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CFD Simulation of a Candle Flame Propagation

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ABSTRACT

The study focused on the modelling of a candle flame using CFD modelling technique. Governing equation which formed the basis of a CFD modelling using SolidWorks flow simulation was developed, and the simulation result was compared with an existing experimental result. Modelling results show that the heat flux is maximum at the wick base and minimum at a distance of 0.1m from the wick tip, where it maintains averagely a constant value of 55.23kW/m^2. This implies that the heat flux generated by a typical candle is large enough to ignite secondary objects such as wood materials located even 100 mm above the wick of the candle as they are capable of auto-ignition at heat flux above 40kW/m^2. However, nearby objects that are not directly over the candle base can also be ignited, but must be located much closer for ignition to occur.

Introduction

When a candle is first lit the flame consumes the wick until it reaches a point just above the wax. This heat from the flame melts the wax by radiation through the air and by conduction through the wick. Only the tip of the wick burns. This liquefied wax climbs the wick to the flame by capillary action, where the molten wax is vaporized. The flame burns the vapour with oxygen supplied by the surrounding air. This reaction releases gases mainly gaseous carbon dioxide and water vapour and heat. The heat released melts more wax, which, again, crawls up the wick and so sustains the candle's flame. This implies that a candle, simultaneously carries out two actions: its flame burns vaporized wax and it delivers wax to that flame to sustain it.

The aim of this study is to proffer an analytical expression and carry out a CFD flow simulation on a candle flame with the following objectives:

- To determine the burning velocity of the candle flame,
- To determine the Candle flame thickness,
- To determine the flame time,
- To determine the flame height,
- To determine the flame temperature,
- To determine the Fuel flow rate,
- To determine the mass consumption rate,
- To determine the view factor,
- To determine the heat flux.

The study will shed light on the chemical and physical changes that go on in candle flames and help in determining the flame structure, propagation, velocity, view factor and heat flux of similar flame types such as methane diffusion gas, match stick flame, bush fire, edge flames which are characterized by a local extinction on their axis because of high strain rates in the vicinity of the stagnation point. It will also contribute to studies on jet flame characteristics and ignition hypotheses.

Research Elaborations

Candle wax is the fuel burned by a candle flame.

The wax is a mixture of long-chain hydrocarbons with the formula C_nH_{2n+2}. Typically the composition of the various hydrocarbons averages to $C_{25}H_{52}$. The wick has two functions. First, the wick conducts heat from the flame to the solid wax. This heat melts the wax. Second, the wick transports the molten wax to the flame: the liquefied wax crawls up the wick via capillary action. The liquid rises almost to the top of the wick, where it is engulfed by flame and vaporized. Only the tip of the wick glows and it turns black as it burns. The flame burns the vaporized wax with oxygen supplied by the surrounding air. This reaction releases gases mainly gaseous carbon dioxide and water vapours and heat. The carbon dioxide is formed from carbon in the candle wax and oxygen in the air, and the water forms from hydrogen in the wax and oxygen in the air. The flame has three regions where different chemical and physical phenomena occur. Combustion, the chemical reaction that produces carbon dioxide and water, occurs in the blue outer edge of the flame. Here the vaporized wax burns completely. Complete means converting all the carbon in the wax to carbon dioxide rather than carbon monoxide. This region, which is the hottest part of the flame, is not uniform: the blue is concentrated at the base of the flame, and decreases toward the top of the flame, where it is only a thin layer at the flame's edge. Combustion also occurs in the greyish-yellow section of the flame that surrounds the tip of the wick. Here the flame vaporizes the molten wax. The liquefied wax cools the flame and so this is the section of the flame with the lowest temperature. The wax here undergoes incomplete combustion. Incomplete combustion happens when there is not enough oxygen to combine with carbon: air, which supplies the oxygen, cannot travel easily into the flame.

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Because the combustion is incomplete some of the carbon from the wax remains in the flame. This darkens the flame creating the greyish cast near the wick. These heated, solid carbon particles, glow. As they rise in the flame they create a bright yellow region.

This brightest part of the flame has a temperature between that of the hot blue region and the cooler greyish-yellow region [1].

The glowing of the carbon particles is called incandescence. This phenomena occurs whenever a solid is heated enough to emit light. This incandescence is a physical change, unlike combustion in other parts of the flame, which is a chemical change. The chemical and physical changes in the flame create its distinctive shape. The flame's heat expands the surrounding air. This less dense air draws up cooler air from below the candle. These convection currents create the teardrop shape of a flame. They also sweep away the carbon dioxide and water formed. The importance of these convection currents to the candle's operation is dramatically illustrated when a candle burns in zero gravity or in a vacuum chamber [2]. In these environments the convection currents no longer occur and so the flame becomes spherical. The oxygen spends more time in the flame and so the combustion is more complete, i.e., more carbon is turned to carbon dioxide and fewer carbon particles exist in the flame. Because there are fewer carbon particles the flame's interior is blue. The flame burns out because, without convection currents, carbon dioxide remains in the flame and smothers it. The amount of the black smoke, depends on the ratio of incomplete to complete combustion. A breeze, for example, can increase the amount of incomplete combustion and cause a candle to emit black smoke. The balanced chemical equation for the complete combustion of a candle is represented by:

$$C_{25}H_{52\,(s)} + 38O_{2\,(g)} \rightarrow 25CO_{2\,(g)} + 26H_2O_{\,(g)}$$

The possibility of a candle flame to ignite an adjacent fuel is mostly undermined in cases where the fuel is not highly volatile. Very little attention is paid to this area as there is a strong demand in applying combustion modelling for building fires, burning materials and of course for engines and furnaces. Most combustion flows, particularly those in fires, are very complicated to study. An understanding of the chemical and physical changes that go on in candle flames which are a type of laminar diffusion flames can be of help in avoiding candle related fires, and also determine the flame structure, propagation, velocity, view factor, heat flux and also jet flame characteristics.

Methodology

Candle Flame Model Equations

Considering the flame characteristics of a candle such as burning velocity, thickness, flame time, height, temperature, fuel flow rate, mass consumption, view factor and heat flux the study in this chapter proffers analytical expressions that will predict approximate experimental values as it regards candle flames and other related laminar diffused flames.

Determination of the burning velocity of a candle flame (S_L).

The burning velocity is defined as the speed at which the flame front propagates towards the unburned mixture. The structure of the laminar diffused flame was described by Mallard and Le Chatelier's thermal flame [3] and a propagation speed for the flame surface, S_L, was deduced. Mallard and Le Chatelier express this flame speed as a function of thermal diffusivity, α, reaction rate, ω and temperature, T:

$$s_L = \sqrt{\alpha\omega\frac{T_b - T_i}{T_i - T_u}} \quad (1)$$

Where: T_b is the burned temperature,
T_i is the ignition temperature and,
T_u is the temperature of unburned reactants.

This relation was based on the following assumptions:

- The flame is propagated in one dimension i.e 1D,
- Combustion occurs as a steady state,
- Lewis number is unity,
- Mach number is low, i.e sub sonic flow.

Determination of the candle flame thickness (δ).

The methodology established by Goodwin [4] in carrying out a free-flame simulation in cantera was employed.

$$\delta = \frac{(\kappa/c_P)}{\rho_u s_L} \quad (2)$$

Where: κ is the thermal conductivity at the inner layer temperature T, C_p is specific heat at T, and ρ_u is density at the unburned reactants' temperature T.

Determination of flame time (t).

The Einstein diffusion equation was used to determine an expression for the flame time. The expression is based on the assumption that the average square displacement of the flame is equal to radius of flame thickness.

The average square displacement of the flame as given by Einstein is stated below:

$$y^2 = 2\mathcal{D}t \quad (3)$$

Where: □ is the diffusion coefficient.

Approximating y^2 by R^2 yields,

$$t = \frac{R^2}{2□} \quad (4)$$

The flame time can also be expressed in terms of the flame height and burning velocity. This is given as:

$$t = \frac{L_f}{S_L} \quad (5)$$

Determination of flame height (L_f).

The flame height is defined as the relative distance between the visible flame tip and the wax pool. The flame height can be determined by using the expression developed by Kanuas [5].

$$L_f = \frac{S_L R^2}{2D} \quad (6)$$

Determination of flame temperature (T).

The expression used by [6] was used to determine the flame temperature.

$$T_{flame} = \sigma T_{air}\frac{I_{air} - I_{back}}{I_{flame} - I_{back}} \quad (7)$$

Where: T is temperature, σ is Rayleigh scattering cross-section of the stoichiometric fuel-air mixture with respect to the cross-section of standard air [7] and I is intensity counts: I_{air} is intensity in cold-flow images, I_{flame} is intensity in flame images and I_{back} is background noise intensity.

Background intensity is equal to 86 counts and varies minimally [5].

Determination of the mass consumption rate ($\dot{m}$)

Mass consumption rate gives the rate at which the mass of the candle wax is lost during the process of combustion. It is expressed as:

$$\dot{m} = S_L \times A_u \times \rho_u \quad (8)$$

Determination of the fuel flow rate (Q_f)

The continuity equation for flows is used to determine the fuel flow rate.

$$Q = Area \times velocity \quad (9)$$

$$Q = \pi R^2 \times S_L$$

Determination of View Factor ($F_{i \to j}$)

In radiative heat transfer, the view factor $F_{i \to j}$ is a geometrical parameter. This parameter determines the proportion of all the radiation which leaves surface i and strikes surface *j*. The view factor between the point *M* (sensor) and the flame front is given as [9].

$$F_{f \to M} = \frac{1}{\pi} \int_S \frac{\cos\theta_{fl} \cos\theta_M}{R^2} dS \quad (10)$$

with *S* the flame surface and *dS* its element. *R* is the distance between the point M and the element d*S*. Θ_{fl} and *M* are respectively the angle between *R* and the normal of fire front and the angle between *R* and the normal of the target.

Determination of Heat Flux (ϕ_I^{th}).

This helps to evaluate the thermal radiation reached by a sensor located at a distance *r* from the fire front, the solid flame model is proposed which considers the visible flame to be a geometrical body that emits radiative energy uniformly throughout its surface like a blackbody [10-12]. Consequently, it is assumed a second approximation: the non-visible zones of the flame are not taken into account. Indeed, Baukal and Gebhart [13] reported that nonvisible radiation was found to be negligible compared with the total heat flux.

$$\Phi_I^{th}(\mathbf{M}) = \tau \varepsilon B T_f^4 F_{f \to M} \quad (11)$$

Where τ is the atmospheric transmissivity, ε is the equivalent flame emissivity, *B* is the Stephan-Boltzmann constant, T_f is the flame average temperature and $F_{i \to M}$ the view factor which is given by Eq. (10).

Computational Flow Dynamics (CFD) Modelling.

A CFD modelling was carried out on the study with the aid of SolidWorks Flow simulation tool, using the model equations as the governing equations. The CFD was run with the independent variables of the model equations established in this study set as input parameters, while the dependent variables was set as output parameters, for each output condition. In carrying out the CFD modelling, the methodology established by Hamins et al. [14] was adopted.

The CFD model assumes that combustion is mixing controlled, and that the reaction of fuel and oxygen is infinitely fast. The mass fractions of all of the major reactants and products were derived from the mixture fraction by means of state relations, empirical expressions arrived at by a combination of simplified analysis, and measurement. Radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering grey gas contained in the flow simulation equation tool. This equation is solved using a technique similar to finite volume methods for convective transport, thus it is known as the finite volume method (FVM). Approximately 150 discrete angles are used to determine the distribution of radiative energy at each point. Thus, SolidWorks flow simulation approximates the governing equations on a rectilinear grid. All solid candle surfaces were assigned thermal boundary conditions in addition to information about the burning behaviour of the material. For application to candle flames, SolidWorks flow simulation needs experimental data to guide model development, and to ascertain the accuracy of the model predictions. The simulation results were evaluated based on accurate visual depiction of the flame shape and height, and comparison of the calculated and measured flux directly above the flame tip. Model input parameters were adjusted to meet these two criteria better and once they were sufficiently met, the additional output parameters were evaluated and compared with the experimental values. For the initial modelling simulations, a 48 x 48 x 80mm^3 (length x width x height) domain was created around the virtual candle. The grid size was 1 x 1 x 2mm^3 around the candle and expanded to 2 x 2 x 2mm^3 near the edges of the domain using the software's CFD linear grid transformation algorithm. This resulted in a total of 53,462 cells. For some cases, the height of the domain was extended, leading to a significantly larger number of cells and more lengthy computational run times. The wax portion of the candle was modelled as a solid inert material. The geometry of the candle including the circular shape and the curved wax pool were represented in as detailed a manner as the grid allowed. This was done to provide a realistic boundary condition for the flow of air into the flame. Preliminary models using a simple square shape produced noticeable effects on the airflow to the flame and on the heat flux to the surfaces above the flame. The boundary conditions for the flame model accounted for the presence of the heat flux gauge itself, which impacted the flow field. The curvature of the wick was approximated and modelled as a 1-mm diameter cylinder that was 12 mm tall, with curvature causing it to extend 5 mm from the centre line in the radial direction. The lower 4 mm of the wick was taken as non-burning, which was consistent with observations that showed that the base of the flame was about 4 mm above the molten wax pool.

The boundary conditions as generated by the CFD Flow simulation is given in table 1.

Table 1. Boundary Conditions.

Outer Wall 1	
Type	Outer Wall
Faces	Face<1>@Revolve2
Coordinate system	Global coordinate system
Reference axis	Y
Heat transfer coefficient	0.500 W/m^2/K
External fluid temperature	293.20 K
Outlet Volume Flow 1	
Type	Outlet Volume Flow
Faces	Face<4>@Revolve2
Coordinate system	Face Coordinate System
Reference axis	Y
Flow parameters	Flow vectors direction: Normal to face Volume flow rate: 3.2700e-006 m^3/s
Environment Pressure 1	
Type	Environment Pressure
Faces	Face<2>@Revolve2
Coordinate system	Global coordinate system
Reference axis	X
Thermodynamic parameters	Environment pressure: 101325.00 Pa Temperature: 350.20 K
Concentrations	Substance fraction by mass Steam1.330 Carbon dioxide 3.125

Results

Results of the simulated candle geometry and flame represented by the iso-surface of stoichiometric mixture fraction, which provides an adequate representation of the flame shape was compared with a photo-image of a burning candle.

The CFD modelled candle flame height is 40 mm as compared to the measured value of 42 mm.

Table 2 shows the results of the CFD modelling for the output parameters of a candle flame and the experimental results carried out by Gaydon and Holfhard, [15].

Table 2. Results of a CFD model and experimental result of a candle flame.

Output Parameter	CDF Model Result	Experimental Result
Burning Velocity (S_L)	6.01 cm/sec	6.82 cm/sec
Flame Thickness (δ)	0.450 mm	0.520 mm
Flame Time (t)	0.666 sec.	0.616 sec.
Flame Temperature (T)	57 ^oC	64 ^oC
Flame Height (L_f)	40 mm	42 mm
Heat Flux (ϕ)	162.24 kW/m^2	168 kW/m^2
Fuel flow rate (Q)	3.27 cm^3/sec	4.01 $cm^3/sec.$
Mass consumption rate ($\dot{m}$)	0.089 g/min	0.105 g/min

With a correlation value of 0.9996, the table reveals that error in CFD model predictions is within the experimental uncertainty band across the range of conditions measured and the experimental result carried out by Gaydon and Holfhard, [15] agree reasonably well with the CFD model simulation results.

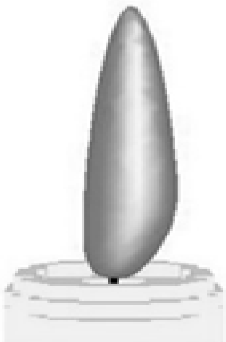

Fig 1. Simulation of the burning candle as represented by the calculated iso-surface of stoichiometric mixture fraction.

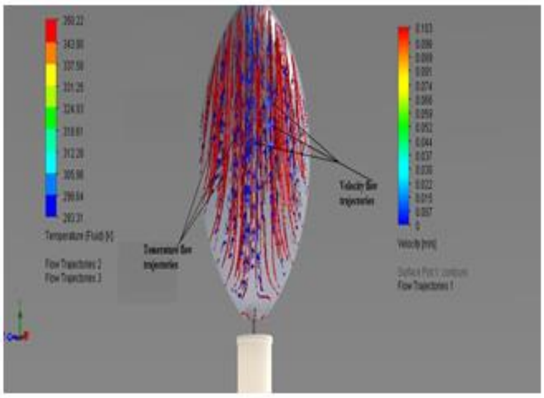

Fig 2. CFD Flow Simulation of the burning candle showing the temperature and burning velocity fields.

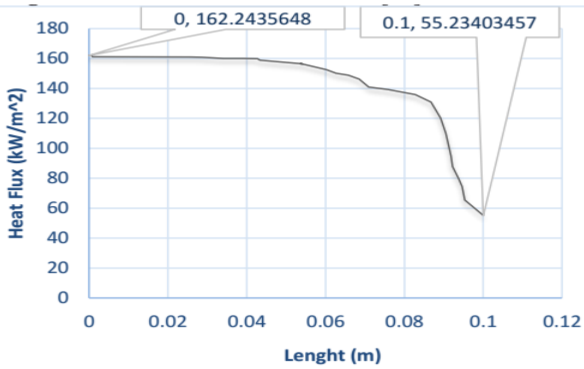

Figure 3. Heat flux of candle flame against distance in y direction.

Figure 3 reveals that the heat flux of the flame reduces with increase in distance along the y axis.

The heat flux is maximum at the wick base and minimum at a distance of 0.1m from the wick tip, where it maintains averagely a constant value of 55.23kW/m^2. This means that the flame is capable of igniting substances at 0.1 m from the wick tip with time, most especially wood materials as they are capable of auto-ignition at heat flux above 40kW/m^2 [16].

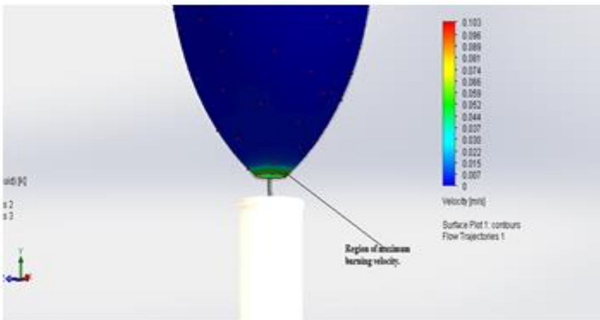

Fig 4. CFD Flow Simulation of the burning candle showing the region of maximum burning velocity.

Conclusion

The study focused on the modelling of a candle flame using CFD modelling technique. The results of the model validation provides insight into the extent at which candle flame can be propagated and also the possibility of its ignition tendency. Through this study, an attempt has been made to bridge the existing knowledge gap in determining if a candle flame can ignite adjacent fuels; it has developed a modelling tool that can be used by fire investigators.

Governing equation which formed the basis of a CFD modelling using SolidWorks flow simulation was developed, and the simulation result was compared to an experimental result carried out by Gaydon and Holfhard, [14].

The study reveals that given enough time, the heat flux generated by a typical candle is large enough to ignite secondary objects located even 100 mm above the wick of the candle. Moreover, nearby objects that are not directly over the candle base can also be ignited, but must be located much closer for ignition to occur. The development and validation of a computer simulation of a candle flame can serve as a good tool to test ignition hypotheses.

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