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The Experimental Study on Transient Surface Temperature of the Piston Coated with Ceramic

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1 Introduction

The surface temperature of a tube or plate wall is usually measured by means of a thermo-couple. The conventional practice is to solder the ends of two wires of different metal directly onto the surface to be measured as shown in Fig.1 . To ensure good contact of the

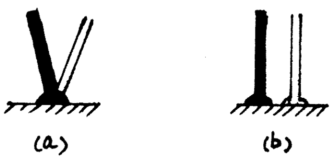

Fig.1 Conventional Thermo-Couple Solder
(a)Vee
(b)Parallel

couple to the surface, the size of the soldered joint must not be too small . The obvious disadvantages of such a conventional couple are as follows

1) It is difficult to apply the conventional thermo-couple onto a non-metallic wall surface , which is non-weldable , thus calling for a more reliable means of connection so that the readings obtained may better reflect the true temperature of the surface ;

2) The bulk of the solder joints offer thermal delay in response to the temperature changes and when such changes are severe , the error introduced will be large ; and

3) If exposed to the flame , the leads to the couple are likely to have a very short life span .

Such disadvantages will be more pronounced in the case of an adiabatic engine with ceramic coating on the piston if ordinary thermo-couple is used for the temperature measurement . To reduce heat loss , the cylinder head bottom and the cylinder liner top wall eveloping the combustion chamber may also be coated with ceramic . As a result of the introduction of such insulation on the chamber walls , the overall temperature of the working cylinder will be increased and the ceramic coating will be subjected to a highly fluctuating temperature .

The ceramic is a brittle material , very sensitive to thermal stress and impact , hence the importance of the study of the ceramic coated surface temperature of the corresponding parts in the adiabatic engine . Indeed , the maximum surface temperature of the ceramic coating of the engine piston lies between 300-800°C which falls inside the range for ordinary thermo-couple measurements . But the high temperature fluctuation calls for higher response speed . Difficulties of soldering and of mounting the leads inside the working cylinder with burning gas are also voters against the use of the ordinary couple .

2 The Sputter-Film Thermo-Couple

Fig.2 gives a sketch of the couple after it has been sputtered onto the

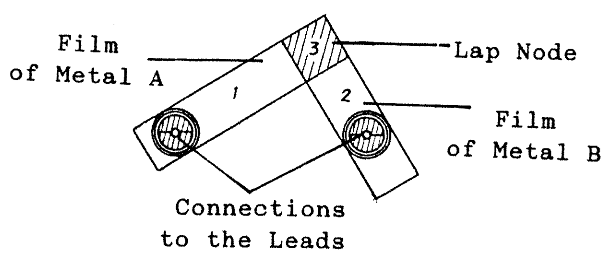

Fig.2 Sputter-Film Thermo-Couple

workpiece . It comprises of two rectangular tape films of two different metals . The lapped ends of the two films form the couple node and its working principle is the same as the ordinary wire couple . But the sputter-film is much thinner , generally of 0.5-1.0 μm thickness only . It adheres much better to the job surface and therefore reflects much closer to the true state of its temperature . Furthermore , since the node is thin and small , the thermal inertia is small , which means that the speed of response is high.

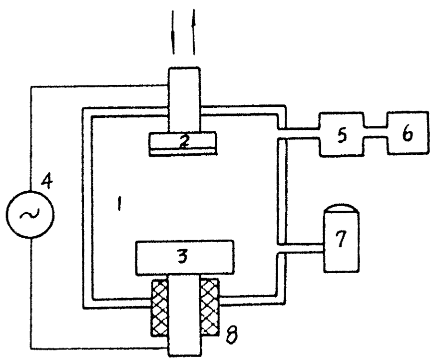

Fig.3 High Frequency Sputter-Coating Arrangement

Fig.3 shows the arrangement of the sputter-coating technique applied to an engine piston . Installed in vacuum chamber 1 are the cathode 2 and anode 3 . The end of the cathode is the target disk of the sputter metal while that of the anode provides with the workpiece to be sputtered on , 4 is the power source of 400 wt and 13.56 MHz .

The target and the workpiece must be chemically cleaned thoroughly and all surfaces covered up by glue paper or other suitable means with the exception of the surface to be sputtered , before they are put into the vacuum chamber at their respective locations of cathode and anode ends . The vacuum of the chamber is built up by means of a 2-stage mechanical and diffusion type vacuum pump . When the pressure drops down to $5*10^{-6}$ Torr , argon from bottle 7 is discharge into the chamber until the pressure increases to $3*10^{-2}$ Torr when ionization flares appear . For the normal working condition , the pressure is kept within a range of $5*10^{-3} \sim 1*10^{-2}$ Torr in which the argon ions under the action of field force , bombard the target metal , causing part of the atoms and radicals to ionize and sputter onto the surface of the anode forming a thin film acting as one terminal of the thermo-couple . The sputtering process is improved by providing an electric heating device , keeping the working temperature at 100 ~ 200 °C , For a power of 400 wt a film thickness of 1 m can be built up in about 30 minutes . The other terminal of the thermo-couple can be formed in the same way by changing the target metal and move the cover to the terminal already formed , leaving a space for the node .

In the making of the sputter-film thermo-couple , one of the main difficulties to be overcome is to ensure good contact at the connection of the lead to the film with thinness of about 1 μm and with little mechanical strength. External loading and thermal distortion are both detrimental so that a special layout of construction of the couple system is essential . Fig.4 shows the arrangement

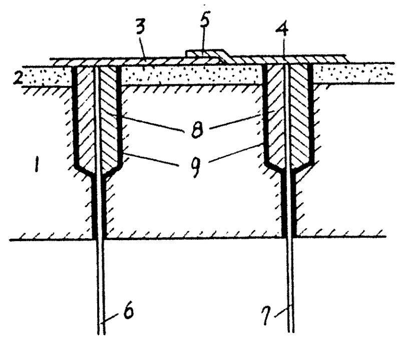

Fig.4 Arrangement of Leads to the Sputter-Film Thermo-Couple

of the authers' design , in which 2 is the ceramic coating on the base metal , 3 and 4 are the sputtered films , the lapped ends of which form the couple node 5 . Two holes of Φ2 are drilled and reamed with a slight taper at a suitable distance away from the node on each side . Inserted into the taper holes are two pairs of cone-halves , grooved at the centre to receive the Φ0.5 leads which are of the same metal corresponding to the sputter films . Cone-halves and leads are provided with insulation against the metal body . Suitable tightness must be ensured to avoid loosening of the leads while the cone-halves are driven in after which the protrusions are ground flash with the ceramic surface . The ends of the leads should be amply covered up after sputtering . Finally , the circuit is checked for all the contacts to be good and then a thermo-couple of high temperature proof with true register of the fluctuating temperature to be measured is completed .

Caliberation of the couple can be done in the same way as that of the ordinary by placing the workpiece inside the furnace and compare the readings with that of the standard thermo-couple . The sputter-film thermo-couple dynamic response speed is very high so that dynamic caliberation of the couple is rarely needed except under very unusual requirements .

3 Results Obtained as an Application of the Sputter-Film Thermo-Couple

The engine tested is a 2-135G Diesel with ZrO_2 coated piston crown of thickness 0.01 mm , with the specifications :

Diesel Engine Type	2-135 of 4-Stroke Cycle
Cylinder Diameter	135 mm
Piston Stroke	140 mm
Rated Speed	1500 r.p.m.
Comp. Ratio	16.5
Comb. Chamb. Type	ω
Rate Output	36 HP

Fig.5 gives the locations of the thermo-couple on the piston crown of the engine with A and B in the cavity and C on the top face. To lead out the electric

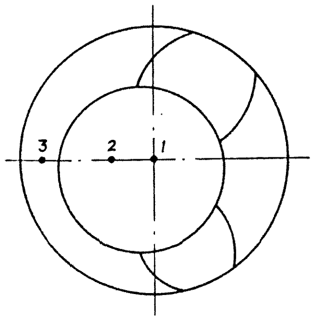

Fig.5 Locations of Thermo-Couple on the Piston Crown

signal from a highly reciprocating member a highly rotating member of the mechanism to the stationary , a 4-Link joint is used , Fig.6 , and proved to be reliable.

Fig.7 shows the scheme of the testing arrangement and data processing system , in which 2 is the brake to register the engine output . A , B and C represent the temperature data on the piston crown which are to be collected by the data acquisition unit 7 controlled by micro-processor 8 with display 9 and printer 10 . Since the temperature of the piston crown varies periodically with the

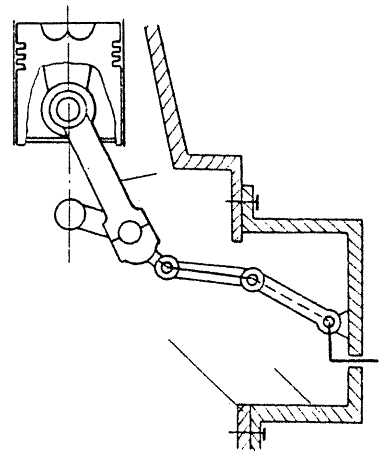

Fig.6 The 4-Link Joint

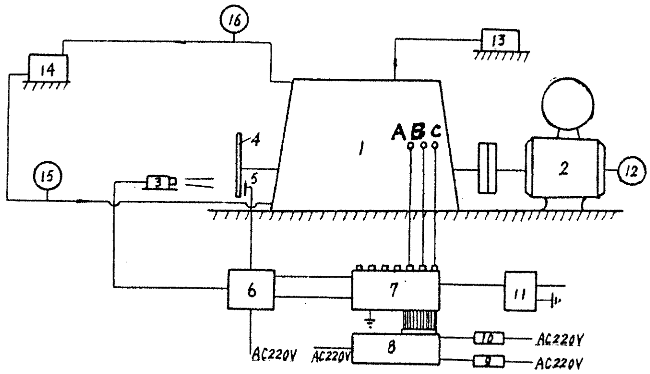

Fig.7 Data Processing System of the Test Arrangement

crankangle positions , the latter have to be registered simultaneously with the temperature and input to 7 by means of the crankangle marking system composed of light source 3 , rotating grid 4 , photo cell 5 , trimmer 6 , etc.

Fig.8 and 9 give the test results of ZrO_2 coated piston as compared with the ordinary . It is seen that at n=1200 r.p.m. an average temperature 330 °C at point A on the original aluminium piston of the 2-135 engine is attained . The temperature fluctuation is 18 °C with an instantaneous peak value of 343 °C . When the piston crown is coated with ZrO_2 the average temperature increases to 415 °C . The temperature fluctuation increases to 60 °C and peak value to 465 °C which takes place at a crankangle slightly earlier . When the speed of the engine drops the temperature fluctuation and the peak will both increase either for the piston with coating or without . The lower the engine speed , the earlier the peak takes place.

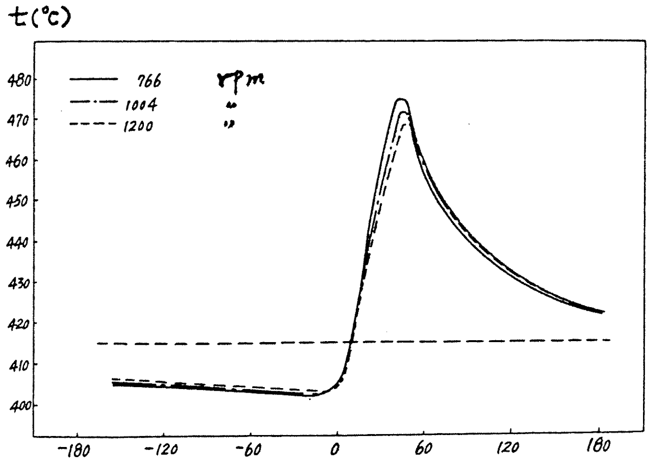

Fig.8 Temperature at Point A on Surface of ZrO_2 Coated Piston

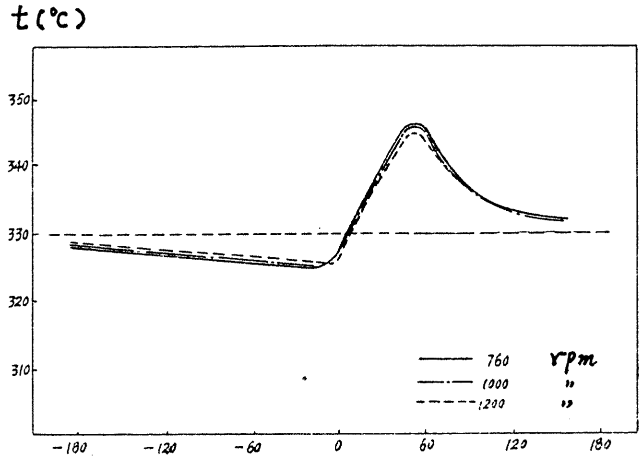

Fig.9 Temperature at Point A on Surface of Uncoated Piston

4 Accuracy and Response Speed of The Sputter-Film Thermo-Couple

Accuracy , response speed , adaptibility to environmental conditions and stability are the main requirements in the measurement of temperature . The dynamic characteristics of the thermo-couple can be visualized by establishing its physical as well as mathematical models .

Let M(kg) be the reduced mass of the node of the couple , Cp(J/kg.K) the specific heat , and A(m^2) the area through which the heat flows . When the couple is suddenly placed in a medium of temperature To , the instantaneous quantity of heat flow to the node can be determined by the temperature difference between the medium and the node , the coefficient of heat conduction between the two and the area through which the heat is conducted . Neglecting the loss due to conduction and radiation , the quantity of heat dQ_1 conducted to the node within time dt can be expressed as

$$dQ_1 = \alpha_c A(To-T)dt \qquad (1)$$

in which

T--instantaneous temperature of node

To-temperature of medium to be measured

and α_c-coefficient of heat conduction between medium and node ($J/m^2.h.K$)

Absorption of heat dQ_2 by node will cause its temperature to rise . This gives

$$dQ_2 = CpMdT \qquad (2)$$

Equation (1) and (2) , the mathematical model of the thermo-couple is obtained as

$$\frac{dT}{dt} + \frac{T}{\tau} = \frac{To}{\tau} \qquad (3)$$

in which $\tau = \frac{CpM}{\alpha_c A}$ --- is a time-constant .

1) Frequency Response of Thermo-Couple

In (3) , assuming the in-put T is sinusoidal ,

i.e. To=TmSinωt

then the function of frequency response will be

$$H(j\omega) = \frac{Y(j\omega)}{X(j\omega)} = \frac{1}{j\omega\tau+1} \qquad (4)$$

with amplitude

$$|H(j\omega)| = \frac{1}{\sqrt{(\omega\tau)^2+1}} \qquad (5)$$

and phase $\varphi = tg^{-1}(-\omega\tau)$ (6)

in which $Y(j\omega)$--Out-put signal

and $X(j\omega)$--In-put signal

Let the engine speed be n=1200 r.p.m. Then the period of the T-wave will be 0.1 sec and the circular frequency will then be $\omega = 2\pi/0.1 = 20\pi$

Table 1 gives the frequency response characteristics of two ordinary and one sputter-film thermo-couples .

Table 1 Frequency Characteristics

Thermo-Couple Type	Time Con. τ (sec)	$\omega\tau$	Ampl. H	Phase φ
Bi-metallic-wire, 0.1mm	0.016	1.005	0.705	45.14
Bi-metallic-wire, 0.05mm	0.011	0.691	0.822	34.64
Sputter-film thickness,1μm	0.0001	0.006	0.999982	0.34

2) Step-Input Response

The temperature in-put at t=0 is T=0 , At t>0 , after the couple was suddenly placed in the medium of To , time is needed for the temperature to be built up due to thermo inertia of the couple . This time can be attained by solving equation (3) which leads to

$$T=To(1-e^{-t/\tau}) \quad (7)$$

The smaller the time constant , the shorter the delay . For comparison , consider T=0.99To , i.e. when the temperature of the thermo-couple reaches 99% of the in-put . The time required will be , from (7) ,

$$t=\tau \cdot \ln 100$$

Table 2 lists the Step-Input Response of the three thermo-couples . It is seen that in the case of sputter-film thermo-couple the response is very much

Table 2 Step-Input Response

Thermo-Couple Type	Time Req'd to Reach 99% of Input (ms)
Bi-metallic-wire ϕ 0.1 mm	73.7
Bi-metallic-wire ϕ 0.05 mm	50.6
Sputter-film thickness,1 μm	0.46

quicker , nearly 160 times as fast as one and 110 times as that of the other . Hence its adaptibility in the field of high frequency fluctuating temperature measurement , ensuring higher precision than that of the ordinary wire type . Fig.10 shows the temperature-time response curves of the three couples .

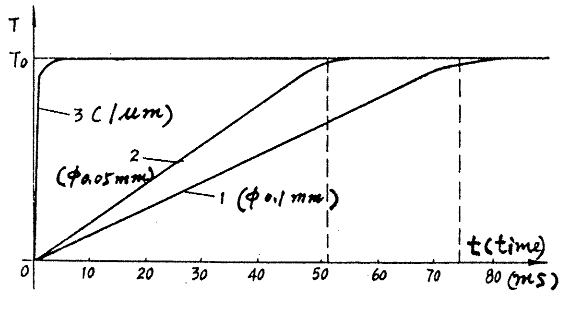

Fig.10 Temperature-Time Response Curves of Three Thermo-Couples

5 Cyclic Temperature Fluctuations of Pistons without and with Ceramic Coating

Consider the combustion chamber wall as a flat plate of thickness contacting with water of temperature Tw on one side combustion gas of temperature Tg on the other . Tg is a cyclic fluctuating temperature which is a unique feature of the engine . Let a point O on the gas side of the wall surface be the origin , axis X points perpendicular and inward to the wall , which is the sole route of heat transfer . Those along axes Y and Z are to be neglected , then

$$\frac{\partial^2 T}{\partial y^2}=\frac{\partial^2 T}{\partial z^2}=0$$

and

$$\frac{\partial T}{\partial \tau}=a\frac{\partial^2 T}{\partial x^2}$$

in which

τ-time(hr)

$a=\frac{\lambda}{C\gamma}$ -coefficient of temperature conductivity

λ-coefficient of heat conductivity

C-specific heat

γ-weight density

The wall temperature T is composed of two parts , a cyclic function f(X,C) which determines the fluctuating part of T , and a temperature-independent function φ(X) which determines the steady portion , [1] , i.e.

$$T=f(X,C)+\varphi(X)$$

The temperature fluctuation on the gas side is then

$$\Delta T=T-Tm=\sum_{\nu=1}^{\infty} C_\nu \cos(\nu\omega\tau-\sigma_\nu)$$

in which

Tm-mean temperature of wall surface on the gas side , corresponding to the temperature produced by steady flow of heat per cycle

T--instantaneous temperature of wall surface on the gas side

ν--harmonic order

ω--engine crank circular frequency

σ_ν--phase difference between temperature wave of gas and that of the wall .

In the case of a 4-stroke Diesel engine

$$C_\nu \propto \frac{\sqrt{2}}{\sqrt{C\cdot\gamma\cdot\lambda}}$$

i.e. the wall temperature fluctuation is inversely proportional to the square roots of the specific heat C(kcal/kg.°C) density γ (kg/m^3) and coefficient of heat coduction λ(kcal/m.h.C) . In the case of the example quoted in this paper , these parameters of the ceramic PSZ coated piston and that of the original are respectively

	0.14	$6.1*10^3$	7.9
and	0.212	$2.66*10^3$	150

which shows that the temperature fluctuation of the ceramic coated piston is 3.53 times as large as that of the original , and this figure agrees fairly well with that obtained by test .

6 Conclutions

1)The high frequency sputter-film thermo-couple is an effective means for the recording of highly fluctuating surface temperature of objects especially non-metallic . Advantages of such a thermo-couple are quick response with small error . Its insertion onto the job would not distort much of the temperature field of the original and can be applied with ease onto the ordinary piston

2)With a sputtered layer of ZrO of 1mm , the increase of average temperature is 85 C , maximum temperature increase 122 C and fluctuation 60 C , and the peak temperature occurs distinctly earlier than that of the original .

3)Tests show that the 4-Link wire guide and the high-speed data acquisition system work well .

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