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Research Article

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MODELING THE AXIAL TEMPERATURE DISTRIBUTION OF A TONGUE OF OXYACETYLENE FLAME

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Abstract

In this piece of work, two models (I and II) relating temperature distribution to the axial length in the flame are developed and compared. Experimental data from other researchers work on the internet were employed to validate the models through curve fitting using MATLAB toolbox 7.9. The result showed that model 15 is far better than model 11 as seen from their R^2 of 0.9998 and 0.93254 respectively. Model 15 is also less cumbersome in derivation and development than model 11. It has a single equation as compared to a pair of equations of models 11,so that, its declared peak length is adjudged better than that of model 11 i.e. 2.262cm and 2.00014cm respectively all at the same peak temperature of 3500^{0}C. Model 13 fairly agrees with the so called Kamalu's hypothesis in terms of peak length. The knowledge of the result of this work can be applied in the welding industry or wherever flame length is being determined.

Note: Kamalu (2009) hypothesis states that "the highest flame temperature occurs at 13/30 of the full flame length measured from the base of an unbiased flame cone". A full flame length in this experiment is 5.1cm so that $X_p = \frac{13}{30}(5.1) = 2.21$cm.

Key Words: Modeling, Oxyacetylene flame,Axial temperature,Pseudo second order.

INTRODUCTION

Modeling is increasingly becoming a powerful tool to study fire behaviour. Typically, fire propagation models can be classified as statistical & empirical models, semi-empirical models and physical models. Statistical and empirical models describe fire behaviour with statistical relationships without taking into consideration physical properties of phenomena. Semi-empirical models are based on a global balance of conservation of energy, not taking into account the mechanisms of energy transfer [1]. Physical models solve the set of conservation equations (mass, momentum, and energy), differentiating between the three types of energy transfer [2]. Whatever the type of model, experimental results are always necessary, both to adjust and to validate the model. A European project has been put forward to develop an improved physical two-dimensional model taking fuel heterogeneity into account. Experimental work was an important part of this project and has been carried out at different scales, from controlled field fire to laboratory experiments performed on burning trays of different dimensions. Results obtained by the authors in the frame of Efaistos have already been used for the purpose mentioned above [3, 4]. Experimental work at the laboratory scale is very important because control of the parameters of the experiment is much tighter than in the field work, and more accurate measurements can be made. Although combustion has been used by mankind for the already more than one million year, it is still the most important technology providing the energy supply for our modern day civilizations. Utilization of combustion leads to the release of unwanted pollutants such as carbon monoxide, unburned hydrocarbons and nitric oxides which affect our environment [5] Environmental awareness and the need for better and more efficient power generation systems have fuelled development of gas turbines for the past two decades. The improvement efforts were focused on reducing NO_x, CO and other pollutant levels in the exhaust improving efficiency and increasing the reliability of equipment [1]. Flame temperature is one of the most important properties in combustion, since it has a controlling effect on the rate of chemical reaction. The flame temperature is determined by the energy balance between the reactants and the products at equilibrium. If the reaction zone is spatially very thin in comparison to the rest of the domain of interest, then it is a common practice to denote the maximum temperature in the reaction zone to be the flame temperature. If the combustion process takes place adiabatically, with no work, or changes in the kinetic or potential energy, then the flame temperature is referred to as the adiabatic flame temperature. This is the maximum temperature that can be achieved for the given reactants because any heat transfer from the reaction zone and any incomplete combustion would tend to lower the temperature of the products [6, 7]. The shape of a tongue of flame is conically 3 dimensional. The temperature distribution of a cone (tongue) of flame is non-linear along the axis. It rises to a peak and falls to a minimum at the apex. It is this axial temperature distribution, and not the surface temperature profile of the flame, that the project intends to model.

The oxyacetylene flame is:

- Is long, bushy, and has a yellowish color. The pure acetylene flame is unsuitable for welding.
- Slowly open the oxygen valve. The flame changes to a bluish white and forms a bright inner cone surrounded by an outer flame. The inner cone develops the high temperature required for welding [8].

The temperature of the oxyacetylene flame is not uniform throughout its length and the combustion is also different in different parts of the flame.

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It is so high (up to 6000°F {3316°C}) that products of complete combustion (carbon dioxide and water) are decomposed into their elements. The temperature is highest just beyond the end of the inner cone and decreases gradually towards the end of the flame. Acetylene burning in the inner cone with oxygen supplied by the torch forms carbon monoxide and hydrogen [9]. As these gases cool from the high temperatures of the inner cone, they burn completely with the oxygen supplied by the surrounding air and form the lower temperature sheath flame. The carbon monoxide burns to form carbon dioxide and hydrogen burns to form water vapour. Since the inner cone contains only carbon monoxide and hydrogen, which are reducing in character (i.e. able to combine with and remove oxygen), oxidation of the metal will not occur within this zone.

The chemical reaction for a one-to-one ratio of acetylene and oxygen plus air is as follows:

$$C_2H_2 + O_2 \rightarrow 2CO + H_2 + Heat \quad (1)$$

This is the primary reaction: however, both carbon monoxide and hydrogen are combustible and will react with oxygen from the air:

$$2CO + H_2 + 1.5O_2 \rightarrow 2CO_2 + H_2O + Heat \quad (2)$$

This is the secondary reaction which produces carbon dioxide, heat and water.

There are three basic flame types: neutral (balanced), excess acetylene (carburizing), and excess oxygen (oxidizing). They are shown in the figures below.

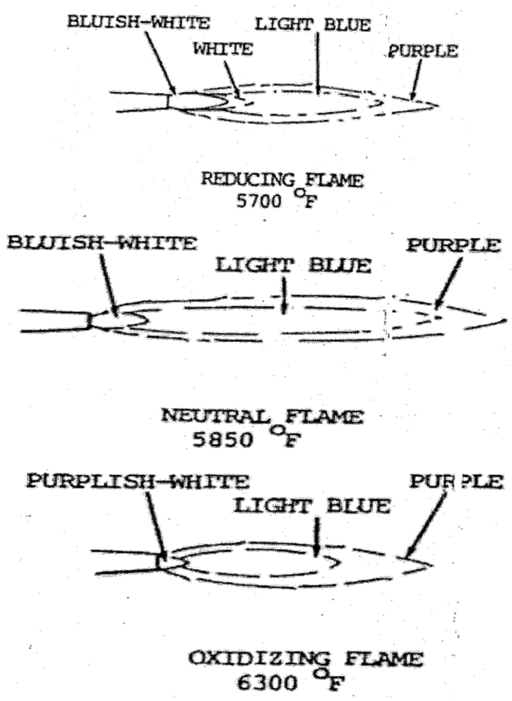

Figure 1 Basic types of flames

- The neutral flame has a one-to-one ratio of acetylene and oxygen. It obtains additional oxygen from the air and provides complete combustion. It is generally preferred for welding. The neutral flame has a clear, well-defined, or luminous cone indicating that the combustion is complete [7].
- The carbonizing flame has excess acetylene; the inner cone has a feathery edge extending beyond it. This white feather is called the acetylene feather. If the acetylene feather s twice as long as the inner cone it is known as 2X flame, which is a way of expressing the amount of excess acetylene. The carburizing flame may add carbon to the weld metal [10].
- The oxidizing flame, which has an excess of oxygen, has a shorter envelope and a small pointed white cone. The reduction in length of the inner core is a measure of excess oxygen. This flame tends to oxidize the weld metal and is used only for welding specific metals [11].

In a tongue of flame, which is usually 3 dimensional, the surface temperature of a particular ring is the same and different from the surface temperature of another ring as you move from the base to the tapering apex or as you move towards the centre. This means that the surface temperature changes as you move along the surface from the base to the apex. The axial temperature does the same but increases to the highest somewhere in between before tapering down to the apex. So in welding and its related works, if a weld material is not positioned at the peak temperature zone, it may not enjoy the full heat work of the welding. Therefore it is this axial temperature distribution of a tongue of a flame that this work intends to model. It is important to study the axial & surface temperature distribution of a tongue of flame to know it's high and low energy zones so that a welder will position his material of weld at the maximum energy zone for quick melting.

The objective of this work is to model the axial internal distribution of a tongue of flame so that the welder can have a pre-knowledge of such zone in his flame.

METHOD

The materials and equipment for determining flame temperature point to point within the flame length cannot be found in developing countries. So in this work, already experimented data on temperature against length from advanced countries of the world is obtained from the internet. The method is therefore to mathematically model the temperature distribution along the axial length of flame and, thereafter, use the internet empirical values to validate the model.

The parameters for the model are:

- Temperature
- Axial distance

Theory of the model

One of the most important parameters in any combustion system is its adiabatic flame temperature, which is temperature under the condition of no heat losses taking place from the combustion system. It plays an important role in the pollutants emitted from the system such as carbon oxides and nitrogen oxides. The temperatures also affect drastically the thermal stresses set up in the combustion system. Such stress may lead to deterioration of the chamber, if not well controlled.

Development of model

Formulation 1: From literature the empirical plots of flame temp versus the flame length are shown as in figures 2 and 3.

The profiles show two distinct regional variations between temperature and flame length. Therefore, in formulating a model two distinct regional variation of temp = f (flame length) will be established.

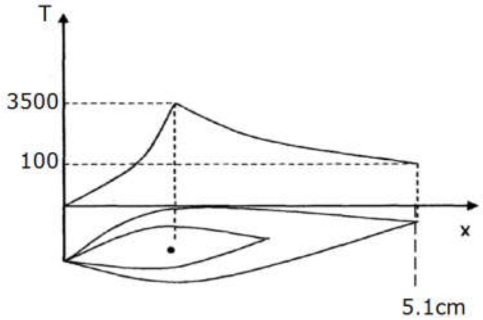

Fig 2 Mapping temperature profile with the flame

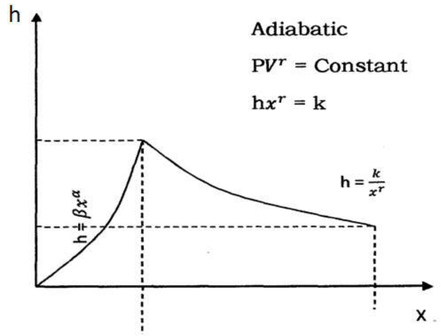

Fig 3 Mapping temperature profile alone

Collision theory

The rate equation under collision theory for two different flame particles A and B is given as:

$$r = f[A][B]\sigma^2{}_{AB}\left(8\pi R_g T\left(\frac{M_A M_B}{M_A M_B}\right)^{\frac{1}{2}}\right) \quad (3)$$

In terms of specific rate constant its

$$r = K\,[A]\,[B] \quad (4)$$

Using Arrhenius equation for K we may write this as

$$r = Ae^{-E/RT}[A]\,[B] \quad (5)$$

Combining (3) and (5) gives, for frequency factor, A as

$$Ae^{-\frac{E}{RT}} = F\sigma^2{}_{AB}\left(8\pi R_g T\frac{M_A+M_B}{M_A M_B}\right)^{\frac{1}{2}} \quad (6)$$

Equation (6) is energy equation of say potential, mgh (at stationary or elevated point). For identical flame particles collision, equating the RHS of equation (6) to potential energy, we have

$$F\sigma^2{}_{AA}\left(8\pi RT\frac{2M_A}{M^2{}_A}\right)^{1/2} = mgh$$

And making T subject of the formula yields

$$T = \left[\left(\frac{(M_A\,g)^2}{f\sigma^2{}_{AA}}\right)\frac{M_A}{16\pi R}\right]h^2$$

Or $T = K_1 h^2$ (7)

From figure 3, the profile of the first region, h $=\beta X^n$ is similar to eqn (7). Hence, we can generalize that the model of the first region is (like a free fall profile) as

$$T = A + Bx^n \quad (8)$$

Postulation1: The temperature of a tongue of flame is partly constant and partly jointly proportional to the flame length raised to power n up to its maximum temperature.

(b) Equating the LHS of equation (4) to potential energy as well

$$Ae^{-E/RT} = mgh$$

and making T subject of the formula, yields

$$T = \frac{E/R}{In\left(\frac{A}{mgh}\right)} \quad (9)$$

From figure 3, the adiabatic profile of the second region,$h = K/x^r$ is substituted into eqn (9) for h as

$$T = \frac{E/R}{In\left(\frac{A}{mgk}X^r\right)}$$

Or generalizing, we have T = $\frac{C}{ln(DX^r)}$ (10)

Postulation 2: After which the temperature decreases adiabatically from the maximum point to a constant tip temperature with increasing flame length of the remaining portion.

Model I

$$T = \begin{cases} A + BX^n & 0 \le x \le X_{opt},\ n > 0 \\ \frac{C}{ln\,(DX^r)} & X_{opt} \le x \le X_t,\ r > 0 \end{cases} \quad (11)$$

Analysis of formulation 1

For oxyacetylene flame,
But T_{opt}= 3500^{0}C, T_t =1000^{0}C, X_t =5.1cm, X_0 =0

1st region: $T = A + Bx^n$

At (0, T_o): $T_0 = A$ (i)

At (X_{op}, 3500): $3500 = A + Bx^n{}_{op}$ (ii)

(ii) – (i): 3500 - $T_0 = Bx^n{}_{op}$ (iii)

2nd region: $Tln\left(Dx^r{}_{op}\right) = C$

At(X_{op}, 3500): $3500ln\left(Dx^r{}_{op}\right) = C$
At(5.1, 1000): $1000\ln\left[\left(D(5.1)^r\right)\right] = C$
At intersection point; $T = A + Bx^n{}_{op} = \frac{C}{In\,(DX^r opt)}$
Or $Bx^n{}_{opt}ln\left(Dx^r{}_{opt}\right) + T_0\,ln\left(Dx^r{}_{opt}\right) - C = 0$
Dividing (v) by (iv) and simplifying gives
$3.5rlnX_{opt} - rln5.1 + 2.5lnD = 0$

Formulation 2

The temperature of an unbiased tongue of flame is partly constant and partly proportional to the product of its length raised to a power and the exponential decrease of the same length to a constant flame tip temperature. i.e.

(7)

1. $T = \text{constant} = d$ (i)

2. T is proportional to $x^n e^{-kx}$ (ii)

Or $T = Ax^n e^{-kx}$

Combining (i) and (ii) as joint variation gives

$$T = d + Ax^n e^{-kx} \quad (12)$$

Analysis of formulation 2

$$T_x = d + Ax^n e^{-kx} \quad (12)$$

At peak, $\frac{dT}{dx} = 0 = A[x^n(-ke^{-kx}) + nx^{n-1}e^{-kx}] + 0$

$Kx^n = nx^{n-1} = \frac{nx^n}{x}$

$Kx = n$

$X = \frac{n}{k} = X_p$(peak length)

$$n = Kx_p \quad (13)$$

Hence, for oxyacetylene flame

At $T = T_0,\ X = 0\ ; T_0 = 0 + d,\ \ T_0 = d$

At $T = 3500,\ x = X_p = \frac{n}{k}, n = kx_p$

$$3500 = AX_p{}^{kxp} e^{-kxp} + T_0 \quad (a)$$

At $T = 1000, x = 5.1, 1000 = A(5.1)^n e^{-5.1k} + T_0$ (b)

Making K subject of the formula from (b)

$$\frac{1000 - T_0}{A} = (5.1)^n e^{-5.1k}$$

Taking natural logarithm,

$$ln\left(\frac{1000 - T_0}{A}\right) = nln(5.1) - 5.1k = 1.62924n - 5.1k$$

But $n = kx_p$ so that

$$ln\left(\frac{1000 - T_0}{A}\right) = 1.62924kx_p - 5.1k = k(1.62924x_p - 5.1)$$

Or $ln\left(\frac{A}{1000 - T_0}\right) = k(5.1 - 1.62924x_p)$

$$k = \frac{1}{(5.1 - 1.62924X_p)} ln\left(\frac{A}{1000 - T_0}\right) \quad (14)$$

Substituting into eqn. (10) yields

Model II

$$T = AX\left[X_p\left(\frac{1}{5. - 1.62924X_p}\right) ln\left(\frac{A}{1000 - T_0}\right)\right] e\left[-X\left(\frac{1}{5. - 1.62924X_p}\right) \ln\left(\frac{A}{1000T_0}\right)\right] + T_0 \quad (15)$$

Data Collection

The flame length-temperature data were obtained from the internet on other researchers experimental works, as presented here below.

Table 1 Raw data (Rana et al, 2010) from flame combustion for eqn (8) and computed data for eqn. (10) (formulation 1)

$X(cm)$	**0.32**	**0.38**	**0.47**	**0.64**	**0.77**	**1.01**	**1.18**	**1.35**	**1.58**	**2.21**
T_x(°C)	86	172	345	689	1051	1723	2179	2584	3015	3500
Computed T_{x1}(°C)	-4268	-5481	-8270	-27181	80641	10927	7361	5953	460.3	3185

Table 2 Raw data (Rana et al, 2010) for flame combustion to be used in equation (12) (formulation 2)

$X(cm)$	**0.32**	**0.38**	**0.47**	**0.64**	**0.77**	**1.01**	**1.18**	**1.35**	**1.58**	**2.21**
T_x(°C)	86	172	345	689	1051	1723	2179	2584	3015	3500

Curve fitting

Formulation1: eqn. (6) was curve-fitted for the first part of figure 4 using the data in the first two rows of table 1. With the constants of eqn (8) determined using point of intersection (see section 3.1) the third row of table 1 is then computed and the plot of fig. 4 completed using eqn. (11) i.e. combination of eqns. (8) and (10).

Formulation 2: Eqn (10) was curve fitted using table 2 data to produce figure 5.

All the computations and plots were made using MATLAB package 7.9.

RESULTS AND DISCUSSION

Result presentation

The results of the computations and plots made in the previous section are presented in Figures 4and 5, and Tables 3 and 4.

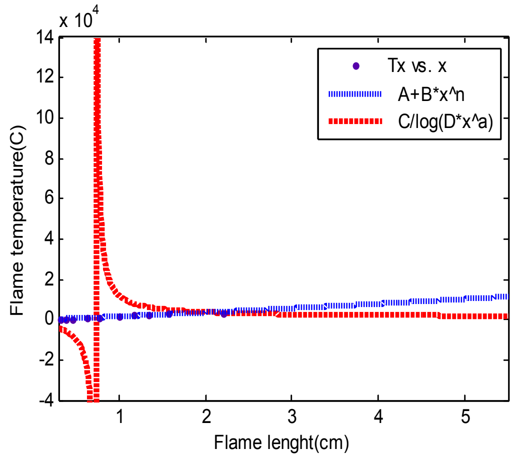

Figure 4 Flame temperature versus flame length of oxyacetylene flame (model I)

Computations of constants (coefficients) of eqn. (10)

Substituting the values from table 3 of eqn. (8) into eqn. (ii) we have;

$$3500 = 6.05 \times 10^{-6} + 1564X_p{}^{1.162}$$

$$X_p = 2.00014$$

If the second curve is adiabatic then $r = 1.4$, so that from eqn. (vii)

$$3.5(1.4)\ln(2) - 1.4ln(5.1) + 2.5lnD = 0$$

$$D = e^{0.4462} = 1.5626$$

Table 3 Coefficients and goodness of fit, for fig 4 (eqn 6)

95% Coefficient Bound	Goodness of Fit
A= 6.05 x 10^{-6} B = 1564 C= 1.162	SSE = 9.395 x 10^5 R^2 = 0.9325 R^2 Adj.= 0.9133 RMSE = 192.1

From eqn. (iv), $C = 3500\ln[1.5626(2)^{1.4}] = 4960$

$$T = \begin{cases} 6.05\times 10^{-6}+1564X^{1.162} & 0 \leq x \leq 2 \\ \dfrac{4960}{ln(1.562X^{1.4})} & \end{cases}$$

Hence,

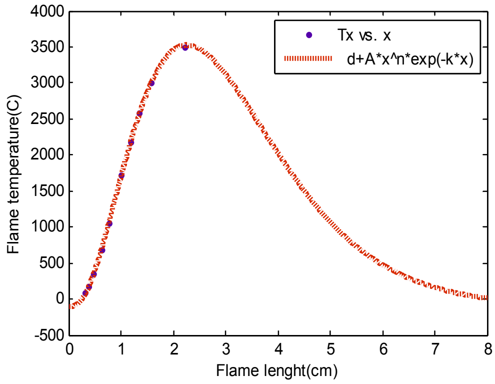

Figure 5 Flame temperature versus flame length of oxyacetylene flame (model II)

Table 4 Coefficients and goodness of fit, for fig 5 (eqn 15)

95% Coefficient Bound	Goodness of Fit
	SSE = 2298
A= 5950	R^2 = 0.9998
T_0 = -111.9	R^2 Adj.= 0.9998
X_p= 2,262	RMSE = 18.12

The result fairly agree with {12] hypothesis.

Kamalu's hypothesis: The highest flame temperature occurs at $\frac{13}{30}$of the full flame length measured from the base of an unbiased flame cone.

DISCUSSION OF RESULT

Model II gave the plot of figure 4: the blue dotted line is the plot of the upper part of the model [eqn. (8)] and the yellow dashed line is the plot of the lower part of the model [eqn. (10)]. The intersection of the blue and the yellow curves in the figure 4 gives peak length x_p = 2.00014cm at peak temperature, T_p = 3500°C. The coefficients and statistical goodness of fit for the upper part of eqn. (11) is declared in table 3. The coefficient of correlation, R^2 = 0.93254 which is a fairly good curve. However, the coefficients of the lower part of the model are computed in section 3.1.

Figure 5 which is the result of curve fitting equation (15) with the data on table 2 gives a smooth dumbbell curve and shows exactly where the temperature of the flame is maximum.

This occurs at 2.262cm at peak temperature of 3500°C. From table 4, the goodness of fit of the plot gave coefficient of correlation, R^2 of 0.9998. Therefore, the best model out of the two models (eqns. 11&15) is equation (15) as seen from the R^2. Equation (15) is also less tedious in development. The result compares favorably and excellently with what is in the literature.

Notice the negative value of $T_0 \cong -112°C$ in Table 4. The oxyacetylene gas mixture is pushed (blow away) from the gun nozzle by their high pressures from the cylinders, thereby creating a cryogenic condition at nozzle before igniting a few millimeters from nozzle. Hence, the temperature at the tip of the nozzle is negative as combustion takes place just outside the nozzle.

CONCLUSSION

In this piece of work, two models (I and II) relating temperature distribution to the axial length in the flame are developed and compared. Experimental data from other researchers work on the internet were employed to validate the models through curve fitting using MATLAB toolbox 7.9. The result showed that Equation 15 is far better than equation 11 as seen from their R^2 of 0.9998 and 0.93254 respectively. Equation 15 is also less cumbersome in derivation and development than equation 11. It has a single equation as compared to a pair of equations of models 11, so that, its declared peak length is adjudged better than that of equation 9 i.e. 2.262cm and 2.00014cm respectively all at the same peak temperature of 3500°C. Equation 15 fairly agrees with the so called Kamalu's hypothesis in terms of peak length. The knowledge of the result of this work can be applied in the welding industry or wherever flame length is being determined.

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