$

When T_w represents the average gas temperature in a cylinder, the average gas temperature at the other points during compression and expansion strokes can be given by

$$T = T_M \frac{pV}{p_M V_M} \frac{G_M R_M}{GR} \quad (2)$$

where p : cylinder gas pressure kg/cm^2

V : cylinder volume cm^3

G : cylinder gas weight kg

R : gas constant $\text{kg cm/kg } ^\circ\text{K}$

Subscript M denotes corresponding conditions to T_M .

Since the minimum temperature may occur in a compression stroke, the gas weight G_M and gas constant R_M at that point can be considered equal to those values at any other points in that stroke, in so far as gas leakage is negligible. Similarly, the maximum temperature may be obtained in an expansion stroke, and therefore $G = G_M$ and $R = R_M$ in that stroke. Consequently, Eq. (2) may be reduced to

$$T = T_M \frac{pV}{p_M V_M} \quad (2)'$$

The accurate measurement of cylinder gas pressure can be easily made with an indicator, and the cylinder volume is, of course, a given function of crank angle. Thus, we can obtain the average cylinder gas temperature during compression and expansion strokes. Since a term involving a rate of response of the wire does not play any role in this measuring principle, the method is independent of the diameter of the wire, in so far as the temperature distribution in the cross-section is considered practically uniform.

3. Instrumentation

Both a thermocouple and a resistance thermometer may be applicable to this method. In respect to the error due to heat conduction along the wire, a thermocouple may be preferable. However, the temperature indicates only local temperature around its junction. On the contrary, a resistance thermometer will be adequate to measure average temperature because it can extend its sensing wire into a cylinder. Besides, a long wire may be effective in reducing the error due to heat conduction along the wire. For this reason, a platinum resistance thermometer was used in this experiment.

Although a thick wire is preferable in respect to mechanical strength in so far as the temperature distribution in the cross-section can be practically considered uniform, it conflicts with the sensitivity

of a measuring instrument because large diameter means low resistance. The diameters of platinum wires finally decided by the compromise were 0.03 mm and 0.05 mm.

The engine used for the experiment is a uniflow-scavenged two-stroke diesel engine with overhead exhaust valves. The bore and stroke are 110 mm and 130 mm, respectively. The compression ratio is 16.

As shown in Fig. 2, the platinum wire was extended triangularly, supported by the mica tips at B and C, and welded to 1 mm diameter rods which

Fig. 2 Location of resistance thermometer

Fig. 3 Cross-section through rod holder

were also made of platinum. Figure 3 shows the construction of the rod holder. The platinum rods were connected to leading wires to form a bridge circuit, which was adjusted to supply a current of 5 mA to the wire.

Cylinder gas pressure was measured with a piezo pickup which was installed in the cylinder head as shown in Fig. 2. In addition, another pickup was attached to the cylinder liner so as to make an accurate measurement of low pressure. The low pressure indicator adapter was opened at 80 degrees after t. d. c. and closed at 80 degrees before t. d. c. by the piston.

4. Experimental results and discussion

Figure 4 shows the synchroscope records of the wire temperature and the cylinder gas pressure measured with both the high pressure and low pressure indicators. The diameter of the platinum wire used was 0.05 mm. The replots from the wire temperature records at three engine speeds are compared in Fig. 5. It is seen from Fig. 5 that the maximum and minimum points of the wire temperature delay with increasing engine speed. Figure 6 shows the data for a 0.03 mm diameter platinum wire. Here it is seen that the thermometer responds more quickly. This is due to its less heat capacity than that of the former. It appears in these figures that the maximum and minimum temperatures occur during expansion and compression strokes, respectively, where the valves and ports are closed. Therefore, the correlation of Eq. (2)' can be established between the

750 rpm, Diam. of platinum-wire 0.05 mm
Fig. 4 Platinum-wire temperature and cylinder pressure recordings for a motored engine

maximum and minimum temperatures, if they represent the average temperature in a cylinder. In Figs. 5 and 6, the temperatures drawn with heavy curves represent the results calculated by the use of Eq. (2)' substituting the minimum temperature for T_M^* . From these figures, it is found that each of the calculated temperature curves crosses the corresponding curve of the wire temperature just at its maximum point. This fact indicates that the maximum and minimum temperatures representative of the temperature of the whole gas in a cylinder.

Fig. 5 Platinum-wire temperature and cylinder gas temperature versus crank angle in a motored engine

Fig. 6 Platinum-wire temperature and cylinder gas temperature versus crank angle in a motored engine

Figure 7 shows the pressure and the wire temperature records of several successive cycles. It is noticeable from Fig. 7 that the wire temperature varies considerably from cycle to cycle, while the pressure does not. Such variation of the wire temperature, however, scarcely gives the difference in the cylinder gas temperature obtained from their maximum or minimum temperature as shown in Fig. 5. This shows that the maximum and minimum points for each of the engine cycles move merely on the same cylinder gas temperature curve. Accordingly, it may be deduced that the variation of the wire temperature is not due to the variation of local gas temperature. One possible explanation might be the variation of heat transfer coefficient between the platinum wire and cylinder gas caused by turbulence.

To confirm this point, another experiment was carried out to measure the wire temperature simultaneously at two different locations in the cylinder. Two platinum wires were extended at A-B and A-C as illustrated in Fig. 1. The supporting rods located at B and C, to which each of the end of the wires was welded, were made of iron. For convenience, the wires of A-B and A-C are called a tangential wire and a radial wire, respectively, in the following description. The measuring error due to electromotive force at the junctions of the platinum wires and the iron rods was considered negligible in preliminary tests. Figure 8 (A) shows the typical record of the two wire temperatures: the curve reaching higher near the maximum point represents the temperature of the radial wire. The difference between the radial and tangential wire temperatures was observed to vary from cycle to cycle, but the former was always observed to be higher than the latter near the maximum point. It will be noted on Fig. 8 (A) that the difference between the maximum and minimum temperatures is larger for the radial wire than for the tangential wire, and in addition the former responds more quickly than the

Fig. 7 Platinum-wire temperature and cylinder pressure recordings of several successive cycles in motoring

* An error in reading crank angles for the maximum and minimum points was about ± 1 deg in this experiment. This error corresponds to an error of approximately ± 10 °C in the maximum temperature calculated on the basis of the minimum temperature.

latter. These facts may suggest that the heat transfer coefficient is higher around the radial wire than around the tangential wire. Then, it may be possible to consider that the temperature difference is related in some degree to the swirl of air charge in the cylinder. Figure 8 (B) shows the data for the engine operated with no supply of scavenging air, which presumably had the effect of preventing a swirl generation. It may be noted on the figure that the difference between the two wire temperatures is much less than in the former. Thus, the cycle-to-cycle variation of the wire temperature might be due to the turbulence of cylinder gas. Accordingly, it may be deduced that the heat transfer coefficient is not uniform along the wire and its cycle-to-cycle

Fig. 8 Comparison of wire-temperature at two different locations, motoring data at 1000 rpm. A: with scavenging air, B: without scavenging air

Fig. 9 Platinum-wire temperature and cylinder pressure recordings for a fired engine

variation causes the temperature variation of the wire from cycle to cycle. However, as stated before, the variation of the maximum and minimum points of the wire temperature scarcely gives an error in calculating the average gas temperature in a cylinder. Figure 9 shows a typical synchroscope records for the firing engine. The engine load was restricted to about 2 kg/cm^2 in mean effective pressure so that the platinum wire might not be melted off by high temperature gas. Figure 10 shows the replots of typical three records under the same operating conditions of the engine at 1000 rpm and 1400 rpm. Here it is seen that the cycle-to-cycle variation of the wire temperature is much larger than that of the motoring data. To calculate the average gas temperature by the aforementioned method, an increase in cylinder gas weight due to fuel injection and a variation of gas constant have to be taken into consideration. However, these differences may be safely disregarded under such a light load, because the fuel weight was estimated at only 0.3 % of the weight of the whole cylinder gas and the variation in the gas constant was evaluated at only 0.1 %. The solid line and dot-dash-line in Fig. 10 represent the cylinder gas temperatures at the two engine speeds obtained by assuming $GR/G_M R_M = 1$, and taking the minimum temperature as T_M . The three minimum temperatures at each engine speed are seen to vary in both amplitude and crank angle from cycle to cycle. However, they give almost the same cylinder gas temperature. Thus, the minimum temperature

Fig. 10 Platinum-wire temperature and cylinder gas temperature versus crank angle in a fired engine

might represent the average gas temperature in spite of its cycle-to-cycle variation.

As for the maximum temperatures, it is seen from Fig. 10 that they do not meet the cylinder gas temperature curves except in one example. This suggests that the maximum temperature is hardly adequate for the determination of the average cylinder gas temperature. Presumably, this deviation is due to the spatial variation of gas temperature existing in a cylinder. Since the spatial variation in cylinder gas temperature would be averaged as the expansion process goes on towards its end, the slower response of the thermometer using a larger diameter wire would be preferable if the average temperature is needed for the maximum point.

5. Estimation of errors

5.1 The error due to the neglect of temperature difference in the cross-section of the wire

As described before, Eq. (1) is valid for the case when the temperature distribution in the cross-section may be considered uniform. The error estimated for the conditions of this experiment is as follows.

Let us consider the unsteady heat conduction in a circular cross-section with a diameter of d_w . Assuming that the heat transfer coefficient on the wire surface is infinite, we have the equation for the difference between the surface temperature and the average temperature on the whole cross-section of the wire exposed to gas, temperature of which varies sinusoidally with an angular velocity of ω and an amplitude of θ_0 degree⁽⁷⁾:

$$\Delta\theta_w = -\frac{1}{32a}\theta_0\omega d_w^2 \sin \omega t$$

where

a : thermal diffusivity cm^2/sec

Accordingly,

$$\Delta\theta_w/\theta_0 \leq \omega d_w^2/32a$$

The maximum error in this experiment would occur for $d_w=0.005\text{ cm}$ and $\omega=1400 \times 2\pi/60$ (1400 rpm). The value of a for platinum is $0.25\text{ cm}^2/\text{sec}$. Using these values, we estimate the error as follows:

$$\Delta\theta_w/\theta_0 \leq 5 \times 10^{-4}$$

Even for higher frequency components with an angular velocity of 10ω , the error amounts to only 0.5 %.

5.2 The error due to the neglect of temperature difference along the wire

For simplicity, attention will be confined here to one-dimensional steady-state heat transfer along the fine wire. The estimation of the error will be represented in the form of the ratio of the average temperature along the wire $\bar{T}_w$ to the temperature of an infinite length wire T_∞ . For present analyses,

the Joule's heat is disregarded, i.e. $\zeta=0$ in Eq. (1). Consequently, T_∞ is equal to T . In this case, Eq. (1) reduces to

$$\eta^2 \frac{d^2 T_w}{dx^2} + T_\infty - T_w = 0$$

The boundary conditions to be met are:

$$T_w = T_r \text{ at } x=0$$

$$dT_w/dx = 0 \text{ at } x=l_w/2$$

where T_r is temperature at both ends of the wire and l_w is length of the wire between the supporting rods. Using the above boundary conditions, the solution of the equation for the constant η is

$$\frac{T_w}{T_\infty} = 1 + \left(\frac{T_r}{T_\infty} - 1 \right) \frac{l_w}{2\eta} \frac{\cosh(2x/l_w - 1)}{\cosh(l_w/2\eta)}$$

From this equation, we obtain the equation for $\bar{T}_w/T_\infty$:

$$\frac{\bar{T}_w}{T_\infty} = 1 + \left(\frac{T_r}{T_\infty} - 1 \right) \frac{2\eta}{l_w} \tanh \frac{l_w}{2\eta}$$

The second term on the right-hand side indicates the error.

The error estimated for the motoring data at 1000 rpm (Fig. 5) is as follows:

(1) The error in the minimum temperature

$$d_w = 0.005\text{ cm}$$

$$l_w = 2.5\text{ cm} \quad (\text{the shortest length of the triangle})$$

$$T_r = 467^\circ\text{K} \quad (\text{the temperature of the platinum wire averaged over one cycle})$$

$$T_\infty = 383^\circ\text{K}$$

$$\lambda_w = 0.17\text{ cal/sec cm deg} \quad (\text{the value for } \bar{T}_w \doteq T_\infty = 383^\circ\text{K})$$

$$\lambda_g = 0.77 \times 10^{-4}\text{ cal/sec cm deg} \quad (\text{the value for } T \doteq T_\infty = 383^\circ\text{K})$$

The evaluation of the Nusselt number N_u was made referring to the relation of N_u to a Reynolds number R_e obtained for the heat transfer between a fine platinum wire and gas⁽⁸⁾. Here R_e is defined as

$$R_e = u d_w / \nu$$

where

u : flow velocity around wire

ν : kinematic viscosity of air

For present calculations, the following values are used:

$$u = 15 \times 10^2\text{ cm/sec}$$

$$(\text{given by the experimental results of the swirl velocity measurement on a similar engine}^{(9)})$$

$$\nu = 0.11\text{ cm}^2/\text{sec}$$

$$(\text{the value for the minimum point conditions: temperature } 383^\circ\text{K, pressure } 2.16\text{ kg/cm}^2)$$

The resulting value of R_e is 68, for which N_u becomes 3.8. These values gives $\eta = 0.061\text{ cm}$. Then the error amounts to 1 %.

(2) The error in the maximum temperature

d_w , l_w , and T_r are the same as those given above.

$$T_\infty = 598^\circ\text{K}$$

$$\lambda_w = 0.18\text{ cal/sec cm deg} \quad (\text{the value for } \bar{T}_w \doteq T_\infty = 598^\circ\text{K})$$

$$\lambda_g = 1.09 \times 10^{-4} \text{ cal/sec cm deg}$$

(the value for $T = T_\infty = 598^\circ\text{K}$)

u is assumed to be the same as that in the above case.

$$\nu = 0.032 \text{ cm}^2/\text{sec}$$

(the value for the maximum point conditions :
temperature 598°K , pressure 16.1 kg/cm^2)

For these values, R_e becomes 230, and then N_u is estimated to be 8.0. Accordingly, η amounts to 0.036 cm. Thus, the error comes up to 0.6 %.

As for the unsteady heat transfer, a similar equation for $\bar{T}_w/T_\infty$ had been obtained with less error than the steady state⁽¹⁰⁾.

5.3 The error due to the neglect of Joule's heat

This estimation is made also from a steady state point of view, and for the infinite length wire.

Rearranging Eq. (1), we have

$$\frac{T_w}{T} = 1 + \zeta \left\{ \frac{1}{T} + \beta \left(1 - \frac{273}{T} \right) \right\}$$

The error is represented by the second term on the right-hand side.

From the experiment, the following values are provided :

$$I = 5 \times 10^{-3} \text{ A}, \quad r_0 = 0.54 \text{ } \Omega/\text{cm}$$

For N_u and λ_g , the same values previously used in the case of the minimum temperature are adopted. The value of β for platinum is 0.00392 deg^{-1} . Then, $\zeta = 3.5 \times 10^{-3} \text{ deg}$ for the minimum point. Thus, the error is estimated to be 0.001 %.

As for the error at the maximum point, $\zeta = 1.2 \times 10^{-3}$ and then the error amounts to 0.0005 %.

6. Conclusion

A new method for determination of the average cylinder gas temperature has been introduced. The measuring principle is as follows: At the maximum or minimum point of the fluctuating temperature of a thin metallic wire exposed to gas, the wire

temperature agrees with gas temperature. This temperature gives the basic temperature to determine gas temperature at the other points of the cycle, using the equation of state in conjunction with an indicator diagram, in so far as the maximum or minimum temperature represents the average temperature of the whole gas in a cylinder. The motoring data taken on a two-stroke diesel engine by employing a platinum resistance thermometer have verified this method. The examination of the firing data has shown that the minimum temperature of the wire appearing in a compression stroke is representative of the whole gas in a cylinder and therefore it is applicable as the basic temperature, while the maximum temperature of the wire occurring in an expansion stroke hardly represents the average temperature. Thus the minimum temperature is found to be the basic temperature to give the average temperature of cylinder gas during compression and expansion strokes. This method would enable us to obtain experimentally cylinder gas temperatures at the beginning of compression and blowdown, which had been previously considered almost impossible.

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