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Gas Temperature Measurement Using Ultrasonic Waves*

By Joji YAMAGA** and Shuji SHIBATA***

If there occurs a rapid temperature change in the gas while constant frequency sound waves are passing through the gas, the waves undergo frequency change after passing through the gas. That is, the receiver receives the sound waves with a frequency different from that of the sound source.

Here, the mathematical relations between the frequency change of the sound waves and the temperature change dT/dt (T : absolute temperature of gas, t : time) of the gas are derived and by integrating these relations the relations between the frequency change of the sound waves and the gas temperature T are obtained. From these relations, using the obtained data of the frequency change of the sound waves, it is possible to measure the temperature T and the temperature change dT/dt of the gas.

The experiments are successfully done with the polytropically compressed air in a rapid compression machine equipped with sound source and receiver using ultrasonic waves. The measured temperature based on this principle is coincident with the temperature calculated from measured pressure volume relations assuming polytropic change of the air in the machine. The maximum temperature change attained in the measurement is about several tens of thousands degrees centigrade/second. From this fact it is surely expected that this method will be applicable for the measurement of instantaneous gas temperatures in reciprocating engines.

1. Introduction

It is one of the most difficult problems to measure the transient temperature of the combustion gas in a reciprocating engine. This is due to the facts that the temperature change in the gas occurs rapidly and the temperature itself is relatively high. Hitherto, thermocouples or resistance thermometers have been used, but these are not successful in the accurate measurement of temperature because of their high heat loss and large heat-capacity of the probe. An optical method was also applied but it was not satisfactory in accuracy. For these reasons, it is customary to estimate thermodynamically the temperature of the gas in the cylinder of the engine during one cycle using $p\sim v$ diagram or pressure-time relation.

On the other hand, there exists what is called the velocity of sound method. This method makes use of the theory that the sound velocity in the gas depends only on the absolute temperature of the gas. The velocity measuring technique by

measuring directly the time for the sound wave to pass through the predetermined length in the combustion gas in engine was developed successfully in MIT⁽¹⁾.

The method here proposed is a modified velocity of sound method but the direct detecting object is the temperature change dT/dt (T : absolute temperature of the gas, t : time). This temperature change is detected by the frequency change of the ultrasonic wave passing through the gas. The principle is to be explained in the next chapter.

2. Nomenclature

- T : absolute temperature of gas
- p : absolute pressure of gas
- a : sound velocity of gas
- m : molecular weight of gas
- γ : specific heat ratio of gas
- R : universal gas constant
- t : time, also representative time between t_1 and t_2
- t_1 : instant at sound source
- t_2 : instant at receiver
- Δt_1 : one periodic cycle of sound wave at sound source
- Δt_2 : one periodic cycle of sound wave at receiver

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** Chief of Planning Section, The Government Mechanical Laboratory, Suginami-ku, Tokyo.

*** Research Engineer, The Government Mechanical Laboratory.

f : frequency of sound wave at receiver

f_1 : frequency of sound wave emitted from sound source at instant t_1

f_2 : frequency of sound wave received at receiver at instant t_2

Δf : frequency change $= f_2 - f_1$

L : distance between sound source and receiver

Subscript

0 : value at initial condition

3. Principle of measurement

In the conventional methods it was tried to measure the gas temperature itself directly. But this new method aims to detect directly the gas temperature change dT/dt and obtain the gas temperature by integrating dT/dt . The principle of measurement is as follows.

If there occurs a rapid temperature change in the gas while constant frequency sound waves are passing through the gas, the waves undergo frequency change after passing through the gas. That is, the receiver accepts the sound waves with a frequency different from that of the sound source. When the gas temperature change dT/dt is positive, that is, when the temperature is increasing, the sound waves passing through the gas increase their frequency, but when the gas temperature change dT/dt is negative, that is, when the gas temperature is decreasing, the sound waves decrease their frequency. The phenomena will be

Fig. 1 Temperature T , sound velocity a and frequency f ~time curves which denote temperature change phenomena

explained mathematically as follows. It is assumed that the absolute temperature T of the gas changes with time t as shown in Fig. 1. In the case of an ideal gas or a real gas of not so high temperature or pressure, the sound velocity of the gas depends only on the absolute temperature. When the specific heat ratio of the gas, the universal gas constant, and the molecular weight of the gas are denoted by γ , R and m , respectively the relation between the absolute temperature T and the sound velocity a is expressed as follows.

$$T = \frac{ma^2}{\gamma R} \dots \dots \dots (1)$$

The change of the sound velocity a of the gas is determined directly by Eq. (1) when γ , R and m are constant, and is shown in Fig. 1.

Here a small portion of the sound velocity curve in Fig. 1 is taken up and shown in Fig. 2. Let Δt_1 be one periodic cycle of the sound waves which start from the sound source at instant t_1 and let Δt_2 be the one periodic cycle of this sound wave at instant t_2 when they reach the receiver.

When the distance between the sound source and the receiver is L , the following equation is given.

$$L = \int_{t_1}^{t_2} a dt = \int_{t_1 - \frac{\Delta t_1}{2}}^{t_2 - \frac{\Delta t_2}{2}} a dt = \int_{t_1 + \frac{\Delta t_1}{2}}^{t_2 + \frac{\Delta t_2}{2}} a dt$$

Because the integration $\int_{t_1 + \frac{\Delta t_1}{2}}^{t_2 + \frac{\Delta t_2}{2}} a dt$ is com-

mon in the above integrals, the following formula is derived.

$$\int_{t_1 - \frac{\Delta t_1}{2}}^{t_1 + \frac{\Delta t_1}{2}} a dt = \int_{t_2 - \frac{\Delta t_2}{2}}^{t_2 + \frac{\Delta t_2}{2}} a dt \dots \dots \dots (2)$$

Eq. (2) shows that the two hatched areas in

Fig. 2 Small portion of sound velocity ~ time curve in Fig. 1

Fig. 2 are equal. From the straight line approximation of the curve in Fig. 2, it follows that

$$a(t_1)\Delta t_1 = a(t_2)\Delta t_2 \dots\dots\dots(3)$$

Let f_1 be the frequency at the sound source and let f_2 be the frequency at the receiver at the instant t_2 , then the relation between the frequency and the sound velocity is given as follows using Eq. (3) and the reciprocal relation of the periodic cycle Δt and the frequency f .

$$\frac{f_2}{f_1} = \frac{a(t_2)}{a(t_1)} \dots\dots\dots(4)$$

For the reason that the instants t_1 and t_2 are mutually adjacent instants, it is reasonable that instant t at a central position between $t_1 \sim t_2$ in Figs. 1 and 2 is a representative instant between the instants t_1 and t_2 . Because the frequency at the sound source is constant, notation f_0 is used hereafter instead of f_1 . Then the following is derived using notation $\Delta f = f_2 - f_1$.

$$\begin{aligned} \frac{\Delta f}{f_0} &= \frac{f_2 - f_1}{f_1} = \frac{a(t_2) - a(t_1)}{a(t_1)} \\ &= \frac{a(t_2) - a(t_1)}{t_2 - t_1} \cdot \frac{t_2 - t_1}{a(t_1)} = \frac{\frac{da}{dt} L}{a(t)} \dots\dots(5) \end{aligned}$$

Here, the approximation $\frac{a(t_2) - a(t_1)}{t_2 - t_1} = \frac{da}{dt}$ and $t_2 - t_1 = \frac{L}{a(t)}$ were used in the derivation. After all, one can write

$$\frac{\Delta f}{f_0} = \frac{L}{a^2} \frac{da}{dt} \dots\dots\dots(6)$$

This equation is the fundamental expression of the measuring principle that is proposed in this paper. Eq. (6) shows that the frequency change Δf at the receiver is proportional to the differentiation of the sound velocity with respect to time and distance L and is conversely proportional to the square of the sound velocity. The curve of measured frequency f at the receiver in Fig. 1 must satisfy Eq. (6) under the condition that the time interval $t_2 - t_1$ is very small compared with the time interval of the whole temperature change.

Substitution of Eq. (1) into Eq. (6) leads to

$$\frac{\Delta f}{f_0} = \frac{L}{2 \left(\frac{\gamma R T}{m} \right)^{1/2} T} \frac{dT}{dt} \dots\dots\dots(7)$$

Using the initial condition that the temperature T is T_0 at the time $t=0$, the integration of Eq. (7) leads to the following.

$$\frac{T}{T_0} = \left\{ 1 - \frac{\left(\frac{\gamma R T_0}{m} \right)^{1/2}}{L} \int_0^t \frac{\Delta f}{f_0} dt \right\}^{-2} \dots\dots\dots(8)$$

The frequency $f (= f_0 + \Delta f)$ of the sound waves received at the receiver in Fig. 1 is the object for

measurement when the temperature T of the gas changes as expressed in Fig. 1 while frequency of the sound source f_0 is constant.

By measuring the frequency Δf and using Eq. (8), it is possible to obtain the absolute gas temperature T as a function of the time t .

When it is desired to get the rate of the change of temperature with respect to time ($=dT/dt$), the following equation has to be used.

$$\frac{d \left(\frac{T}{T_0} \right)}{dt} = \frac{2 \left(\frac{\gamma R T_0}{m} \right)^{1/2} \frac{\Delta f}{f_0}}{\left\{ 1 - \frac{\left(\frac{\gamma R T_0}{m} \right)^{1/2}}{L} \int_0^t \frac{\Delta f}{f_0} dt \right\}^3} \dots\dots\dots(9)$$

In our experiment the ultrasonic waves are chosen as the sound waves because of the following merits.

(1) By using ultrasonic waves, it is easy to avoid the mixing of the noises from the environment.

(2) Precision of the measurement is increased owing to their high frequency.

(3) Good directivity of the ultrasonic waves minimizes the interferences and the reflections of the waves.

4. Experiment

The rapid compression machine and the connected electrical circuits used in the experiment are shown in Fig. 3.

Before starting the experiment, the compressed air (gauge pressure 4~6 kg/cm²) fills the accumulator which is separated by a cellophane membrane from the adjacent chamber, and the sound source driven by the oscillator through amplifier emits the ultrasonic waves in the direction of the receiver which maintains a predetermined distance from the sound source. By instantaneous breaking of this membrane with a needle, the compressed air flows out, pushes the piston and compresses the air in the air chamber. At the left-side part of the air chamber in Fig. 3 there exists a cylindrical

Fig. 3 Rapid compression machine and connected electrical circuits

cal air space in which the sound source and the receiver made with Barium Titanate are installed. This cylindrical air space has dimensions of length 80 mm and diameter 24 mm. The temperature of the air in the air chamber is raised through the polytropic compression of the air and at this instant the receiver receives the ultrasonic waves which undergo the frequency change while passing through the air.

Electrical signals from the receiver are amplified by the preamplifier and pass through the discriminator and the integrator, and finally the frequency change $\Delta f/f_0$ and the integrated frequency change $\int \frac{\Delta f}{f_0} dt$ are recorded by the pen-writing oscillograph as shown in Fig. 3.

In these electrical circuits, full care is taken in filtering the electrical and mechanical noises from all sorts of sound sources. For instance, the electrical output of the receiver originating from the pressure change of the air has to be filtered.

The stroke of the piston is detected by the sliding resistor and the output of the sliding resistor is fed to the pen-writing oscillograph.

For the comparison of the measured temperature data of this new technique with the temperature derived from measured pressure using polytropic change equation, a pressure pick-up is attached at the central position of the space, and the pressure is recorded by the pen-writing oscillograph through pressure monitor. The details of the air space are shown in Fig. 4. A Barium Titanate piece for the sound source has dimensions of thickness 13 mm and diameter 10 mm and one for the receiver has thickness 2 mm and diameter 10 mm. They are 38 mm apart, that is, the length L equals 38 mm.

Before performing the experiment, it is necessary to check whether the dimensions of this experiment may satisfy the condition of approxi-

Fig. 4 Details of measuring equipment in cylindrical air space

mation for Eq. (6) or not. The condition of approximation is that the time for the sound waves to pass the length L is sufficiently small compared with the time interval of the total temperature change phenomena. In this experiment, the time for the sound waves to go length L is approximately

$$\frac{L}{a_0} = \frac{0.038}{340} = 1.12 \times 10^{-4} \text{ sec}$$

On the other hand, the time interval of total temperature change phenomena is approximately $3.0 \times 10^{-2} \text{ sec}$

From the above values, it is clear that the dimensions of the experiment may satisfy the condition.

Fig. 5 Measured data with accumulator gauge pressure of 4 kg/cm^2

Fig. 6 Measured data with accumulator gauge pressure of 5 kg/cm^2

Fig. 7 Measured data with accumulator gauge pressure of 6 kg/cm^2

The experiments are done by changing the compressed air pressure in the accumulator. The pressure is 4, 5 and 6 kg/cm² gauge. The frequency f_0 of the ultrasonic waves at the sound source is 180 kc/sec. Measured data are shown in Figs. 5, 6 and 7. In each figure, the curves of the stroke, the pressure, the frequency and the integrated frequency are shown against time with unit scale.

Fig. 8 Measured temperature~time relations (accumulator gauge pressure 4 kg/cm²)

Fig. 9 Measured temperature~time relations (accumulator gauge pressure 5 kg/cm²)

It appears that the higher the pressure of the accumulator the larger the frequency change. It is observed that the curves of the frequency change contain very high frequency waves or noises. It seems that they occur by the pressure waves from the moving piston or by the vibrations of the structure. It is interesting that these noises are filtered and the curves become smooth when the integration with respect to time are performed electrically.

The temperature of the air is calculated by Eq. (8) using the data of the integrated frequency change in Figs. 5, 6 and 7.

These temperature changes are shown in Figs. 8, 9 and 10 as full lines. Also, the temperature changes calculated with polytropic index estimated from the measured stroke and pressure relations are shown in Figs. 8, 9 and 10 as broken lines for comparison. The coincidence between the two lines of temperature change is especially good in the beginning part of each curve. This is due to the fact that the polytropic index for the calculation of polytropic equation is determined by the starting part of log-log relations of the stroke and the pressure. After all, the coincidence between the full and broken lines proves that the data obtained by this new measuring technique are reliable.

5. Conclusions

From the above mentioned measuring principle

Fig. 10 Measured temperature~time relations (accumulator gauge pressure 6 kg/cm²)

and experiment, the following conclusions are reached.

(1) It is possible to measure rapidly changing gas temperature by detecting the frequency change of the sound waves passing through the temperature changing gas.

(2) For the success of this new technique, it is necessary that the ultrasonic waves be used for the sound waves and that the time for the ultrasonic waves to travel the distance between the sound source and the receiver be very small compared with the total time interval of the temperature change phenomena.

(3) From the experiment using the rapid compression machine, it is concluded that the temperature change of about several tens of thousands degrees centigrade / second can be measured by this new technique.

(4) In this experiment, the distance between the sound source and the receiver is 38 mm and their diameters are both 10 mm. It will be possi-

ble to make these dimensions more smaller by proper design and arrangement.

(5) For the reasons mentioned in (3) and (4), the measurement of the combustion gas in reciprocating engines using this new technique will be possible by cooling the sound source and the receiver.

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