Mechanized Oxyfuel Control with Ion Current Sensing

An approach for sensing standoff distance and fuel-oxygen mixture using only the electrical characteristics of the flame is described

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ABSTRACT

This paper advances an approach to sensing in mechanized oxyfuel systems where sensors are eliminated and the electrical characteristics inherent to the torch, flame, and workpiece are used to measure standoff distance and fuel-oxygen ratio. Electrical properties are also shown to be correlated to preheat flow rate and work temperature. These measurements were conducted by applying voltage to the torch and measuring the resulting current transmitted through the flame. Measurements with an Oxweld C-67 torch heating a temperature-stabilized plate revealed a nonlinear current-voltage characteristic with three regimes at signal level voltages (-10 to 10 V). These regimes were dominated by different physical phenomena that empowered the observer to understand various parameters of the system typically only available by mounting sensors in the vicinity of the flame. Eliminating sensors from the “hot zone” had positive cost implications, but there was an even stronger potential benefit to the reliability of the system, because those sensors were susceptible to damage from the process.

KEYWORDS

• Oxyfuel Cutting • Ion Current • Height Control • Sensing

Introduction

The present paper advances an approach to sensing in oxyfuel systems whereby active sensors were obsoleted by relating the electrical properties of the flame to process parameters. While the immediate application envisioned here was in mechanized oxyfuel cutting systems, the same physics and concepts were relevant to welding, heating heads, scarfing, and other more specialized applications.

Background

A niche has been carved out by mechanized oxyfuel cutting where cost, material thickness, or both typically determine the process selection. It might be said that the century-old cutting process competes adeptly against its more modern peers when these concerns are paramount. However, oxyfuel cutting has proved challenging to find the sensing suite necessary for total automation that does not also undermine the system’s cost, reliability, or some other important aspect of the process. As a result, oxyfuel cutting has largely retained its old demands on the operator’s attention, knowledge, and skill.

To illustrate the challenge, one might consider the capacitive rings that have long been favorites for sensing torch standoff from the workpiece. For a cost potentially in excess of the torch itself, these systems suffer from poor performance at the plate’s edge, susceptibility to electrical interference, unpredictable drastic behaviors in the presence of moisture, and regular degradation and ultimate destruction due to long-term exposure to heat and slag. A desire for immunity to edge and moisture effects dares designers to place the ring ever closer to the flame with predictable implications on the longevity of the sensor.

This paper describes an approach for sensing standoff distance and fuel-oxygen mixture using only the electrical characteristics of the flame. Measurements were also presented demonstrating how total flow and plate temperature might be measured. In this approach, the torch was presumed to be electrically isolated from the workpiece, and the torch tip and workpiece acted as electrodes.

Literature Review

The aggregate of several studies spanning roughly a century and a half is a relatively complete picture of the physical processes at work (Refs. 1, 5). Electrical currents in flames have been the subject of interest since at least the eighteenth century (Ref. 1). Identifying them to be caused by the formation of ions during the chemical reaction was an important part of understanding the electrical structure of the atom (Refs. 2, 3).

By the middle of the twentieth century, it was clear that the currents to and from metal (absorbing) surfaces near a flame were due to unequal bombardment of positive and negative ions (Refs. 1, 4). This information is in harmony with the now canonical kinetic theory of gases. The painstaking process of identifying those ions in different flames would span the remainder of the century (Ref. 5), with several important works in this area casting light on the internal structure of flames (Refs. 6, 7).

In a flame, free electrons are far more mobile than their heavier, positively charged molecular counterparts. An electric field applied between two surfaces adjoining the flame will drive electrons away from one (cathode) and towards the other (anode). When positive ions impact a metal surface, they...
The torch height was regulated to constant electrical excitation to the flame by a control system applying a constant electrical excitation to the flame. By standoff alone was sensed that the name ion current sensor is borrowed. This type of sensing has been used to tackle the perplexing problems controlling ignition internal combustion engines (Ref. 11) as well as diagnosing combustion dynamic problems in diesel engines (Ref. 12) and engine knock. Meanwhile, engineers in the furnace industry today favor what they call flame rectification for burner diagnostics ( Refs. 13, 14). Ion currents have been used for robust diagnosis of combustion dynamics in gas turbine burners (Ref. 15), and the application of more intense electric fields has even been used to control burning rates of gases (Ref. 16) and solid propellants (Ref. 17).

A pair of patents assigned to the Caterpillar Tractor Co. in 1974 (Ref. 18) and 1982 (Ref. 19) probably represent the most advanced documented application of ion current sensing to the oxyfuel process. The latter was acquired by Messer Cutting Systems, and served the basis of their systematic oxyfuel control systems in the 1990s. The system was eventually dropped from the Messer catalog due to the limitations of the economical processor power at the time (Ref. 20).

This brief review of ion current sensing suggests two reasons for why the approach has not been widely adopted in the oxyfuel industry, such as gaps in the fundamental understanding of the physics and limitations of the available electronics. Since the processing capacity of a mp3 player would be more than is required for the measurements proposed below, the availability of robust and economical electronics is no longer a realistic concern. The remainder of the paper is devoted to constructing the argument that the physics involved are complex but easily measured.

### Experiment

Controlled tests of the voltage-current characteristic of a methane-oxygen preheat flame on an Oxweld C-67 torch with a ½-in., two-piece tip while varying the flow rate, fuel-oxygen ratio, standoff, and coupon surface temperature were conducted. The flame was stagnated over a 2½-in.-diameter (54 mm) SAE 4140 steel test coupon with internal cooling channels to stabilize the temperature. The surface temperature was approximated with a thermal model for the plate based on two thermocouples embedded in the coupon — Fig. 1. The coolant was a mixture of air and water adjusted to stabilize the coupon surface temperature independently of the heating conditions.

While the details of the thermal model are beyond the scope of this paper, the author offers some discussion in Ref. 21. Figure 1 shows the experiment illustrated with the classical "inner" and "outer" cone structure of the oxyfuel flame.

The flame was interrogated by a...
+/10 V triangle wave, and signals indicating the current and voltage were simultaneously returned by the circuit shown in Fig. 2. The circuit was calibrated using a series of shunt resistors to simulate the flame, and the four potentiometers were adjusted to provide command/response precision to 0.1% of measurements taken with an Agilent precision multimeter. The TL074 quad-opamp was selected for its frequency response and ultra-low bias current to avoid corrupting the current measurement. The distance between the torch and the workpiece precludes the possibility of a twisted pair-noise rejection strategy, so foil shielded signal wire was used to good effect.

While the circuit allows for either voltage or current command mode, these tests were conducted entirely with respect to voltage. Fuel and oxygen flow rates were monitored with thermal mass flow meters. Standoff height was changed by indexing a rack-and-pinion height adjustment.

Results

Figure 3 presents voltage and current waveforms beside three current-voltage characteristic curves exemplifying data collected in 97 tests at various standoffs, plate temperatures, flow rates, and fuel-oxygen ratios. Each curve expresses three distinct regimes. At the center, the flame acted like a quasi-uniform plasma with some volume resistivity (Ref. 4). Bracketing this regime were abrupt saturations limiting the current observed (Ref. 2). Once this occurs, additional voltage drives no more current, barring some secondary mechanism, which was observed here.

Figure 4 shows an electrical model exhibiting the behaviors as they have been described thus far. The interaction between each surface and the plasma was represented as a unique semiconductor component. For example, in Regime 2, the sleeve component behaved as a short, but it transitioned into a constant current source, which we called I1. Similarly, the stagnation junction saturated at a current, I2. The insert junction was not shown to saturate at these currents, so it acted as a short under all conditions.

Figures 5 through 13 were produced by fitting the current-voltage characteristics with a piecewise function.

\[
I = \begin{cases} 
\frac{(V - V_1)}{R_1} + I_1 & V < V_1 \\
\frac{(V - V_0)}{R_2} & V_1 \leq V < V_2 \\
\frac{(V - V_2)}{R_3} + I_2 & V_2 \leq V
\end{cases}
\]

Here, each regime was characterized by a corresponding resistance, R1, R2, and R3. The saturation voltages — V1 and V2 — were calculated in terms of the floating potential, V0, and the saturation currents, I1 and I2.

\[
V_1 = V_0 + I_1 R_2 \\
V_2 = V_0 + I_2 R_2
\]

The outer cone resistance, ROC, was the resistance responsible for the slope of the current-voltage characteristic in Regime 2. It should be equal to R2 so it can be measured directly as the slope in Regime 2.

\[
R_{oc} = R_2
\]

The inner cone resistance, RIC, determined the slope in the partial saturation observed in Regime 1. If R1 was the resistance determined by the slope in Regime 1, then

\[
R_{ic} = R_1 - R_{oc}
\]

It is worth mentioning that the floating potential, V0, would be more correctly modeled as the aggregate of potentials generated at the surfaces, but the ultimate effect is similar. In this work, we make no effort to quantify the components of the floating potential contributed by the torch and work, but treat the floating potential as a single parameter.

The Regime 3 resistance was motivated by the observation that, in many
conditions, the work saturation did not seem to be bounded as the ideal model would predict. While this paper will not address the matter entirely, more detail is provided in the sections discussing sensing flow and work temperature.

Discussion

The “partial” saturation between Regimes 1 and 2 of Fig. 3 was due to an interaction between the complexity of the flame structure and the tip geometry. Since the path from the work through the outer cone to the sleeve formed the shortest electrical path, the sleeve surface was expected to saturate first, and any additional current would be forced through the longer path through the inner cone (Ref. 21). The resulting abrupt change in the flame’s apparent resistance produced the transition to Regime 1 in Fig. 3. It stands to reason that at strongly negative electrical potentials, a second saturation occurred, but practical considerations have motivated us to consider only signal level voltages (-10 to 10 V) in the present study.

The positive saturation in Regime 3 appeared to, more closely, resemble the hard saturation described by most researchers, but close inspection showed a small declining positive slope. While Regimes 1 and 2 enjoyed remarkable immunity to changes in the work surface condition, the work surface saturation causing Regime 3 exhibited drastic changes from test-to-test. These phenomena are afforded some discussion in the sections on sensing flow rate and plate temperature below.

The need for the “floating potential,” $V_0$ in the electrical model is also apparent in Fig. 3, since zero current did not occur at zero voltage but at some offset voltage. This has long been understood to be due to the dissimilar rates of bombardment of negative (electrons) and positive (ionized atoms and molecules) ions (Ref. 1). Conducting surfaces inserted in plasmas (like flames) are assumed, either through absorption or through exchange of electrons, to neutralize ions on impact. As a result, a flow of current between the surface and the plasma will occur when the impact of small, quick electrons outpaces the sluggish positive counterparts. The floating potential is the voltage required to counteract that effect in balance between the two conducting surfaces. If all conditions at the surfaces are symmetrical, then the floating potential will be zero (Refs. 2, 3).

Sensing Height

While standoff was shown to im-
pact all the regimes in some form, its impact was most disentangled from the secondary effects in Regime 2. At most conditions, the outer cone length was proportional to $R_{OC}$, as shown in Fig. 5. The data were collected with the total flow at 20 ft$^3$/h (9.4 L/min) and at a fuel-to-oxygen ratio of 0.55 by volume (stoichiometric is 0.5).

The black squares of Fig. 5 represent separate measurements taken above a 1½-in.-tall steel slat arranged in an edge-start configuration while varying flow and mixture. The torch was positioned such that half of the flame stagnated on the top of the slat and the other half washed over the vertical face. The tight cluster of black squares include data at 20 and 27 ft$^3$/h (9.4 or 12.7 L/min) and 0.50 F/O ratio. The outlier point was produced by increasing the F/O ratio to 0.60 while holding the flow rate at 20 ft$^3$/h. These represent a deliberate effort to confuse the measurement by manipulating the plate surface, flame stagnation geometry, flow rate, and mixture. Only the mixture seemed to have produced a severe effect. The following sections are devoted to quantifying the measurement’s sensitivities, but a detailed study of variable work geometry is left to future study.

**Height Sensitivity to Mixture**

As the outlier of Fig. 5 suggests, variations in the F/O mixture stand to impact the height measurement. Figure 6 shows outer cone resistance (Regime 2 slope) at three standoff distances while varying the F/O mixture at a constant total flow rate. At leaner mixtures and small standoffs, substantial changes in mixture were required to produce a noticeable effect. However, the lean flames exhibited drastically shorter outer cones, causing a nonlinear increase in resistance at high standoff (black triangles).

As the mixture was pushed richer, eventually the flame was made to lift off the torch and stabilize on the coupon surface. Beginning around the 0.75 F/O ratio, the lifted flame caused resistance to approach infinity, but rather than trending to infinity as a multiple of one another, the data drifted upward as a group. This behavior suggests the flame resistivity was unchanged, but some series resistance had been added.

At a low F/O ratio, the outer cone resistance was linearly proportional to the cone length, which implied some uniform bulk resistivity. If that bulk resistivity were to trend upwards, then the outer cone resistances at different standoffs should always be in the same ratio to one another as the distances at which they were observed. Instead, Fig. 6 suggests some offset resistance is added to all of the values equally.

$$R_{OC} = R_{OC_{REF}} + \Delta R_{OC}$$  \hspace{1cm} (5)

If this increase in resistance is caused by the beginnings of flame liftoff, then it should also have a strong impact on inner cone resistance. Figure 7 shows the Regime 1 resistance and the inner cone resistance calculated from Equation 4.

The collapse of data onto a single curve suggests the electrical model was correct. Furthermore, the similar shapes of Figs. 5 and 6 encourage the notion that they may be subject to the same phenomenon.

$$R_{IC} = R_{IC_{REF}} + \Delta R_{IC}$$  \hspace{1cm} (6)

Figure 8 shows deviations in the outer and inner cone resistances while varying the F/O ratio. The F/O ratio 0.60 was selected as the reference value because the outer cone was supposed to be in proper electrical contact with the plate at the highest standoff. The resulting scatter was not small enough to be completely neglected, but the argument for a linear correlation seems quite strong. These results indicate that as the flame approach liftoff conditions, an electrical barrier grew between both cones and the torch. While that barrier does not affect the two equally, it did seem to maintain a strong proportionality even as the inner and outer resistances were increased several times over. That proportionality could hardly be expected to be similar for different tip geometries, but for the tip under test, that ratio was about 15.6%.

**Fig. 5 — Standoff distance vs. the Regime 2 resistance. Data were collected with 20 ft$^3$/h (9.4 L/min) and 0.55 fuel-to-oxygen ratio (by volume). The black squares represent four tests conducted in an edge-start configuration with flow rates 20 or 27 ft$^3$/h (9.4 or 12.7 L/min) and with 0.50 or 0.61 fuel-to-oxygen ratios.**

**Fig. 6 — Outer cone resistance (Regime 2 resistance) at various standoff distances vs. fuel-to-oxygen ratio (by volume). Data were collected at a 20 ft$^3$/h (9.4 L/min) flow rate.**
If measurements in $R_{IC}$ are performed simultaneously with the measurements of $ROC$, a sufficiently aware controller could be configured to compensate for drifts in the F/O mixture during a long operation using a trivial correction.

**Height Sensitivity to Flow**

Figure 9 shows the outer cone resistance measured over a wide range of flows. At stoichiometric conditions, a 10% increase in flow caused about a 10% decrease in outer cone resistance. This represented the worst case measured. At rich conditions, any impact from the flow rate was not discernible from the scatter.

The substantial scatter in the data were due to insufficient experimental control of the F/O ratio at rich conditions. Recall from Fig. 6 that small changes in the F/O ratio had drastic effects in rich conditions. The same scatter is not visible at leaner conditions because of the insensitivity to the F/O ratio those conditions exhibit.

**Sensing the Preheat Mixture**

The section titled height sensitivity to mixture provides a method for using the inner cone resistance as a means for compensating the height measurement for changes in the fuel-to-oxygen ratio, but fully autonomous multitorch systems should be capable of detecting gas pressure balance across torches. If some torches burn hot, it can cause irregularities in the part geometries, while a cold torch can cause a costly lost cut.

To this end, the inner cone resistance was not an ideal quantity for sensing, because it was insensitive to the mixture over much of the range studied here. Instead, negative saturation current, $I_1$, offered a preferable alternative. The electrical current at which the sleeve's surface saturates

\[
\Delta R_{OC} = 0.16 \Delta R_{IC} \tag{7}
\]

Fig. 7 – A and B — Regime 1 resistance taken directly from measurements and inner cone resistance calculated by subtracting the outer cone resistance from $R_1$.

Fig. 8 — Deviations in inner cone and outer cone resistance, due to changes in the F/O mixture, plotted against one another at various standoffs.

Fig. 9 — Outer cone resistance vs. total preheat flow rate for various standoffs and F/O ratios.
was certain to be a strong function of the temperature and concentration of ions at the sleeve surface.

Figure 10 shows the saturation current plotted vs. the F/O ratio at various standoffs. Even while the inner cone resistance is relatively flat, $I_1$ demonstrates a strong dependence on the F/O ratio while remaining insensitive to standoff. Measurements of $I_1$ sensitivity to flow showed sensitivities no larger than $0.5 \mu A$ per ft$^3$/h (1 $\mu A$ per L/min). If nothing was known about the flow, these sensitivities could not be ignored. If mixture adjustments are made while making even a meager attempt to preserve total flow, they are justifiably neglected.

**Mixture Errors at High Standoff**

Using a saturation current method to detect the mixture can work with very little knowledge of the torch location relative to any other electrode. However, there are extreme cases when a “neutral” or stoichiometric flame’s short outer cone fails to engage with the work; the outer cone resistance can actually grow to overwhelm the inner cone resistance. In these conditions, the change in the voltage-current characteristic becomes quite subtle, instead of the severe changes shown in Fig. 3, and the saturation current becomes difficult to determine with any certainty. To illustrate this point, the error bars in Fig. 10 were approximated by presuming a 5% error in the Regime 1 and 2 resistance measurements.

Once aware of the phenomenon, this effect was easily avoided by taking intermittent mixture measurements during a preheat operation. These conditions can be relied upon to have the workpiece in a stable location a short distance from the torch with excellent engagement between flame and work.

**Sensing Preheat Flow**

That none of the measurements discussed so far bore a strong dependence on flow was helpful to our approach. However, it left few options but to turn to the dubious class of measurements that rely on the workpiece to serve as the primary sensing surface. For a given mixture, the strongest impact that flow will have is to elongate the flame’s luminous zone. It seems reasonable to conjecture that something similar would happen to the flame’s electrical structure.

Equation 1 uses a resistance, $R_3$, to characterize the continued rise in current after the positive saturation. In some conditions, this behavior was nearly negligible. In others, it was more substantial than the saturation current itself. The author has offered some explanation for the behavior (Ref. 21), but it remains to be seen whether this is correct. Though the present study offers no means to quantify the effect, the rise of current in Regime 3 seems to correlate with the surface area of the flame’s luminous zone that washes over the coupon’s surface.

To investigate the effect, some equivalent of $R_3$ for the plate surface were considered

$$R'_3 = R_3 - R_{OC} \quad (8)$$

which was the component of the effective resistance after saturation occurred that was not due to the outer cone.

Figure 11 shows the results plotted against flow for selected mixtures and standoffs. Despite the scatter, there was an excellent correlation between flow and electrical engagement with the work. However, without a theoretical basis for confidence in the measurement, the scatter was sufficient to cast doubt on its feasibility in practice. Further work is required.

**Surface Irregularities**

The appearance of repeatable outliers along the bottom of the plot belied the ambition that this measurement might be insensitive to the plate condition. The measurements were shown in the legend in the order they were taken. Some of the data collected in this study took the plate surface to its melting point, after which small beads of molten metal were allowed to freeze on the plate’s surface. Those formed a complex surface geometry that seemed to have burned off at high
flow rates, creating the hysteresis loop formed by the white circles. It is possible that an alternative method could be developed by which the torch is lowered until the $R_3$ values stabilize to some large threshold. The implications on flame length could be interpreted as an indirect measurement of flow without dependence on the work surface, but no such investigation was performed in this study.

Plate Temperature Measurement

Attempts to measure the work temperature using electrical characteristics were frustrated by the same severe sensitivities to the surface condition as the flow measurement, but the situation was helped somewhat by the importance of plasma and plate temperature in shaping the positive saturation. In the course of this investigation, floating potential, Regime 3 resistance, and positive saturation current were examined as possible means for detecting plate temperature. Regime 3 resistance formed a scatter that seemed to be more predominantly determined by the plate surface roughness than anything else. As a happy accident, this may actually offer a controller the means for qualitatively assessing the level of oxidation, scale, or other potentially undesirable impurities on a workpiece.

Were one to approach the question without data to act as a guide, there is good reason to speculate that floating potential might bear a good sensitivity to plate temperature. Measurements showed the floating potential varied between about 0.5 to 1.0 V, and plots controlling for plate temperature implied a modest positive correlation. However, the extreme scatter was discouraging. It is possible that chemical action at the plate surface may be influencing the measurement, so we were compelled to abandon it for the present purpose. However, if chemical action contributed to the floating potential, it may prove an excellent indicator for the burning rate in a cut.

Figure 12 shows the positive saturation current for four data series in which the plate temperature was allowed to vary. Because all other data showed a strong dependence on the mechanical condition of the plate surface, these data series were organized by the order they were taken. Each data series represented consecutive measurements that were collected without removing the torch from the coupon. No care was taken to control the plate condition between data series. Similar controls were used in all other data presented here, but these are the only results that show chronological sensitivity. In data series 1, the height of the torch was varied. In the other experiments, the plate coolant was varied.

Given the shape of the trend and the temperatures involved, it is possible that thermionic emission may have been responsible for the abrupt rise, or a cold plate could have been cooling the plasma and retarding the rate of ion bombardment. It is difficult to perform even an order-of-magnitude approximation of thermionic emission currents since the phenomenon is widely known to be sensitive to surface roughness and composition, neither of which is well controlled in this experiment. While it seemed unlikely to be the direct cause for changes in saturation, it should also be noted that the melting temperature for the steel used was usually reported to be about 1440°C.

To give some indication of the repeatability of these measurements, Fig. 13 shows positive saturation current plotted for all data collected at 0.23-in. standoff. The F/O ratio was not controlled. Flow was not controlled for the black diamonds.
The preheat fuel-oxygen ratio can be sensed via the negative partial saturation current. This measurement was insensitive to standoff and only very weakly sensitive to flow rate. Provided the measurement is performed with a sufficiently low standoff, the data suggests that better than 0.025 error in the ratio is possible.

The piecewise linear model for ion currents seemed to be inadequate in Regime 3. A more complete electrical model for the workpiece surface might offer calibrated measurements for flow and plate temperature.

Preheat flow rate had little impact on most of the electrical properties of the flame, but it did have the effect of lengthening the outer cone. Though its theoretical validity may be questionable, the Regime 3 resistance showed an excellent correlation to flow, but the measurement approach suffered from dependency on the physical condition of the workpiece.

Work temperature seemed to be correlated to the positive ion current saturation levels. While this is clearly the most difficult of the measurements, its potential value motivates further investigation. The data collected thus far were not sufficient to place confidence in the measurement technique, but neither was there a satisfactory electrical model for the flame-plate interaction.

Conclusions

The data presented here confirms the feasibility for measuring standoff and fuel-oxygen mixture using flame electrical characteristics. Methods for measuring work temperature and preheat flow rate were also presented, but additional work characterizing the work saturation phenomena is necessary before they will be practical.

The quantitative measurements made were specific to the Oxweld C-67 burning methane with a ½-in. two-piece tip, but the phenomena should be extensible to any torch with a similar geometry. Acetylene single-piece tips may pose the most interesting variant for future attention because they often have no recessed surface to which the partial saturation of Regime 1 is attributed.

The simplest of the measurements, standoff distance, was proportional to the Regime 2 resistance. Under stable fuel and oxygen flow rates, the data collected suggests that accuracies better than 0.05 in. may be achievable.

Variations in flow have a minor impact on the measurement, while variations in mixture can be important. Measurements suggest that effects due to unexpected drifts in the F/O ratio can be compensated for by simultaneously observing the Regime 1 resistance.

References


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