exact mechanism of halo formation is still not clearly understood. It is known, however, that weld metal from titanium-covered electrodes seems to be more prone to halo formation than other types, and that the principal inclusions in weld metal susceptible to this phenomenon are rhodonite and manganese sulphide, although there is not sufficient evidence to relate these inclusions with the inception of haloes. There is also sufficient evidence available to state that the presence of appreciable strain and hydrogen are necessary factors, and that no haloes appear in impact tests on susceptible weld metal.

The fact that appreciable strain is necessary is exceedingly important and should inspire greater confidence in weld metal generally, as it means that the incidence of haloes can only occur at strains which could not be tolerated in the design of any structure."

ACKNOWLEDGMENTS

This work was undertaken as a co-operative investigation by several members of the FM.3 Committee. The names of the members, together with the laboratories and organizations in which the work was undertaken were as follows:

Mr. G. L. Hopkins, Armament Research Department.
Mr. W. J. Colbeck, Hadfields Ltd.
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REFERENCES

The Iron-Oxygen Combustion Process

A STUDY RELATED TO OXYGEN CUTTING

By A. A. Wells, Ph.D., B.Sc.

FOREWORD

The FM.10 Committee of B.W.R.A. was set up in April, 1951, to consider ways and means of studying the fundamentals of the oxygen-cutting process. It was believed that a better understanding of the phenomena would ultimately lead to improvements in the actual cutting operation, for instance, in greater economy of oxygen or in specificity and more effective cutting.

As often happens in research on an industrial process, it was found extremely difficult to make accurate measurements under the actual conditions of practical operation. It was therefore decided to make an experimental study with an apparatus specially designed for the purpose, in which a slowly rotating cylindrical bar of the material to be cut is moved end-ways into the oxygen jet; in this way the rate of cutting may be measured directly as the rate of feed of the bar into the jet. The report which follows describes results which have been obtained by this technique, and which appear to me to throw new light on a number of aspects of the problem, particularly concerning the effects of the composition of the metal to be cut and of the purity of the oxygen.

The Committee is aware that there are important differences between the conditions of the present experiments and those of practical cutting which may render it unsafe at this stage to draw too general conclusions from the present work. But it is hoped that a stimulus has been given to the further study of the problem, and to the ultimate application of the results to the improvement of practical oxygen cutting.—O. A. Saunders (Chairman)

THE basic process by which a jet of relatively pure oxygen is used to cut a locally preheated steel plate is fairly well known and need not be described in detail. Quantitative investigations of the process have been made by a number of workers to determine cutting speeds and the most economical conditions, with changes of material thickness, oxygen purity and velocity, preheat intensity, and nozzle diameter and Report FM.10 10c:55 of B.W.R.A., circulated to members 28th March, 1955. The opinions presented in the paper are those of the author and not necessarily those of the FM.10 Committee.

Dr. Wells is Chief Research Engineer at the Association's Research Laboratories, Abington.

SYNOPSIS

Measurements of the combustion rate between iron and oxygen are compared with calculations that determine the rate of diffusion of oxygen to the combustion face through a stagnant boundary layer of gaseous impurities. The thickness of this boundary layer is determined from a heat-flow analogue. With certain exceptions, it is concluded that the combustion rates for commercially pure reacting materials are mainly controlled by this diffusion mechanism.

form. It is as a result of these investigations that manufacturers of oxygen-cutting equipment now make their recommendations.

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However, comparatively little is known about the combustion of iron in oxygen, and it was therefore decided to concentrate on this aspect. The objective was to examine theoretically and by experiment the rates of heat generation on unit area of combustion face for ranges of values of oxygen purity, velocity, and the combustion-face geometry. In the course of the work, it was realized that the carbon content played a significant part in the process. The combustion process is now seen to depend on three components, namely, chemical combination, physical diffusion, and aerodynamics. Of these, the possible chemical combination rate was found to be so great that it did not prove to be a controlling factor except in some marginal cases. The physical diffusion process, as in most other combustion cases, was found to be important, and dependent in turn on the aerodynamic conditions, which have still not been exhaustively studied.

The report is presented in three parts:

(i) The conditions for heat flow by conduction away from the cut, which determine the heat input resulting from combustion
(ii) The diffusion process at the combustion face, which determines the effect of impurities in gas and iron on the combustion rate
(iii) The aerodynamics, which control the thickness of the stagnant gas layer on the combustion surface, and hence the diffusion rate

Further work is contemplated, but it is not the purpose of this report to anticipate the form that it will take.

HEAT FLOW BY CONDUCTION

When a steel plate is cut by means of an oxygen jet, heat must be supplied not only to melt the material removed by the cut, but also to maintain a temperature gradient in the remainder of the plate, so that the melting temperature may be supported at the edge of the cut: the heat conducted away from the cut may be an appreciable proportion of the total supplied. Equations predicting the temperature distribution from a heat source travelling with uniform velocity were first set up by Roberts. These were widely applied to fusion welding by Rosenthal, and have been rationalized for application by the present author.

If oxygen cutting is applied to an infinite plate of uniform thickness, the heat source is assumed to supply Q units of heat per unit thickness per unit time, when travelling with uniform velocity v. The value of Q to maintain a cut width of d is then given by:

\[ Q = \frac{8kT(\frac{v^2d}{4x} + \frac{1}{2})}{4x} \]  

(1)

if

\[ \frac{vd}{4x} > 0.1 \]

\[ k = \text{Thermal conductivity} \]

\[ \alpha = \text{Thermal diffusivity} = \frac{k}{\rho c} \]

\[ \rho = \text{Density} \]

\[ c = \text{Specific heat} \]

\[ T = \text{Melting temperature above that of the surroundings.} \]

The term \( \frac{vd}{4x} \) is non-dimensional and is related to the conduction loss efficiency \( e \) as follows:

\[ e = \frac{\frac{5vd}{4x}}{2\left(1 - \frac{5vd}{4x}\right)} \]  

(2)

Thus, however quickly heat is supplied to make the cut, at least one-half must always be lost by conduction. Under most practical conditions, the conduction efficiency is much less than this.

These equations have been compared by the author with metal-arc welding experiments conducted by Jackson and Shrubsole, and the good agreement shown suggests an equal authenticity for the equations when applied to oxygen cutting. Although the equations relate to plates of infinite extent, it may be readily shown that the error involved with limited plate sizes is small.

Inserting actual values for steel into equation (1), taking \( T = 1500^\circ\text{C} \), \( k = 0.10 \text{cal./cm.} \times \text{sec} \times \text{cm.}, \text{it appears that more than 240 cal./sec.cm. must always be supplied to maintain a cut. A figure of 500 to 1000 cal./sec.cm. is a more usual practical value. For 1000 cal./sec.cm. and } \alpha = 0.082 \text{ sq.cm./sec., the value of } vd \text{ becomes } 0.21 \text{ sq.cm./sec.} \]

EFFECTS OF GAS AND IRON IMPURITIES ON COMBUSTION RATE

Very large combustion rates may be supported when pure iron is allowed to burn in pure oxygen. The limiting chemical combination rate does not appear to have been measured at any time, although Tucker, in 1911, described how the burning time for an iron wire in oxygen of high purity could be increased eight-fold by decreasing the oxygen purity to 50%. Nusselt, in 1916, showed that the reduced combustion rates with impure materials could be explained by taking into account the diffusion of the oxidizing gas through stagnant layers of its own impurities and the gaseous products of combustion near the combustion face. Nusselt's analysis was concerned with the case of carbon, in air or oxygen. This hypothesis also applies to iron and oxygen combustion if the resistance due to the thin molten oxide layer, as well as the chemical resistance, may be ignored.

In the present work, experiments have been made to determine the changes in combustion rate associated with changes of purity of the oxygen and iron.

THEORY

For the steady diffusion at constant temperature of one gas through a second gas, stagnant at the interface, the rate of diffusion, \( N \) g.mol./sec., of the first through unit area of the interface has been shown by Stefan to be given by equation (3) if there is no change of total pressure across the boundary layer:

\[ N = \frac{DP}{RT_x} \log_{e} \frac{p_1}{p_2} \]  

(3)

where

\[ D = \text{Diffusion constant of the first gas through the stagnant gas (sq.cm./sec.)} \]

\[ p = \text{Total pressure (atmospheres)} \]

\[ R = \text{Gas constant for 1 gram-molecule (82.1 c.g.s. units)} \]

\[ T = \text{Absolute temperature (K.)} \]

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where \( p_i/P \) is the partial pressure ratio, equal to the volumetric fractional impurity \( \eta \) of the diffusing gas.

The boundary-layer thickness \( x \) depends on the aerodynamics of the combustion face and gas flow system, just as in the analogous conditions of friction and heat transfer in fluid flow.

If the solid contains \( y \% \) by weight of a contaminant, which reacts with each molecular volume of diffusing gas to replace \( m \) times the quantity of main solid and form \( n \) molecular volumes of gaseous contaminant which must diffuse back into the stream, it follows that the mainstream purity at the edge of the boundary layer is reduced by an amount \( \eta \), given by

\[
\eta = \frac{mny}{1 + y(m(1+\eta)-1)} \quad \ldots \ldots \ldots (5)
\]

The value of \( \eta \) may then be added to \( \eta \) in equation (4) to derive the corresponding diffusion rate. The theoretical suppressing effects on combustion rate of iron and oxygen due to the contaminating elements carbon, phosphorus, and sulfur are summarized in Table I. Carbon is seen to be by far the most important element.

If equation (4) is now to be applied numerically to the iron-oxygen combustion case, it is first necessary to establish the boundary-layer temperature. In practice, this will vary from the melting point of iron at the combustion face to ambient temperature in the main stream, since it may readily be demonstrated that the main oxygen jet passes across the combustion face without suffering appreciable rise of temperature. The mean of these two temperatures may therefore be used for calculation. In addition, the convenient approximation may be used that the heat of formation of the products FeO, FeO\(_2\), FeO\(_2\), CO, P\(_2\)O\(_5\), and SO\(_2\) is 4000 cal./g. of oxygen involved. The error is greatest with the elements P and S, but these will always be present in comparatively small quantities. The diffusion constant is taken to relate to oxygen and nitrogen, since these may be regarded as the most important substances present, together with the values appropriate to the mean boundary-layer temperature and pressure. Taking \( D = \sqrt{2\cdot30}\) sq.cm/sec, \( P = 1 \) atm., \( R = 82.1 \) c.g.s. units, and \( T = 1000^\circ\)K., equation (4), in terms of cal./sec. sq.cm., becomes

\[
q = 3.58 \frac{1}{x} \log_2 \frac{1}{\eta} \text{ cal./sec.sq.cm.} \quad \ldots \ldots \ldots (6)
\]

Thus, the boundary layer must be extremely thin to support adequate combustion rates with normal purities of iron and oxygen. It is, therefore, not surprising that in cutting steel plates the heat of combustion of iron must be reinforced by a preheating flame. In this connection the experiments of Seymour-Semper\(^7\) show that only a limited proportion of the heat generated by a preheating flame reaches the plate. In general terms it can be said that the heat supplied by the preheat flame to the plate during an oxygen cut is only one-third of that from iron and oxygen combustion, and may be even less when thick plates are cut.

**Combustion Apparatus**

Although combustion rates could have been studied using equipment intended solely for plate cutting, this would have had two main disadvantages, arising from the uncertainty of the amount of heat evolved: (a) that a preheat flame would be necessary to maintain combustion under most conditions, and (b) that the estimate of heat evolution from equation (1) would necessitate accurate knowledge of the cut width \( d \) at each point. On the other hand, the method adopted, of burning the end of a bar, allowed free combustion without simultaneous preheat, and gave an immediate measure of the combustion rate from the rate of melting of the bar. It may easily be shown that, for one-dimensional heat flow, there is no conduction loss as defined in equation (1), and that all the heat flows back into the bar and contributes directly to melting.

The apparatus used is shown in Fig. 1. The flattened nozzles were geometrically similar for each bar diameter. Combustion was initiated by means of a carbon arc directed at the end of the bar. The bar, of circular section, was rotated at a slow constant speed (60 r.p.m.) during combustion so as to stabilize.

---

**Table I**

**Effects on Combustion Rates of Contaminating Elements Present in Iron**

<table>
<thead>
<tr>
<th>Gaseous Contaminant</th>
<th>( n^* )</th>
<th>FeO</th>
<th>Fe(_2)O(_3)</th>
<th>FeO(_2)</th>
<th>Oxygen Impurity Equivalent to 1 wt. % of Combustion,</th>
<th>FeO</th>
<th>Fe(_2)O(_3)</th>
<th>FeO(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (CO(_2))</td>
<td>1</td>
<td>9:33</td>
<td>7:00</td>
<td>6:22</td>
<td>7:94</td>
<td>6:20</td>
<td>5:58</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (P(_2)O(_5))</td>
<td>0:4</td>
<td>4:51</td>
<td>3:70</td>
<td>3:00</td>
<td>1:71</td>
<td>1:42</td>
<td>1:16</td>
<td></td>
</tr>
</tbody>
</table>

\( n = (\text{Vol. of gaseous contaminant})/(\text{Vol. of oxygen used to form it}) \)

\( n = (\text{Mass of iron per vol. of oxygen})/(\text{Mass of contaminant per vol. of oxygen}) \)

\( \eta = (\text{Impurity}) + 0:01 \{ \text{Impurity} \} \)
combination conditions. The rate of rotation had little effect on the actual combustion rate. The bar feed rate was accurately controlled by using a motor-driven travelling carriage, and the limiting combustion rate for any given oxygen flow condition was determined by slowly increasing the bar feed rate until combustion was just on the point of ceasing. At this stage, the combustion face was not perpendicular to the axis of the bar and simulated the drag condition in oxygen cutting (see Fig. 2). Slow rotation of the bar caused a small step to be formed on the face on the side advancing towards the nozzle. At the critical point the step could not be maintained and it passed over the top of the bar, thereby stopping combustion. Without rotation the drag can reach larger values, and the limiting combustion rate is not easily defined. For each adjustment, in the experiments described below, the limiting combustion rate was determined about ten times, so as to obtain a reliable average value.

To check the heat balance for combustion, the combustion-face temperature was measured with a radiation pyrometer. For a steel with a melting point of 1550°C, this temperature was 1570°C for a low combustion rate and 1630°C for a higher value. The superheating is evidently occasioned by the need to maintain a thin fluid layer with a high rate of transverse heat flow.

A further attempt to check the combustion rate was made by means of a slag analysis. Slag was collected under water at various depths below the nozzle, the minimum depth being 7 in. Under all the conditions of test the slags contained 89% ± 2% of free and combined iron, and the point of collection did not appear to be significant. If the iron were just oxidized sufficiently to bring the slag temperature to 1500°C, the theoretical iron content in the slag would be 93.3%. Thus, the slag analysis suggests the generation of 66% more heat than that which reaches the bar. Since radiation and convection losses from the combustion face may be shown to be a very small proportion of the heat generated, it must be concluded that oxidation continues after the slag leaves the combustion face. For this reason the analysis of slags was not pursued any further for the checking of the rate of generation of heat.

Finally, the velocity distribution of the oxygen flow from the flat nozzles was investigated by means of a Pitot tube traverse. This showed that there was almost complete uniformity, so that values for the oxygen velocity \( u \) could be inferred from the well-known adiabatic relation of St. Venant and Wanzel:

\[
u = \sqrt{\frac{2 - \frac{Y}{Y-1} RT (1 - n^{-1}) p}}
\]

\[= 7.25 \times 10^4 \times \sqrt{(1 - n^{-1}) cm/sec} \text{ for oxygen}^* \text{. (7)}
\]

* Under supersonic conditions, the velocity of flow may be somewhat affected by shock waves, but the above may be retained as a conventional value for the purpose of combustion studies.

Table II

<table>
<thead>
<tr>
<th>Material</th>
<th>Dia., in.</th>
<th>Composition %</th>
<th>Equiv. Oxygen Impurity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
<td>P</td>
</tr>
<tr>
<td>Swedish iron</td>
<td>2</td>
<td>0.025</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Armco iron</td>
<td>0.355</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Free-cutting steel</td>
<td>2</td>
<td>0.14</td>
<td>1.22</td>
</tr>
<tr>
<td>Low-carbon steel</td>
<td>0.195</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>Medium-carbon steel</td>
<td>0.195</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>High-carbon steel</td>
<td>0.99</td>
<td>0.245</td>
<td>0.245</td>
</tr>
<tr>
<td>Razor steel</td>
<td>1.19</td>
<td>0.275</td>
<td>0.275</td>
</tr>
<tr>
<td>Cast iron</td>
<td>—</td>
<td>Not determined</td>
<td>—</td>
</tr>
</tbody>
</table>

* Reduced from 0.450 in. by lathe turning.

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where
\[ y = \text{Specific-heat ratio} = 1:4 \]
\[ T = \text{Reservoir temperature} \]
\[ p = \text{Nozzle-pressure ratio} \]

The above result is correct for gas at 15°C in the nozzle chamber. This was found to be the approximate temperature when the oxygen passed through a heater after leaving the manifold cylinders. The velocity could then be determined from the pressure in the nozzle tube, measured by means of a thread of mercury in a long glass capillary tube that was closed at one end and connected to the nozzle tube at the other. This gauge had the advantage of giving a direct measure of \( n \), since isothermal compression could be assumed, and the control reading could be obtained with no oxygen flow.

**Combustion Experiments**

The object of these experiments was to determine the changes in combustion rate associated with changes of purity of the oxygen and iron. To vary its purity, oxygen at a standardized purity of 99.7% was diluted with nitrogen supplied at gauge pressure through calibrated capillary metering tubes. Oxygen was supplied at a fixed pressure equivalent to a velocity of 25,000 cm/sec., for which a flow-rate calibration was also available. Exploratory tests gave no indication of different relative combustion rates at other velocities. The bars used were all \( \frac{2}{3} \) in. dia.; their compositions are given in Table II. Bars of 0.195% C steel were used in the experiments to investigate the effect of oxygen purity, and bars of varying carbon content, from Swedish iron to cast iron, were used when the effect of residual contents was being examined.

The results given in Tables III and IV are plotted on a semi-logarithmic scale in Figs. 3a and b. The relative combustion rates predicted by equation (6) when plotted against equivalent oxygen purities in this way should give straight-line relationships. For these results, equivalent oxygen purities were derived from the actual purities, by making the correction for residual contents in the iron from equations (5) and Table I, assuming oxidation to \( \text{FeO} \) or \( \text{Fe}_2\text{O}_3 \) as alternatives. (The results for \( \text{Fe}_2\text{O}_3 \) lie between these two.) Relative combustion rates are related to unity for the 0.195% carbon steel and 99.7% oxygen purity, and have been corrected for the differences of melting point shown in Table IV.

**Table IV**

<table>
<thead>
<tr>
<th>Actual Oxygen Purity, %</th>
<th>Equiv. Oxygen Purity, %</th>
<th>Burn-Off Rate, cm/sec.</th>
<th>Relative Combustion Rate*</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.70</td>
<td>97.96</td>
<td>98.48</td>
<td>0.91</td>
</tr>
<tr>
<td>99.61</td>
<td>97.87</td>
<td>98.39</td>
<td>0.95</td>
</tr>
<tr>
<td>99.54</td>
<td>97.80</td>
<td>98.32</td>
<td>0.98</td>
</tr>
<tr>
<td>99.11</td>
<td>97.37</td>
<td>97.89</td>
<td>0.83</td>
</tr>
<tr>
<td>98.3</td>
<td>96.67</td>
<td>96.10</td>
<td>0.74</td>
</tr>
<tr>
<td>97.6</td>
<td>95.9</td>
<td>96.4</td>
<td>0.67</td>
</tr>
<tr>
<td>96.1</td>
<td>94.4</td>
<td>94.9</td>
<td>0.60</td>
</tr>
<tr>
<td>94.6</td>
<td>92.9</td>
<td>93.4</td>
<td>0.57</td>
</tr>
<tr>
<td>93.9</td>
<td>92.2</td>
<td>92.7</td>
<td>0.55</td>
</tr>
<tr>
<td>91.8</td>
<td>90.1</td>
<td>90.6</td>
<td>0.47</td>
</tr>
<tr>
<td>90.8</td>
<td>89.1</td>
<td>89.6</td>
<td>0.44</td>
</tr>
<tr>
<td>86.5</td>
<td>84.8</td>
<td>83.3</td>
<td>0.36</td>
</tr>
</tbody>
</table>

* Taken as unity for no dilution

To assess any possible effect of entrained air in the oxygen jet on the combustion rate, an auxiliary experiment was conducted with 0.195% C steel and 99.7% purity oxygen, both with and without an oxygen-filled hood over the combustion zone. After extensive tests it was concluded that the oxygen hood gave rise only to a 3.7% increase in combustion rate, equivalent to an additional purity of 0.10% of the oxygen. Air entrainment has therefore been dismissed as a factor contributing to the results given in Table IV and Fig. 3b.

The results show a general agreement with the theoretical combustion rates, with some notable exceptions. In Fig. 3a, the combustion rate for the Swedish iron is about three-quarters of the expected value, which should be greater than that for mild steel. The reason for this is not clear. It is unlikely, for instance, that the slag already trapped in the iron could have an influence as great as this. A possible explanation might be that the high viscosity of the liquid metal caused a thick liquid boundary layer which could not be easily removed. None of the cast-iron specimens could be burned at all in the apparatus. At first the high melting point of the oxide relative to that of the cast iron was suspected of causing this. However, it was not possible to induce combustion by fluxing the

**Table III**

<table>
<thead>
<tr>
<th>Material</th>
<th>Equiv. Oxygen Purity, %</th>
<th>Burn-Off Rate, cm/sec.</th>
<th>Melting Point, °C</th>
<th>Corrected Burn-Off Rate, cm/sec.</th>
<th>Combustion Rate Relative to Low-Carbon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swedish iron</td>
<td>99.35</td>
<td>99.46</td>
<td>0.59</td>
<td>1540</td>
<td>0.61</td>
</tr>
<tr>
<td>Armco iron</td>
<td>99.40</td>
<td>99.48</td>
<td>1.15</td>
<td>1337</td>
<td>1.18</td>
</tr>
<tr>
<td>Free-cutting steel</td>
<td>97.65</td>
<td>98.28</td>
<td>0.61</td>
<td>1516</td>
<td>0.62</td>
</tr>
<tr>
<td>Low-carbon steel</td>
<td>97.96</td>
<td>98.48</td>
<td>0.71</td>
<td>1495</td>
<td>0.71</td>
</tr>
<tr>
<td>Medium-carbon steel</td>
<td>95.89</td>
<td>97.02</td>
<td>0.57</td>
<td>1465</td>
<td>0.55</td>
</tr>
<tr>
<td>High-carbon steel</td>
<td>95.78</td>
<td>94.13</td>
<td>0.51</td>
<td>1350</td>
<td>0.46</td>
</tr>
<tr>
<td>Razor steel</td>
<td>89.96</td>
<td>92.91</td>
<td>0.40</td>
<td>1320</td>
<td>0.35</td>
</tr>
<tr>
<td>Cast iron (No combustion)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

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oxide away by means of a borax coating on the bar. A more likely explanation is thought to be the added chemical resistance to combustion arising from the low combustion-face temperature, which could not be much greater than 1100°C. This is borne out by the combustion rates for other conditions of severe metal impurity, as shown by the consistent divergence of the experimental points from the theoretical straight lines in Figs. 3a and 3b for the same conditions.

EFFECTS OF OXYGEN VELOCITY AND BAR DIAMETER ON COMBUSTION RATES

It is well known that high combustion rates between iron and oxygen may be supported when high oxygen pressures and velocities are used, and vice versa. This might result simply from the need to supply oxygen to the reaction face at a sufficient rate to satisfy the combustion demand, or possibly from the need to remove the products of combustion which scour off the molten oxides accumulated on the reaction face. However, there is another factor which can be applied to combustion with impure materials, and this is implied in equation (6), which shows the combustion rate to be inversely proportional to the gas boundary-layer thickness x. It is known from aerodynamics that for any given body the boundary layer becomes thinner with increasing gas velocity, so that the dependence of the combustion rate on this thickness becomes of paramount importance. Further, it has been repeatedly proved that this boundary-layer thickness on a given body can have analogous influences on such diverse processes as fluid friction, heat transfer, and evaporation, as well as on combustion. The heat-transfer process, in particular, provides a useful analogy for the experimental determination of the boundary-layer thickness.

THEORY

Most of the expressions for boundary-layer thickness, for the systems mentioned, are of the non-dimensional form

\[ d = a \left( \frac{u \delta}{\mu} \right)^b \]  

The term \( d \) is a representative dimension, such as the length in the direction of gas flow of a flat plate in a gas stream flowing parallel to it, or the diameter of a tube within which, or across which, the gas flows. The term \( \rho \) is the density of the gas in the main stream (approximately atmospheric in the oxygen-jet case), and \( \mu \) is the viscosity pertaining to the boundary layer. The Reynolds number \( u \delta / \mu \) is a non-dimensional quantity. The constants \( a \) and \( b \) may apply only to limited values of the Reynolds' number, \( e.g. \), within the laminar and turbulent flow regimes. However, they may be expected to possess similar values for the same ranges of Reynolds' number for heat flow as well as mass transfer.

In the case of heat flow, there is in addition the relation:

\[ q = \frac{At}{x} \]  

where

- \( q \) = Heat-flow rate per unit area
- \( t \) = Temperature difference between wall and core of the gas flow
- \( k \) = Thermal conductivity of gas within the stagnant boundary layer.

The analogy between heat flow and combustion may now be established, and the boundary-layer thickness determined.
HEAT FLOW ANALOGY

In this analogue experiment, replicas of the bar and a steadily maintained flat oxygen jet were used as shown in Fig. 1, but with the bar stationary. The end of the bar remote from the jet was maintained at 100°C, and the sides of the bar were insulated by means of lightly packed cotton wool. The temperature at the end of the bar that was cooled by the oxygen jet was determined by means of a thermocouple.

Three temperatures were recorded at the jet face of the bar. These were the steady temperature with gas flow, but with the apparatus at room temperature ($t_1$); the steady temperature with the remote end of the bar at 100°C and no gas flow ($t_2$); and the steady temperature with the remote end of the bar at 100°C with gas flow ($t_3$). Thus, $t_1$ gave the main-stream gas temperature, with compensation for any difference as that between the main-stream adiabatic temperature and the boundary-layer recovery temperature; $t_2$ gave the temperature of the remote end of the bar, with correction for surface heat losses (which were always small, in any case). The boundary-layer thickness $x$ for heat flow was then obtained from the temperatures and the bar length $l$ from the following relation:

$$l = \frac{x}{K} \cdot \frac{t_1 - t_2}{t_1 - t_3}$$

where $K$ and $k$ are the thermal conductivities, over the appropriate temperature ranges, of the steel and oxygen respectively.

The results are given in Table V and Fig. 4. In Fig. 4, $d/x$ is plotted against the Reynolds' number $\text{Re}_{\text{p}}$ for three bar diameters, and this method of plotting appears to satisfy equation (8), with $\alpha = 0.0011$, $b = 1$. The correspondence of the results for different bar diameters is not as good for high Reynolds' numbers, but the deviation is not regular. It was noticed that the temperature of the end of the bar was very sensitive to the relative positions of the face and jet, being lower when the face protruded into the jet. As far as possible, the face and the side of the jet opening were main-

tained as coincident planes. The results show a spread of the same order as that reported by McAdams, who discusses separate experiments with flat plates in a parallel gas stream carried out by Jurges, by Elias, and by Fage and Faulkner (extrapolated from lower Reynolds' number). These results are plotted for comparison in Fig. 4.

**Combustion Rate Measurements**

These experiments differed from those already described only in that 99.7% standardized-purity oxygen was used throughout, at varying velocities, with mild-steel bars of $\frac{1}{2}$, $\frac{3}{4}$, and 1 in. dia. The same technique of combustion-rate measurement was used, and the measured combustion rates are given in Table VI. Burn-off rates $r$ are plotted against oxygen velocities in Fig. 5, from which it appears that the relationship between the two, for different bar diameters, is somewhat complex. No great improvement of correlation appears when $ud$ is plotted against $ vd$, as in Fig. 6. This type of plot is suggested by equations (6) and (8), since $\alpha = \eta m$, where $m$ is the heat of melting per cubic centimetre of bar (1800 cal./cu.cm.).

Thus:

$$d = \frac{\alpha d}{3.58 \log \frac{q}{\eta}} = \frac{\alpha d}{30 \log \frac{q}{\eta}}$$

for steel containing 0.195% C, where $\log (1/\eta) = 4.2$

<table>
<thead>
<tr>
<th>Table V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BOUNDARY LAYER THICKNESSES FROM HEAT FLOW ANALOGY</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bar Dia. $d$, cm.</th>
<th>Gas Velocity, cm/sec.</th>
<th>'Reynolds' Number $\times 10^5$</th>
<th>$d/x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.63</td>
<td>4.600</td>
<td>2.17</td>
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<td>49.2</td>
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<td>7.35</td>
<td>69.9</td>
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<td>8.96</td>
<td>82.8</td>
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<td>14.6</td>
<td>119.4</td>
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<tr>
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<td>3.900</td>
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<td>32.4</td>
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<td>5.800</td>
<td>4.13</td>
<td>44.4</td>
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<td>5.62</td>
<td>60.4</td>
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<td>12.8</td>
<td>160.0</td>
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<td>14.4</td>
<td>174.0</td>
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<td>15.6</td>
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<td>18.5</td>
<td>246.0</td>
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<td>264.0</td>
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<td>34.400</td>
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and \( u_0 \mu \delta = u_d \times 3.08 \), for atmospheric pressure and 
\( \mu \) at 1000°C.

However, when the results of Fig. 4 are transferred to Fig. 6 by means of these calculated relationships, there is an encouraging comparison with the measured combustion rates for equivalent sizes of bar. It is possible that by means of a different method of plotting, using additional non-dimensional groups such as the Mach number, the results of Fig. 6 might be reduced to uniqueness. A more successful but theoretically correct correlation has not been found, however, and it is concluded that further results should be obtained with an aerodynamically cleaner combustion system.

**DISCUSSION OF RESULTS**

The results suggest that the stagnant-film diffusion theory, with certain limitations, typified by equations (4) and (5), gives an accurate description of iron-

**Table VI**

**COMBUSTION RATES FOR DIFFERENT GAS VELOCITIES AND BAR DIAMETERS**

<table>
<thead>
<tr>
<th>Gas Velocity, cm/sec</th>
<th>( u_d )</th>
<th>Burn-Off Rate, cm/sec</th>
<th>( v_d )</th>
<th>Gas Velocity, cm/sec</th>
<th>Burn-Off Rate, cm/sec</th>
<th>( v_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{2} ) in. (0.635 cm.) bar</td>
<td>1.480</td>
<td>0.960</td>
<td>0.38</td>
<td>0.24</td>
<td>1.880</td>
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<td>2.480</td>
<td>1.570</td>
<td>0.47</td>
<td>0.30</td>
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<td>0.21</td>
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<td>0.44</td>
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<td>0.83</td>
<td>17.800</td>
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<td>30.800</td>
<td>19.500</td>
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<td>1.02</td>
<td>20.700</td>
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<tr>
<td></td>
<td>0.8 in. (2.035 cm.) bar</td>
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<td>0.18</td>
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<td>0.42</td>
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<td>0.52</td>
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<td>21.600</td>
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<tr>
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<td>1.14</td>
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<tr>
<td></td>
<td>27.800</td>
<td>26.400</td>
<td>1.20</td>
<td>1.27</td>
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<td>27.200</td>
<td>27.700</td>
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<td>1.46</td>
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<td>29.900</td>
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<td></td>
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</tr>
</tbody>
</table>

**SEPTEMBER, 1955**

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oxygen combustion with impure materials. Thus, it
describes the effects of: (a) Gas impurity, (b) iron
impurity, (c) gas velocity, and in addition it gives
the correct order of magnitude of the combustion rate.

For the research work so far undertaken, the theory
does not agree, on the aerodynamic side, in the estima-
tion of the effect due to change of combustion-face
dimensions, with geometrical similarity. Also, under
special cutting conditions, the combustion rates may
be modified by low combustion temperature or high
liquid-metal viscosity, but these need not necessarily
occur in practice.

In view of the satisfying general agreement with
theory of the results of the experiments relating to
combustion rates with impure oxygen and iron, it is
important that the anomalous low combustion rate for
wrought (Swedish) iron should not be forgotten. It
is agreed among those with experience of the process that
irons of low carbon content behave in like manner
when being cut under practical conditions. Neverthe-
less, at higher carbon contents, experience supports
the theory as well as the experiments described above.
In practice the effect of the fluid slag layer on the cut is
apparently more marked than was the case in these
experiments. The nature of the metallic oxides in the
slag evidently has some importance, and might explain
the anomalous behaviour of the wrought iron in these
experiments. (This material was the only one, of those
tested, to have little manganese present). It is agreed in
practice that there is little point in increasing com-
mmercial oxygen purities beyond present values, since
possible gains in combustion rate would be offset by
increased cost and by the effects of steel impurities.

CONCLUSIONS

(1) In the oxygen-cutting heat balance, the two
important factors are the heat generated by iron
-oxygen combustion and that lost by conduction in the
steel.

(2) The rate of heat loss per unit thickness into a
plate by conduction from a progressing oxygen cut
may be readily and accurately estimated by a simple
equation, equation (2). The rate mainly depends on
the volumetric rate of metal removal by melting and
combustion.

(3) The rate of heat generation by combustion for
unit area of combustion face depends, for commer-
cially pure materials, on the possible rate of
diffusion of oxygen to the combustion face through
the stagnant boundary layer of impurities. If the
gas-forming impurities in the oxygen and iron are
known, the rate of heat generation may be readily
determined for each boundary-layer thickness by a
further pair of equations, equations (5) and (6).

(4) The boundary-layer thickness for combustion-
rate determination is at least approximately the same
as that for heat transfer, and may therefore be
obtained from a heat-flow analogue.

(5) For given oxygen flow conditions in the
experiments described, the combustion rate depended
more on the carbon content of the steel than on the
oxygen purity. Thus, 1% of carbon in the steel had the
same suppressing effect as 6-2% of nitrogen in the oxygen.

(6) Other influences on combustion rates that were
noted were (a) the combustion temperature, which
could not be adequately maintained when it was
attempted to burn cast iron, and (b) an unexplained
effect which caused Swedish iron to burn more slowly
than mild steel, although the former contains less carbon.

(7) The aerodynamics of the combustion apparatus
were too complex for the absolute effect of combustion-
face size to be uniquely determined. It is hoped later to
introduce modifications to experiments which will
enable this to be done.

ACKNOWLEDGMENTS

Grateful thanks are expressed for the considerable
assistance which has been received with this investiga-
tion, and especially for technical advice from the
Chairman and members of the F.M.10 Committee, and
Dr. D. B. Spalding, of Cambridge University Engineer-
ing Laboratory. Dr. Spalding was responsible for
suggesting the application of the diffusion treatment in
calculating combustion rates. Combustion-face tem-
peratures were measured by Mr. Simons, of B.I.S.R.A.,
through the co-operation of Professor Thring. Slag
analyses were also carried out at Professor Thring's
department. Loans of equipment were made by the
British Oxygen Co., Ltd., and Hancock and Co. (Engineers) Ltd., and special arrangements for the
supply of standardized 99-7% purity oxygen were also
made by the British Oxygen Co., Ltd.

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