
By Umezio Yosida.

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Abstract.

The sodium line reversal method of determining the temperature of a flame was applied to the engine flame. A special cylinder, with two quartz windows, that would cause a beam of light from the source to pass through the combustion chamber, was constructed. Upon adding a small quantity of sodium ethylate to the fuel, the temperature of the engine was compared with the colour temperature of the light source. A tungsten pointolite, a tungsten lamp, and a carbon arc lamp were used as the light source.

The D-line intensity of the flame was measured by a photoelectric cell. By comparing the D-line intensity with its temperature, it was found that the temperature measured by this method was the correct temperature of the flame.

The spectrum in the visible region of the engine flame consisted of CH 4300 Å, CC swan bands, and the continuous bands. The spectra obtained at various crank angles showed that as the crank angle proceeds, the CH and CC bands became fainter, and that the temperature in the cylinder was not uniform.

The maximum temperature at various air fuel ratios was measured with the engine running at 800 r.p.m. Although the correct air fuel ratio in the fuel under test was 13.8, the temperature was always maximum at 11.5, which was higher than that obtained by Hersley and Panton and nearly agreed with the calculated value.

Introduction.

When a mixture of gases is burned at atmospheric pressure, the temperature of its flame may be estimated by experiments (by colouring it with sodium vapour and comparing the brilliancy of its doublet with the continuous spectrum of a tungsten strip or a carbon arc lamp) that have already been made by a number of investigators with several hydrocarbon gases, such as acetylene, methane, etc, and carbon monoxide by mixing with them the sprays of the sodium salts solution.

Although the temperature determined in this way by several investigators agrees with the value determined by the change in

resistance of a current-bearing platinum wire in the flame, some reports show that this method of temperature determination give results much in excess of the true temperature, which is proportional to the mean molecular kinetic energy in the gas flame. For over-rich mixture particularly this value greatly exceeds that determined by the platinum thermometry method. When thallium salts are used instead of sodium salts, the temperature becomes lower, whence it is concluded that there is no definite law between these values and the true temperature of the flame.

But Jones, Lewis, and Elbe believe that this method does give the correct temperature, as supported by numerous experiments. The temperature determined by the platinum wire method is low, because conduction and radiation loss cannot be prevented. Thallium salts do not evaporate so easily as sodium salts.

But for naturium vapour in Bunsen flame, Kohn has definitely shown by a measurement of its emissive and absorptive power within the range of from 900°C to 1800°C, that the black body temperature at certain point in the flame is identical by equal to the value measured by the natrium reversal method. The value observed is independent of vapour density within the range 1:2000.

It has been shown by Griffith and Awbery that the reversal temperature of the flame is independent of its vapour concentration and thickness, and equal to its black body temperature. Tingwaldt has found, for an acetylene and oxygen flame at about 3100°C, that its reversal temperature measured by an infra red sharp band of CO₂, λ 4.39μ agrees with the value measured by naturium line.

It may be considered that in flame chemical reactions are taking place and part of their energy may be radiated by chemiluminescence. But from these experiments of determining the temperature of the flame over 900°C, it may be judged that thermal equilibrium is established between the natrium atoms in excited (2P), normal state (2S) and the flame gases. The natrium atoms may be regarded to emit and absorb the D line as thermal radiators. We can apply Kirchhoff's law to it.

In general the condition for the pure thermal equilibrium may be more nearly obtained, the higher the temperature of the flame under the same condition. As the flame in an internal combustion engine is in high temperature, these facts make possible to measure its tempera-
ture by the natrium reversal method.

1. The Experiments (General Arrangement).

The writer used this method in measuring the temperature of the flame in the cylinder of an internal combustion engine, and photographed the spectra of the flame by means of a small glass spectroscope in order to ascertain the intermediate product in the flame.

A small petrol engine of 2HP was used for test. A new cylinder with a somewhat elongated top, and having two quartz windows, was constructed, as shown in Fig. 1.

The diameter of the quartz plate was 2.8 cm, and the thickness 0.8 cm, the diameter of the middle parts through which passed the light ray from its source being 1.5 cm.

The compression ratio of the engine is 4.12 and the spark advance being 5°. The volume of the combustion chamber is from 515 c.c. to 125 c.c., the distance between the two quartz windows being 13 cm. The light ray from the source, as a parallel beam, passing through the quartz window 1 enters the combustion chamber. This parallel beam after passing through the second window 2, and the stroboscopic shutter, is focussed by lens 2 on the slit of the spectrograph. In this way, the sharp image of the light source is focussed on the slit.

![Fig. 1](image)

**Fig. 1.**

1. Pointolite  
2. Quartz window  
3.  
4. Spectrograph  
5. Arc lamp  
6. Optical wedge  
7. Stroboscopic Shutter  
8. Stroboscopic Shutter

The stroboscopic shutter which revolves with half the engine speed picks up the light from the engine cylinder at various crank angles. There is a spark plug on the same horizontal plane as the light path, 2.8 cm behind its centre and 1.8 cm behind the edge of
the light path. The diameter of the metal disc of the stroboscopic shutter is 36 cm and that of the slit which allows the ray to pass is 1.2 cm. For engine load, an electric generator of 1.5 KW was rotated, the output power of the generator being consumed in electric resistance. By changing its resistance continuously, the rate of rotation of the engine is kept constant under various conditions.

For light source, a tungsten pointolite and a tungsten lamp were used for low temperature regions, their apparent temperature being changed by the current they consumed. For high temperature, a carbon arc lamp of 3300°C was used, the gap distance of whose electrodes was kept constant mechanically during the experiment, and the current kept constant by a large choke coil. The intensity of the light that enters the engine cylinder is regulated by an optical wedge. At a chosen point of combustion cycle as determined by the phase of the stroboscopic shutter and other engine conditions, the light which passes through the engine cylinder as a parallel beam is adjusted in the manner just mentioned.

When the apparent temperature of the light source is adjusted relatively low, a brilliant natrium D-line appears on the background of continuous spectrum of the light source. By increasing the temperature of the source continuously, the brilliant line becomes fainter compared with the continuous spectrum, and finally it disappears into the continuous spectrum. By increasing the temperature further more, it changes into a reversed dark line on the continuous background.

At the moment when a balance is obtained between the D-line and the continuous background, the engine is quickly stopped and the
quartz plate, which is shown on the left side of Fig. 1 is removed and the colour temperature of the right source is measured through this window by means of an optical pyrometer of disappearing filament type.

It is shown in the introduction of the present paper that the natrium atoms in 5P state are in thermal equilibrium with the flame gases and emit and absorb D-line as thermal radiators. As the reflectivity of the flame is negligibly small compared with its absorptive power, at the moment when the balance is obtained between the light source and the engine flame, \( E_F \) must be equal to \( A_F \), where \( E_F \) is the emissive power of the light source and \( E_F \) is emissive and absorptive power of the flame respectively.

\[
E_F = A_F E_s \Rightarrow E_s = E_F/A_F.
\]

As the natrium atoms in the engine flame emit and absorb the D-line as thermal radiators, \( E_F/A_F \) is constant and equal to emissive power of black body at the same temperature. This equation shows that the temperature of the flame is equal to the colour temperature of the light source. Hence by measuring the colour temperature of the light source, the temperature of the engine flame can be directly obtained.

Since a deposit of oil and smoke gradually forms on the windows, a correction for this is made with every experiment. As the deposit consists of almost entirely of carbon particles, its colour is dark. Although the electrode of the carbon arc lamp is considered as a nearly perfect black body, tungsten besides being grey, has different spectral emissibilities at different temperatures, so that if tungsten is used as a light source, a correction becomes necessary for colour temperature in order to ascertain the true temperature of the flame. The engine temperature is determined by comparing it with the colour temperature of the tungsten lamp by the sodium reversal method, while the latter is measured by an optical pyrometer with red glass, on the wavelength 6650Å, whence it is necessary to find the correction for the tungsten lamp corresponding to the two wavelengths.

By Wien's law of radiation of a black body, the intensity of a grey body is

\[
K_1 \lambda^2 e^{-\lambda/\lambda_1} = A \frac{1}{\lambda_1^2} e^{-\lambda_1/\lambda_1},
\]

where \( \lambda_2 = 1.432 \). Let \( T_1 \) be the true temperature of the tungsten lamp, when its colour temperature is equal to \( T \) on wave length 5890Å, then

\[
K_1 \frac{1}{\lambda_1^2} e^{-\lambda_1/\lambda_1} = A \frac{1}{\lambda_1^2} e^{-\lambda_1/\lambda_1}
\]

or

\[
\frac{1 - \lambda_1}{T_1} = \frac{\lambda_1}{\lambda_2} \log K_1, \quad \lambda_1 = 5890\text{Å}.
\]

If the temperature of the source is measured by an optical pyro-
meter on wave length 6650Å, as colour temperature \( T_2 \), then

\[
K_2 A \frac{1}{\lambda_2^4} e^{-\frac{\lambda_2^3}{k_2 T_2}} = A \frac{1}{\lambda_1^4} e^{-\frac{\lambda_1^3}{k_1 T_1}}
\]

or

\[
\frac{1}{T_1} - \frac{1}{T_2} = \frac{\lambda_2}{c_2} \log K_2, \quad \lambda_2 = 6650Å.
\]

\( K_1, K_2 \) have different value for each temperature \( T \). For example if \( T = 2400°K \), then \( K_1 = 0.441, K_2 = 0.427 \)\(^{(1)} \).

\[
\frac{1}{T} = \frac{1}{T_2} - 5.6 \times 10^{-6}
\]

To obtain the black body temperature of the flame, this correction will have to be made on the pyrometer reading, \( T_2 \). The correction for the smoke particle deposited on the window can be made in a similar way by an optical pyrometer. If a light source of colour temperature \( T_1 \) is observed through the dirty window of the cylinder and the pyrometer reading is \( T_0 \), and the transmission coefficient of the window is \( \alpha \), then

\[
\alpha K_1 e^{-\frac{\lambda_1^3}{k_1 T_1}} = K_2 e^{-\frac{\lambda_2^3}{k_2 T_2}},
\]

\[
\log \alpha = -\frac{c_2}{\lambda_1} \left( \frac{1}{T_1} - \frac{1}{T_2} \right), \quad \lambda_1 = 6650Å.
\]

Hence once \( \alpha \) has been determined in this way, the corrected black body may be calculated from the pyrometer reading.

2. Spectrum of the Engine in the Visible Region.

A spark plug is located 2.8 cm distant from the centre line between the windows. Although when the position of the stroboscopic shutter is continuously changed from the spark point to the combustion cycle, no light appears at the sparking point. When the position of the shutter is gradually changed from this point, an irregular white light that changes at each revolution is observed. At about 20° from the spark point, white light at each revolution is continually observed through the stroboscopic shutter. It is at this point that uniformity of the temperature in the combustion chamber is established. When the flame is viewed with the naked eye, without the stroboscopic shutter, at first a white blue stream, like an electric spark in air, which seems to be the flame front makes its appearance, after which the flame uniformly fills the engine chamber.

A direct photograph of the flame was taken by I. Withrow and

\(^{(1)}\) Forsythe and Worthing, Astrophys. Jour., 37 (1915), 38; ibid. 61 (1925), 146.
G. Rassweiler by means of a high speed motion picture camera\(^1\). In their experiment a special engine was built, the usual cast iron cylinder head being replaced by a transparent top. Their results show that the flame spreads in all directions compressing the unburned portion of the charge. In successive explosions there is considerable variation in the form of the flame front and in its velocity of propagation, apparently being influenced by the gas movement and the chamber shape. In their experiment, the flame front spreads over the chamber at about 20° crank angle, and not instantly as is expected in thermodynamical calculation. The shape of the flame is irregular from the ignition point to this crank angle. As the light of the flame at each combustion is observed continuously through the stroboscopic shutter from 20° crank angle in our experiment, it is considered that the flame spreads over the chamber at this angle as their experiment. The white blue streak stated above is considered to be the flame front, compared with their high speed photographs.

Starting from a crank angle of about 20°, at interval of every 30°, the spectrum of the flame through the shutter is recorded, as shown in plate II. The spectrum of the engine flame has already been studied by a number of investigators\(^2\). Without knocking the spectra obtained by these investigators are similar, namely CH 4300 Å and C\(_2\)-Swan band 4300-6780 Å appearing in the visible region on a continuous background. Although this continuous spectrum is believed to be due to CO\(_2\), owing to the low dispersion of the spectrograph, it cannot be said for certain. The spectrum of the same fuel burned in a torch lamp at ordinary atmospheric pressure is shown in Plate II. The inner cone of the flame is focused on the slit of the spectroscope. Hence, only sharp CH and C\(_2\)-bands appear, without the continuous background. Except the difference of pressure, the mechanisms of burning in these two cases are regarded to be identical. The spectrum at each crank angle shows that at later crank angle the CH and C\(_2\)-bands become fainter, with only a continuous spectrum remaining. In our experiments, the engine was first run for a long time without any sodium salts added to its fuel. There are some reports in which it is shown that the flame front emits only the CH, C\(_2\)-band spectrum, and the afterglow only a continuous spectrum, whereas in our case, each spectrum of the afterglow contains the CH, C\(_2\)-band faintly.

The impurities on the wall of the combustion chamber were

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Photograph of Na-D-line reversal at various Crank angle.

Plate II.
burned out as much as possible in this way. The natrium line is due to the impurities still remaining in the fuel and on the wall of the combustion chamber although its quantity is very small.

The spectrum at this condition is shown in Plate I, the crank angle being from 20° to 120°. When a small quantity of sodium ethylate (a few drops of ethylate into one litre of fuel) is introduced into the fuel, a bright natrium line appears in the spectrum as shown in Plate I, which is due to the constant quantity of sodium vapour in the engine flame. It is at this condition that the sodium reversal method of measuring the temperature is applied.

By increasing or decreasing the natrium concentration the temperature is measured at the same condition. However, it is found that the concentration of natrium vapour has no influence on the results. Kohn has already found the same results, by changing the vapour density within the range 1000:1.

In the range of vapour concentration in our experiments, the statistical equilibrium is established between the upper state of the D-line of the natrium atoms and the flame gases.

In this condition, in which the rotation of the engine is kept constant at 800 r.p.m., and the air fuel ratio of the engine is changed, no large difference is obtained in the spectrum.

The fuel supply was kept constant and the air was changed in descending order from 1 to 5. But, the spectrum had no special difference for any of these conditions.


The intensity of the D-line of the engine flame when a certain amount of sodium ethylate has been introduced into the fuel, is measured by an electric device consisting of a photo-electric cell and an amplifier, as shown in Fig. 3. Its current is recorded by a Duddell oscillograph. The D-line is filtered out from the engine spectrum by a red glass filter placed in front of the photocell. In this case, by changing the concentration of natrium atoms, the D-line intensity is regulated to become strong compared with the continuous band. Therefore, no serious error may be introduced if we consider that only the D-line has been filtered out with the red glass.

As will be seen from the oscillograms of the intensity of the D-line in Fig. 4, the intensity is not constant, but changes about 20% from its mean value of each revolution. Many photographs at the same condition were taken at different times and the mean of its maximum value was adopted as the maximum D-line intensity at a
certain engine condition. In order to compare this intensity of the D-line with the temperature of the flame, the consumption of the fuel at every second was kept constant, while the quantity of the air was changed for each engine condition, in descending order from 1 to 5 (see following table). These five conditions are the same as the experiments in previous part (2).

<table>
<thead>
<tr>
<th>Engine Condition</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo Current</td>
<td>5.0</td>
<td>6.3</td>
<td>7.3</td>
<td>8.0</td>
<td>10.0</td>
</tr>
<tr>
<td>log (Photo Current)</td>
<td>1.61</td>
<td>1.84</td>
<td>1.99</td>
<td>2.08</td>
<td>2.30</td>
</tr>
</tbody>
</table>

4. Engine Temperature and D-line Intensity.

The maximum temperature of the flame in the above five conditions was measured by the sodium reversal method, the spectrum with the reversed sodium line in the above five conditions being shown in Plate II. On its right side is shown the current of a pointolite or a lamp. The temperature difference corresponding to each spectrum for one engine condition is about 30°C. The balance of the temperatures between the lamp and the engine lies somewhere between these two spectra, as will clearly be in the Plate.

<table>
<thead>
<tr>
<th>Engine Condition</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. black body</td>
<td>1660</td>
<td>1760</td>
<td>1840</td>
<td>1940</td>
<td>2010</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>1933</td>
<td>2033</td>
<td>2133</td>
<td>2213</td>
<td>2283</td>
</tr>
<tr>
<td>l/Max Temp. 10^{-1}</td>
<td>5.47</td>
<td>4.91</td>
<td>4.73</td>
<td>4.52</td>
<td>4.37</td>
</tr>
<tr>
<td>log (Photo current)</td>
<td>1.61</td>
<td>1.84</td>
<td>1.99</td>
<td>2.08</td>
<td>2.30</td>
</tr>
</tbody>
</table>

In the above five conditions, the fuel consumption ratio was constant but the air quantity was changed for each engine condition, the rotation of the engine being maintained at 800 r.p.m. If the sodium vapour and the engine flame are in thermal equilibrium the number of excited atoms is \( N_0 e^{-E/kT} \), \( E=\hbar\nu \) where \( T \) is the thermodynamical temperature of the flame. As the number of sodium atoms is the same for each engine condition, the spectral intensity must be proportional
The logarithm of maximum photo current must therefore be proportional to reciprocal of the temperature. Let \( i \) be the intensity of the D-line, 

\[
\log i = \text{const} - 1.00 \times 10^4 \frac{1}{T}
\]

This is verified in Fig. 3. From this experimental curve, we obtain 

\[
\log i = \text{const} - 0.95 \times 10^4 \frac{1}{T}
\]

This value nearly accords with the theoretical formulae. Hence it may be said that the black body temperature determined by the sodium reversal method is the thermodynamical temperature of the flame in this experimental condition.

As it is clear in Fig. 4 the D-line intensity at each combustion changes about 20% from its mean value. For the flames of the mean temperature 2000°K, the temperature variation corresponding to it is about ±40°C.

Fig. 4. D-line intensity curve at various time; Temperature indicator.
From this oscillograph record of the D-line intensity, the temperature of the engine flame at each combustion can be calculated completely, when its temperature at a certain condition is once determined by the sodium reversal method. By the reversal method only the mean temperature can be measured and therefore, the temperature variation at each combustion can not be found. The process of determining the temperature at each crank angle is very troublesome and its mean value can only be determined. But this record shows the temperature variation at each crank angle of one combustion.

From this record, it is found that in successive explosion there is considerable variation in the maximum temperature and in the rate of cooling of the flame. This may be considered to be influenced by the gas movement and the shape of the combustion chamber. This record may be considered as the temperature indicator of the engine.

In the knocking explosion of the flame, it is generally known that the spontaneous inflammation appears and the violent vibration of the flame frequently follows it. The flame in the knocking condition shows greater rate of cooling than in the nonknocking condition, by transferring its heat to the wall by violent convection and conduction. If this method of recording the D-line intensity is applied to the flame in the knocking condition, its temperature at violent vibration and the rate of cooling may be found completely. Therefore, this method may be successful in finding the state of combustion of the flame in the knocking condition.


The maximum temperature of the engine at different air fuel ratios was measured at 800 r.p.m. The temperature of the cooling water was kept between 58°-62°C, at the outlet for each engine conditions.

An electric generator is revolved by this engine by a belt, its generated power being consumed in electric resistance. Since the true power of the engine is not represented, it is not shown in the table. The temperature of the engine can be measured only by the sodium reversal method, in connection with which, however, a few experiments were recently made.

It is known that the temperature of the flame for every crank angle is not the same. Since the flame front proceeds from a spark plug, and the remaining gas burns afterwards, there is a complex temperature distribution in the flame. But, by measurements in this experiment, it is found that the flame temperature is maximum at about 20° crank angle. The flame spreads over the combustion cham-
ber at about this crank angle after explosion, and is comparatively uniform in the combustion chamber.

The following data (Table I) give the mean temperature on the centre line of the combustion chamber, which is considered the average value in the chamber.

The temperature of the engine at various air fuel ratios has been calculated by a number of investigators\(^1\), assuming the state of complete statistical equilibrium in the burned gas (i.e. equilibrium of molecules in rotation and vibration and in kinetic energy; equilibrium of the concentration of dissociation products i.e. \(2\text{CO}_2 \leftrightarrow 2\text{CO} + \text{O}_2\), \(2\text{H}_2\text{O} \leftrightarrow 2\text{H}_2 + \text{O}_2\)).

In thermodynamical treatment of the performance of a gasoline engine, it is assumed that combustion occurs instantaneously releasing all the energy of combustion, when the piston is at top dead centre, only the state immediately after combustion being therefore calculated by assuming the initial conditions (air and fuel quantity and their temperature, temperature of the residual gas, etc.). Hence thermodynamical treatment is not adequate enough to explain the part of the cycle where the combustion takes place or to give the rate of chemical reaction at each cycle of the engine explosion. Only the state when the flame spreads over the combustion chamber may be considered to correspond to the condition immediately after combustion in thermodynamical treatment. In this experiment the maximum temperature is reached at about 20°. As the difference of volume between this point and the tope dead centre is however only about 12 c.c., it can be neglected. Therefore, no serious error may be introduced, if we compare the result with the case in which the maximum temperature occurs at the top dead centre. H. Kuhl calculated the case of compression ratio 5, assuming dissociation of \(\text{CO}_2\) and \(\text{H}_2\text{O}\) to occur at high temperature. When there is no dissociation, the maximum temperature is reached at correct air fuel ratio, whereas if dissociation is taken into account, the maximum temperature is displaced towards the rich side.

Tanaka and Awano calculated the maximum temperature for the fuel, consisting of benzene and gasoline in proportion of 2:1 in weight and the heat of combustion is \(10000\) K Cal/Kg. In the case of no dissociation and no heat loss during combustion, the maximum temperature is obtained at correct air fuel ratio (which is put as equal to 1). In the case where heat dissociation of \(\text{CO}_2\) and \(\text{H}_2\text{O}\) is taken into account, it is reached at rich mixture of about 0.9 corresponding to

1.0 correct mixture. In thermodynamical treatment of an engine, the heat loss during combustion is always assumed to be about 7\% of its heat of combustion. With this correction the maximum temperature becomes lower by the amount about 100\°C, but the air fuel ratio corresponding to it is the same as in the case of no heat loss. Some other reports relating to this problem lead almost the same results.

The temperature of an engine at various air fuel ratios was measured only by Hersley and Panton\(^{(1)}\) who used an engine of compression ratio of 3.86. The range of the air fuel ratio was from 12 to 14, the measured temperature being several hundred degrees lower than the calculated value. Lloyd, Evans and Watt\(^{(2)}\), using a special carbon arc for light source, measured the temperature of the flame of the air fuel ratio 14.6, 13.6 and 11.1 at each crank angle. Although a few other data have been still published relating to this problem, no report has been made public in which the engine condition as well as the temperature are accurately recorded. Since the calculated temperature was found to be higher than that measured by sodium reversal method, the following experiment was further made to ascertain the difference between them.

The tested engine was kept running at 800 r.p.m., the temperature of the cooling water lying between 58-62\°C. As light source, a tungsten pointolite, a lamp and a carbon arc with an optical wedge, was used. The balance of temperature between the light source and the engine was obtained by naked eye-observations. In this way, the temperature was measured within an accuracy of 10\°C. When the engine condition become steady, the engine was suddenly stopped, and the correction for the dirt of the window made at every time as in the previous experiments.

When the quantity of air increases, as determined by the inlet suction pressure of the inlet pipe, the temperature increases, as it is evident from table I. If the quantity of air is kept constant, but that of the fuel changed, maximum temperature is obtained when a certain quantity of fuel which, if increased or diminished from this point lowers the temperature of the flame.

Plotting these values against the air fuel ratio by weight, we get the curve in Fig. 6. In order to compare these results with the calculation, the correct air fuel ratio used in this case (13.8) was used as reference to 1, and all other air fuel ratios are represented referring

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(2) Lloyd, Evans and Watt, Engineering, 139 (1935), 48.


**Table I.**

**Engine Condition**

- Compression ratio 515 c.c./125 c.c.
- Cooling water at outlet: 58 °C.
- Revolution per minute: 800 r.p.m.
- Spark advance: 5°
- Specific weight of fuel at 18°C: 0.750

**Atmospheric Condition**

- 76.4 cm Hg pressure
- 17 °C.

<table>
<thead>
<tr>
<th>air g/sec</th>
<th>fuel g/sec</th>
<th>air-fuel ratio</th>
<th>max. temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 1.27</td>
<td>0.119</td>
<td>10.7</td>
<td>1900</td>
</tr>
<tr>
<td>1.27</td>
<td>0.113</td>
<td>11.3</td>
<td>1900</td>
</tr>
<tr>
<td>1.35</td>
<td>0.105</td>
<td>11.9</td>
<td>1930</td>
</tr>
<tr>
<td>1.24</td>
<td>0.100</td>
<td>12.7</td>
<td>1950</td>
</tr>
<tr>
<td>1.22</td>
<td>0.081</td>
<td>15.0</td>
<td>1900</td>
</tr>
<tr>
<td>(2) 1.52</td>
<td>0.180</td>
<td>8.0</td>
<td>2920</td>
</tr>
<tr>
<td>1.52</td>
<td>0.158</td>
<td>9.0</td>
<td>2350</td>
</tr>
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<td>1.52</td>
<td>0.145</td>
<td>10.5</td>
<td>2330</td>
</tr>
<tr>
<td>1.50</td>
<td>0.129</td>
<td>10.8</td>
<td>2300</td>
</tr>
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<td>1.50</td>
<td>0.113</td>
<td>13.4</td>
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<tr>
<td>(3) 1.85</td>
<td>0.225</td>
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<td>0.174</td>
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<td>0.156</td>
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<td>0.160</td>
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</tr>
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<td>0.151</td>
<td>12.2</td>
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</tr>
<tr>
<td>1.84</td>
<td>0.225</td>
<td>16.4</td>
<td>1880</td>
</tr>
<tr>
<td>(4) 2.45</td>
<td>0.270</td>
<td>9.1</td>
<td>2000</td>
</tr>
<tr>
<td>2.44</td>
<td>0.253</td>
<td>9.6</td>
<td>2250</td>
</tr>
<tr>
<td>2.40</td>
<td>0.225</td>
<td>10.7</td>
<td>2170</td>
</tr>
<tr>
<td>2.35</td>
<td>0.199</td>
<td>11.8</td>
<td>2450</td>
</tr>
<tr>
<td>2.52</td>
<td>0.109</td>
<td>14.9</td>
<td>2230</td>
</tr>
</tbody>
</table>

**Suction pressure of the inlet pipe**

<table>
<thead>
<tr>
<th>Condition (1)</th>
<th>air 1.27–1.22 g/sec</th>
<th>−9.5 cm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2)</td>
<td>3.52–1.50</td>
<td>—740</td>
</tr>
<tr>
<td>(3)</td>
<td>1.82–1.85</td>
<td>—660</td>
</tr>
<tr>
<td>(4)</td>
<td>2.52–2.40</td>
<td>—430</td>
</tr>
</tbody>
</table>

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*Note: All temperatures in °C.*
to it, dividing them by 13.8. The maximum temperature referring to this new air fuel ratio is shown in Fig. 8.

The specific weight of the fuel used in this experiment is 0.750 at 18°C, and its low heat of combustion 10640 K Cal/Kg. In this case the maximum temperature becomes about 100°C higher than that calculated for the fuel 10000 K Cal/Kg. This result is shown in Fig. 9.

In our experiment, it was not practicable to carry out the measurement opening the air value thoroughly. However, since the maximum air quantity is calculated by inlet suction pressure $-4.3 \text{ cm Hg}$, our case may certainly be regarded as equal to the case of full opened valve, neglecting the small difference of pressure, $4.3 \text{ cm Hg}$.

By comparing Fig. 8 Fig. 9, it is readily recognized that the

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measured value of maximum temperature, as well as its position referring to the air-fuel ratio agree nearly well with those obtained by calculation, provided that the difference in compression ratio (i.e. 4-12 and 5 or 6) is taken into account.

The calculated (thermodynamical) temperature is higher by the amount 50°C than the experimental (black body) value. It has been shown that for the engine flame the thermodynamical temperature agrees exactly well with the black body temperature. If it is assumed that 9-10% of heat of combustion is lost during the combustion and 9-10% during the expansion stroke, the experimental value agrees exactly well with the calculated value. Therefore, in case of a small gasoline engine, in order to calculate its temperature, it is necessary to assume a greater heat loss than that assumed in ordinary thermodynamical calculation.

6. Conclusion.

The sodium line reversal method of determining the temperature of a flame was applied to the engine flame. Upon adding a small quantity of natrium ethylate to the fuel, the temperature of the engine was compared with the colour temperature of the light source. A number of investigations has been carried out to find the character of radiation of the natrium vapour in the Bunsen flame. It may be considered that in the flame chemical reactions are taking place and part of their energy may be radiated by chemiluminescence. But from these many experiments, it has been found that the thermal equilibrium is established between the natrium atoms in excited state (2P), normal state (2S) and the flame gases.

The natrium atoms may be considered to emit and absorb the D-line as thermal radiators. As the flame in an internal combustion engine is in high temperature, the condition for pure thermal equilibrium may be established. Then the natrium line reversal method may be believed to give the true thermodynamical temperature of the flame. The writer used this method in measuring the temperature of the flame in the cylinder of an internal combustion engine.

A small petrol engine of 2 HP was used for test. A new cylinder with two quartz plate through which passed the light from the source, was constructed. The volume of a combustion chamber is from 515 c.c. to 125 c.c., i.e. the compression ratio is 4-12 and the spark advance is 5°. The light ray from the source, passing through the quartz plate as a parallel beam, enters the combustion chamber. This beam, after passing through the second quartz plate and a stroboscopic shutter which revolves with half the engine speed, is focussed on the slit of
the spectrograph. As the stroboscopic shutter picks up the light from the engine cylinder at various crank angles, the temperature of the flame at each crank angle can be determined. By this arrangement, the temperature can be measured within the accuracy 10° by the naked eye observations and 20° by the photographic method.

When the position of the stroboscopic shutter is continuously changed from the spark point, no light appears at first. At above 20° from the spark point, the uniform light at each revolution is continually observed through the stroboscopic shutter. The flame may be considered to spread over the chamber at about this crank angle. Starting from a crank angle of about 20°, at an interval of every 30°, the spectrum of the flame through the shutter is recorded. In the visible region of its spectrum CH 4300 Å and C2-Swan band, 4300—6580 Å appear on a continuous background. The spectrum of the same fuel burned in a torch lamp at ordinary atmospheric pressure consists only of sharp CH and CC bands, without the continuous background. The CH and CC bands become fainter at later crank angle, only the continuous spectrum remaining.

In the condition in which the rotation of the engine is kept constant at 800 r.p.m. and the air fuel ratio of the engine is changed, no large difference is obtained in their spectra.

The intensity of the D-line of the engine flame when a certain amount of sodium ethylate has been introduced into the fuel is measured by an electric device consisting of a photocell and an amplifier. Its current is recorded by a Duddel oscillograph. The mean of its maximum value is adopted as the maximum D-line intensity in a certain engine condition. In order to compare this intensity with the temperature of the flame, the fuel consumption ratio was kept constant, but the air quantity was changed for each engine condition, the rotation being maintained at 800 r.p.m.. By comparing its intensity with the temperature, it is found that the natrium vapour in excited state (2P) is distributed after Boltzmann's law and is in thermal equilibrium with the engine flame. The black body temperature determined by the sodium reversal method agrees well with the thermodynamical temperature.

From this oscillograph records of the D-line intensity, the temperature variation of the engine at each combustion can be calculated completely, when the temperature in a certain condition is once determined by the sodium reversal method. The D-line intensity at each combustion changes about 20° from its mean value. For the flame of mean temperature 2000°K, the temperature variation corresponding to it is about 40°C. This variation may be considered to be influenced by the gas movement and the shape of the combustion chamber.
If this method of recording the D-line intensity be applied to the flame in the knocking condition, its temperature at violent vibration and the rate of its cooling may easily be obtained. This method may be successful in determining the state of combustion of the flame in the knocking condition.

The maximum temperature of the engine at different air fuel ratios was measured at 800 r.p.m., the temperature of the cooling water being kept at about 60°C. The temperature of the flame can be measured only by the sodium reversal method, in connection with which, however, a few experiments were recently made. But no report has been made public in which the engine condition as well as the temperature are accurately recorded. In the thermodynamical treatment of a four cycle gasoline engine, it is generally assumed that 7% of its heat of combustion is lost during the explosion and 7% during the expansion stroke. It is already found that for the engine flame the thermodynamical temperature is equal to the black body temperature.

The state of the combustion of the flame in the engine cylinder changes at each revolution, but it is found that mean of its maximum temperature is lower by the amount about 50°C than the calculated value. But, if it is assumed that 9-10% of its heat of combustion is lost during explosion, and 9-10% during the expansion stroke, the calculated temperature agrees exactly well with the measured value. Therefore in the case of a small gasoline engine, in order to calculate its temperature, it is necessary to assume a greater heat loss than that assumed in ordinary thermodynamical calculation.

In conclusion, the writer acknowledges his great obligations to Dr. J. Obata and Mr. S. Awano in Aeronautical Research Institute, Tokyo Imperial University, under whose suggestions this experiment was carried out and to Dr. M. Kimura in Kyoto Imperial University in preparing this paper.

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