CHAPTER VI.

EXPERIMENTAL III - MEASUREMENT OF
REVERSAL TEMPERATURES AND RESULTS

In Chapter II we have given a brief account of various methods available for measurements of translational temperatures and have discussed in brief the advantages of line reversal method over other methods. The main difficulty with these other methods, particularly for temperatures of flames, is that the heat receiving element introduced in to the flame for measuring the temperature is large enough to disturb the flame conditions and hence do not give a reliable temperature measurement. Ferry's (1903) line reversal method, on the other hand, is a convenient and more accurate way of measuring temperatures of flames. The validity of the method is discussed in detail by Lewis and von Elbe (1951), Loomis and Perrot (1928) and others.

According to Gaydon (1952), when spectral lines of relatively higher frequency (usually those in the U.V. region) are used for reversal temperature measurement, generally, high values of temperature are obtained. But using sodium lines for the reversal observation the temperatures derived are reasonably the accepted normal values
for the flames concerned. Strong and Bundy (1954) have applied this sodium line reversal technique to even complex flames and their results of temperature have been in the close range of expected normal flame temperature values.

Principle of the Method.

If a radiating black body is placed behind a flame coloured with sodium and a spectroscope is sighted through the flame on to the black body, there will be some temperature of the black body at which its brightness in the spectral region of the D-lines equals the brightness of the light in this region transmitted through the flame, plus the brightness of the D-lines from the flame itself. This means that the spectrum of black body remains undisturbed by the passage of light through the flame, as the flame emits as much as it absorbs. If the temperature of the black body is lowered, the D-lines appear bright by contrast against the continuous background. At higher temperatures of the black body the D-lines appear dark against the continuous background. At the critical point of reversal, the condition to be satisfied is,

$$B_\lambda(\lambda) = B_\lambda(b)\left[1 - a_\lambda(c)\right] + B_\lambda(d)$$

where, $B_\lambda(b)$ = spectral brightness of black body.
\[ B_\lambda (f) = \text{spectral brightness of flame.} \]
\[ a_\lambda (f) = \text{spectral absorptivity of the flame} \]
\[ \lambda = 0.5890 \mu \]
\[ \frac{B_\lambda (f)}{B_\lambda (f + \Delta f)} = a_\lambda (f), \]

which is Kirchhoff's equation. The temperature of the flame is, therefore, identical with the reversal temperature.

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Experimental.

(i) The optical system: The optical system is shown diagramatically in Fig. 14.

In practice it is not necessary to use a black body as comparison radiator; instead, a light source calibrated against a black body in the optical range under consideration may be used. In the present investigation a tungsten band filament lamp was used.

For the measurement of temperature in the inner cone the bright tungsten filament is focussed on the centre of the inner cones by means of a lens \( L_1 \), the image being of the same size as the filament. The burner is clamped horizontally the same way as in photographing the spectra for intensity measurements as described in the chapter IV. The lens \( L_2 \) focusses the composite image of the filament and the inner cones on the slit of the constant deviation. spectroscopy
This image is also of the size of the first image and covers the entire slit of the spectroscope. Owing to the shifting of the cones away from or nearer to the grid, collimation had to be very carefully arranged. Erratic results are obtained if either the base or the tip of cones get focused on the slit. Very great care in collimation is therefore required.

A diaphragm $D_1$, is used to isolate radiation coming from filament which is focused on the slit of the spectroscope. Another diaphragm $D_2$ is used between the lens $L_2$ and the flame, in order to reduce the general illumination and to increase the contrast of the D lines. With this arrangement the point of reversal could be noted with ease. The diaphragm $D_2$ does not, however, affect the measure of temperature, provided the collimation is good, since it reduces the radiation from the filament and the flame in the same proportion.

(ii) Tinting of flame with salt: The flame can be coloured either (a) by placing small crystals of sodium chloride along grid of the burner (Kohn, 1914) or (b) by atomiser spray (Griffith and Awbery 1929) or (c) by sparking the salt solution in an enclosed vessel (Lewis and von Elbe 1943). We have found the last method more
convenient. Since temperature measurements have to be made under conditions identical with those under which the spectra were observed, the burner had to be used in the horizontal position, which eliminated the use of salt on the grid. In the atomiser spray method a rapid current of air is required to develop the spray, which makes the systematic variation of the air/fuel ratio difficult. From all points of view, the introduction of salt by sparking method is found to be convenient. In particular the sparking of solution yields adequate concentration of salt in the inner cones. Though the validity of the sodium line-reversal method is independent of the concentration of sodium atoms in the flame, the facility of obtaining reversal of lines and the ease of noting it depends upon high concentration of the sodium (Lewis and von Elbe 1943, Strong and Bundy 1954 etc.). Another advantage of the sparking method lies in the fact that this introduces minimum amount of water vapour in the flame. Even this minimum water vapour could be removed, if the gases after passing through sparking vessel are made to pass through a vessel containing a drying agent.

For colouring the flame with characteristic sodium radiation by the sparking method indicated above, it was necessary to allow the flow of sodium vapour into the mix-
ture prior to ignition. This had to be achieved without, in any way, disturbing the condition of the various flames chosen for investigation. For this purpose, the main air current which fixes the air/fuel ratio is divided into two portions, the major portion passes through the vapourizing chamber, where it meets the fuel, while the rest passes through the sparking chamber N (Fig.1) and joins the other current in the flame trap. The salt vapourizer consists of a vessel in which salt solution drips at the tapering end of the thistle funnel. Two metal coils connected to the secondary of the induction coil (I) dip into this vessel with two bent glass tubes. With the passage of the spark between the lower open ends, the sodium in solution vapourises and it is carried by the air current on to the burner via a tube containing calcium chloride.

(iii) Source of continuous radiation: The source of continuous radiation against which the reversal of the sodium lines in flames is observed, is a tungsten lamp having a band filament of width 2 mm. It is fed by D.C. through an adjustable resistance and an ammeter so as to cause a gradual variation of current for marking the exact reversal point and the corresponding value of the current.

(iv) Calibration of the source: The temperatures of the filament at various currents at regular intervals were
measured by an optical pyrometer (Hartmann and Braun) of a disappearing filament type giving a range of temperature values from 800° to 2800°C. The pyrometer was tested for its calibration against a standard source of known temperature viz., Band Lamp No. 2634, calibrated at the physical laboratory of the University of Utrecht (Holland). The calibration curve is prepared by plotting measured temperatures against corresponding current and is given in graph 15.

(v) Variation of current: During the calibration and also observation of the reversal, the lamp current has to be varied by very small values. Ribaud (1939) in his experiments, followed the reversal of sodium line by using in the lamp circuit a rheostat fitted with a small additional resistance which could be short circuited when required. Laud (1951) has used two small equal resistances in such a way that by short circuiting one of them the current in the lamp could be increased while by introducing the other the current could be decreased by small amounts. But in our experiments it was found more convenient to have a long rheostat (1 ft.) with 1 ohm resistance and the contact was guided, very slowly by a rotating disc both forwards and backwards. With this arrangement it was possible to fix the limits of currents for appearance and disappearance of
the reversal, and consequently the accuracy of the determination of the reversal. In all the measurements of the reversal temperature the means of the two currents for the limits of appearance and disappearances as above was taken to give the reversal point.

(vi) **Observing the reversal point:** First of all, it was necessary to ascertain the extent to which the reversal point becomes sensitive to the order of magnitude of temperature changes occurring in flames with change in air/fuel ratios proposed to be investigated in this work.

Observations were begun for the inner cone with very rich mixture. When the point of reversal for this stage was sighted, the air/fuel composition of the mixture was altered to the next value, leaving the current unaltered. Looking for the lines again they were found to be there in emission. The current was then increased to attain the point of reversal again. Flames with successive values of air/fuel ratios were tested in this way for observation of reversal point and the readings repeated.

(vii) **Derivation of reversal temperature** Final readings were then taken for the current corresponding to reversal for each of the eight air/fuel ratios. They were con-
verted to the temperature from the calibration graph
(graph 15) prepared, as indicated earlier. Reversal temp-
erature readings could be reproduced within 10°C within the
limits of observed temperatures (1800\textdegree K - 2100\textdegree K).

For taking readings in the outer cone the image of
the filament was obtained in the body of the outer cone.
Care was taken to see that the part for which temperature
was determined was away from the tips of inner cones and
not near the tip of the outer cone. This part represents
on an average the temperature of the outer cone which con-
tains the partly burnt gases. At the tip of the inner
cones the temperature is highest and the fringe of the
outer cone has lowest temperature. If one restricts to
the body of the outer cone, the temperatures are roughly
uniform and the change in size of the cone at different
air/fuel ratios will not materially affect the temperature
readings. The temperatures were determined for the outer
cone in the same way as above.

All the readings were corrected as described
below.

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Corrections.

1) Lens correction: In order to obtain true temperature
it was necessary to make correction for absorption and
reflection losses at the lens \( L_2 \). Pyrometer readings were, therefore, taken for various temperatures, of the tungsten lamp with and without lens and a graph was plotted of correction against temperature (graph 15). The correction is evidently negative.

(ii) Colour correction: As the brightness temperature of the band lamp is measured in the red (0.655 \( \mu \)) and the temperature of the flame in the yellow (0.589 \( \mu \)) a colour correction is necessary.

The relation between the true temperature \( T \) and the brightness temperature \( S_\lambda \) as derived from Wien's equation is,

\[
\frac{1}{T} - \frac{1}{S_\lambda} = \frac{(2.303 \ k \ \lambda \ \log E_\lambda)}{c \ \lambda} \quad \ldots (1)
\]

\[
\frac{1}{T} - \frac{1}{S_\lambda'} = \frac{(2.303 \ k \ \lambda' \ \log E_\lambda)}{c \ \lambda'} \quad \ldots (2)
\]

where, \( T \) is the black body temperature in absolute units,

\( \lambda = 0.655 \mu \); \( \lambda' = 0.589 \mu \) and

\( E_\lambda \) and \( E_\lambda' \) are the spectral emissivities of red and yellow light.

\( S_\lambda \) = brightness temperature as observed on the pyrometer.

\( S_\lambda' \) = Temperature of the flame. From (1) and (2),

\[
\frac{1}{S_\lambda} = \frac{2.303 \ k \ \lambda}{c \ h} \left[ \frac{\lambda \ \log E_\lambda - \lambda' \ \log E_\lambda'}{\log \frac{E_\lambda}{E_\lambda'}} \right] + \frac{1}{S_\lambda'} \quad \ldots (3)
\]
Data for spectral emissivities of temperatures were obtained from Forsythe and Worthing (1925). Values of $S_\lambda$ were then determined for all the temperature readings.

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Results

It was interesting to note that the absorption correction (quartz lens) and colour correction work in opposite directions and approximately by the same magnitude. So the temperatures obtained directly from the observation, generally, represent the reversal temperatures without any appreciable error and may be used as such. The temperatures obtained are collected in Table IV and are represented graphically as a function of air/fuel ratio (graph 10).

Table IV.

<table>
<thead>
<tr>
<th>Air/fuel ratio</th>
<th>Inner cones $^\circ$K</th>
<th>Outer cone $^\circ$K</th>
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<tbody>
<tr>
<td>4.40</td>
<td>1806</td>
<td>2007</td>
</tr>
<tr>
<td>4.80</td>
<td>1349</td>
<td>2038</td>
</tr>
<tr>
<td>5.20</td>
<td>1871</td>
<td>2084</td>
</tr>
<tr>
<td>5.54</td>
<td>1900</td>
<td>2114</td>
</tr>
<tr>
<td>5.87</td>
<td>1892</td>
<td>2139</td>
</tr>
<tr>
<td>6.17</td>
<td>1882</td>
<td>2123</td>
</tr>
<tr>
<td>6.48</td>
<td>1349</td>
<td>2119</td>
</tr>
<tr>
<td>6.76</td>
<td>1812</td>
<td>2103</td>
</tr>
</tbody>
</table>
Before closing the chapter, a mention may be made of the fact that the flame became slightly larger on introduction of sodium into it. This effect has been observed for different hydrocarbon flames by Arthur and Townend (1954) and our observation seems to support the existence of expansion of flame with introduction of sodium. This, the above authors explain as due to the action of atomic hydrogen in the flame. The hydrogen atoms are supposed to be trying to diffuse through the flame and react with sodium salt to release sodium, in a process considered to be neutral and in that act make the flame bulge. So the effect may be taken as an indication of the presence of free hydrogen atoms. It must be added that the sodium concentration is a function of free hydrogen atoms, but not the reversal temperature which is a function of the ratio of concentration of excited sodium to concentration of normal sodium and hence, represents the temperature of the hot gas and does not depend on the concentration of hydrogen atoms. (Arthur 1952, 1950).
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