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EXPERIMENTAL INVESTIGATION OF THE EXTINCTION DEPTH FOR A CANDLE DIFFUSION FLAME UNDER CONFINEMENT

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Abstract. *This work aims to analyze the instability of a diffusion flame produced by a paraffin candle, which is confined within a glass tube, observing the flame behavior and its extinction as a function of the confinement depth in the tube and the wick length. An experimental apparatus was used to carry out this analysis, in order to obtain the flame dimensions, from photographs, as well as to observe the temperature distribution and the combustion gases release, from thermal images. The confinement depth and the flame dimensions were obtained using an image processing program, considering two candles with different wick lengths. The temperature distribution was observed from the thermal images showing the highest temperatures in the flame region. The candle with smaller wick did not extinguish the flame, even at the maximum confinement length. The candle with larger wick extinguished the flame for a 48 mm confinement depth. The wick length increase results in higher fuel vaporization rates and higher flame volume. This produces a greater amount of combustion gases, that difficult the oxidant arrival in the flame and together with the confinement influences the magnitudes of the diffusion and convective terms of the governing equations in the combustion process.*

Keywords: *combustion, flame, thermal analysis.*

1. INTRODUCTION

The energy sources diversity used in any industrial process is of great importance, especially when one wants to increase profit and reduce costs, as well as activities agility, population welfare, etc. Due to the release of pollutant and toxic gases, the energy production from combustion processes has several negative aspects, but its use is still of great interest, mainly due to its application ease in the present day, besides allowing the obtaining of high temperatures in these processes. Therefore, the combustion processes control is very important so that a good burning efficiency is obtained, reducing the impacts caused by this process kind. Thus, several studies have been carried out to better understand the flames behavior and its applications.

The combustion process may or may not result in the flames formation. In turn, flames can be classified into two types: premixed and non-premixed (called diffusion flames). In premixed flames, the oxidant mixes with the fuel before combustion occurs. On the other hand, in diffusion flames, the oxidant mixes with the fuel only at the combustion exact moment, as a consequence of the molecular diffusion and convective movements of the chemical species near the flame region (Turns, 2000).

Due its applications and importance, theoretical and experimental studies have been carried out to better understand the diffusion flames behavior (Kirkby and Schmitz, 1966; Mitchell *et al.*, 1980; Gonçalves *et al.*, 2006; Lima *et al.*, 2006; Cristaldo, 2008; Oldenhof *et al.*, 2011; Sunderland *et al.*, 2011; Thomsen *et al.*, 2017).

Kirkby and Schmitz (1966) have observed that steady-state diffusion flame can be unstable in a non-adiabatic system or when the Lewis number exceeds unity. His work consists of an analytical study to obtain solutions of one-dimensional diffusion flames in the permanent regime, to investigate the stabilities with respect to small oscillations, as well as to obtain complete solutions for transient cases. They found that extinguishment in unstable flames occurs because of variations in the increase in temperature and concentration range for a short time and eventually decays into an extinction state. Mitchell *et al.* (1980) also analyzed the confinement effect on a laminar diffusion methane/air flame, seeking a solution to determine the temperature, velocity, and species concentration profiles.

Cristaldo (2008) carried out a numerical study on diffusion flames in which he presented results for fuel/air mixture fraction, the mass fraction of fuel/oxygen reactants, the mass fraction of carbon dioxide/water vapor and temperature products. Their results were validated against analytical and experimental data in the literature. The objective of his work was to obtain a simpler solution with low computational cost using the finite difference method for the governing equations solution of the combustion process.

Pereira *et al.* (2010) and Vaz (2010) investigated analytical solutions for the diffusion flames behavior. The first one aimed at obtaining solutions for the axial velocity and average mixing fraction of a turbulent diffusion flame jet in cylindrical coordinates. The second presented a study of a turbulent diffusion methane flame, comparing its analytical and numerical results of the temperature, the mixing fraction and the mass fraction of the species with experimental data found in the literature.

Ghosh *et al.* (2010) studied the diffusion flame dynamic behavior of a candle placed inside a cylindrical glass tube. Sunderland *et al.* (2011) performed a theoretical-experimental analysis of stable laminar flames of candles, through an experiment considering candles with wicks of various length and width. They observed that the flame fixation point on the wick depends directly on the characteristics or dimensions of the flame. From this experiment, they obtained empirical correlations to determine the width and height of the flame, as a function of the width and length of the wick, with a satisfactory precision. Subsequently, Carpes (2012) sought to develop a methodology applied to the stabilization of turbulent diffusion flames.

Through measurements using laser combined with a Modulated Absorption/Emission (MAE) technique, performed in stable laminar candle flames, Thomsen *et al.* (2017) observed that the volumetric fractions of soot produced vary directly with the dimensions of the candle wick. This dependence occurs as a consequence of the amount of fuel released by the wick, which alters the firing rate achieved by the candle.

The present study aims to analyze the diffusion flame instability of a paraffin candle, which is confined within a borosilicate glass tube. From the results of this analysis, it is desired to obtain information on the behavior related to the flame extinction, as a function of the confinement depth of this flame inside the tube. This study is carried out using an experimental apparatus assembled for this work, in which it is possible to observe the flame behavior of a candle and its extinction as a function of the confinement depth in the tube, as well as to determine the flame dimensions from photographs taken during the experiment. In addition, it was observed the temperature distribution and the combustion gases release from thermographic images.

2. MATERIALS AND METHODS

The methodology presented in this paper is divided into two parts: one regarding the formulation of the diffusion flame model adopted in this work and another regarding the experimental apparatus and measurements made in the diffusion flame analyzed.

2.1 Model formulation

The model considered in this work is similar to that presented by Kirkby and Schmitz (1966) and consists of a paraffin candle immersed inside a glass tube of diameter D, whose wick base of length L_w, can move relative to the tube top of a depth L, as shown in Fig. 1. The fuel evaporates on the wick surface since from its base to its top and moves by convection to the flame region. In turn, the oxidant descends from the tube top by diffusion to the flame region, which is in the form of an ellipsoid of length L_f and maximum diameter D_f, where burning finally occurs.

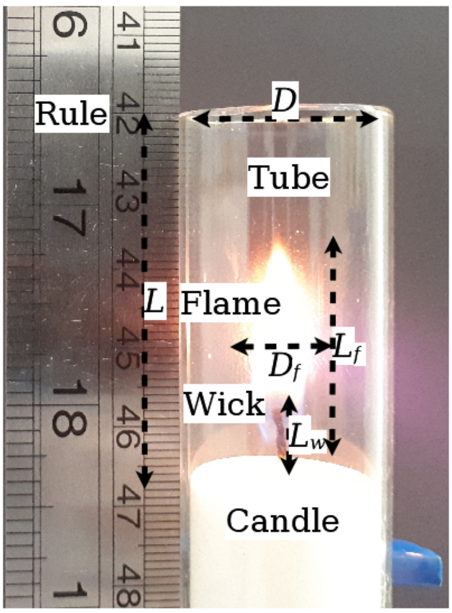

Figure 1. Configuration of the experimental model analyzed in the present work.

The following conditions are assumed for the present mathematical model: laminar flow, steady-state and unidimensional; adiabatic tube walls. The dimensionless forms of conservation equations of chemical species, fuel (F) and oxidant (O), as well as of energy, are defined by Eqs. (1), (2) and (3), respectively:

$$-\frac{\mathrm{d}^2 Y_F}{\mathrm{d}Z^2} + M\frac{\mathrm{d}Y_F}{\mathrm{d}Z} = -R \tag{1}$$

$$-\mathrm{Le}_O\frac{\mathrm{d}^2 Y_O}{\mathrm{d}Z^2} + M\frac{\mathrm{d}Y_F}{\mathrm{d}Z} = -R \tag{2}$$

$$-\mathrm{Le}_F\frac{\mathrm{d}^2 \theta}{\mathrm{d}Z^2} + M\frac{\mathrm{d}\theta}{\mathrm{d}Z} = R \tag{3}$$

Where Z is the dimensionless axial position, Y_F and Y_O are the dimensionless mass fractions of fuel and oxidant, respectively, θ is the dimensionless temperature, M is the dimensionless rate of fuel feed and R is the dimensionless rate of fuel consumption. Le_F and Le_O are the Lewis numbers of the fuel and oxidant, respectively.

For the diffusion flame problem analyzed in this work, the Eqs. (1), (2) and (3) present a set of boundary conditions defined according to Tab. 1.

Table 1. Boundary conditions of the conservation equations.

Conservation equation	Z	
	0	1
Fuel, Eq. (1)	$Y_F'(Z=0) = M(Y_{F,0} - 1)$	$Y_F(Z=1) = Y_{F,1}$
Oxidant, Eq. (2)	$Y_0'(Z=0) = \frac{M}{\mathrm{Le}_O} Y_{O,0}$	$Y_O(Z=1) = Y_{O,1}$
Energy, Eq. (3)	$\theta'(Z=0) = \frac{M}{\mathrm{Le}_F}(\theta_0 - \theta_1)$	$\theta(Z=1) = \theta_1$

Being that the subscripts 0 and 1 are used to represent the value of the variables at $Z = 0$ and $Z = 1$, respectively.

According to Williams (1985) and Turns (2000), in many cases, the fuel and oxidant Lewis numbers can be considered equal to the unit, i.e., $\mathrm{Le}_F = \mathrm{Le}_O = 1$. Thus, the problem reduces only to the solution of Eq. (3), instead of the equations system solution, Eqs. (1) to (3), whereas the dimensionless fuel and oxidant mass fractions, Y_F and Y_O, can be expressed as a function of the dimensionless temperature, θ, using the Shvab-Zeldovich relation. As a consequence of this simplification, the problem solution is dependent only on the dimensionless rate of fuel feed, M, and the dimensionless rate of fuel consumption, R, which in turn depend on the characteristic scale, L, which corresponds to the confinement depth in the pipe, according to the definitions presented in Eqs. (4) and (5):

$$M = \frac{mL}{\rho\Lambda_F} \tag{4}$$

$$R = \mathrm{Da}Y_F Y_O e^{-\epsilon/\theta} \tag{5}$$

Where m is the rate of fuel feed, ρ the fuel density, Λ_F is the fuel mass diffusion coefficient, ϵ is the dimensionless activation energy and Da represents the Damköhler number, which is also dependent on the characteristic scale, L (confinement depth).

2.2 Experimental apparatus and measurements

In order to perform the experimental analysis, it was necessary to leave the upper surface of the paraffin candle (wick region) parallel to the horizontal plane, so that during the burning process it was possible to visualize the flame dimensions without changing the other experimental parameters. An experimental apparatus photograph is shown in Fig. 2. This experimental apparatus consists of an iron base with a $45\,\mathrm{cm}$ length aluminum rod, to fix a claw supporting the glass tube, with $26\,\mathrm{mm}$ internal diameter and $90\,\mathrm{mm}$ length, as well as other claws used to support the $30\,\mathrm{cm}$ long ruler used to measure of flame dimensions and confinement depth. The candle is inserted into the glass tube with a negligible cylindrical gap, sufficient only for the candle gliding inside the tube. The candle base is supported by a Jack lifting platform, used to vary the confinement depth of the candle flame in a smooth way.

To verify the influence of the fuel amount in the experiment, two analyzes were performed considering candles presenting different wick lengths, but as the same diameter. The wick initial length was determined from a ruler and checked with a Vernier caliper. To facilitate the visualization in the experiment, as well as obtaining the photographs, a black background was placed behind the experimental apparatus. A camera was used to take the photographs, which in turn were used to determine the flame dimensions, using the image processing program called ImageJ version 2, as well as visualization of the flame extinction process. In addition, photographs were taken using a FLIR thermographic camera, model T-440, to allow visualization of the temperature distribution in the flame and the combustion gases release.

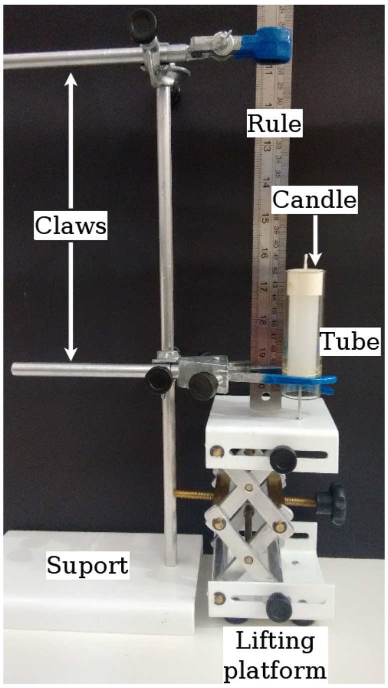

Figure 2. Experimental apparatus photograph.

The experimental procedure consists of lighting the candle, with the wick base positioned above the tube top (without confinement). Thereafter, the candle held by the Jack lifting platform is moved into the tube, with a photograph taken every $5\,\mathrm{mm}$ along the tube length from the initial position at the tube top (without containment). Still, in this initial position, thermal photographs are taken, which are used to visualize the flame temperature distribution, as well as to observe the behavior of the combustion gases released in the flame and their influence in the extinction process due to the confinement in the glass tube.

3. RESULTS AND DISCUSSION

The results presented in this section are divided into two cases for analysis, referring to candles with $4.9\,\mathrm{mm}$ and $9.4\,\mathrm{mm}$ wick length, respectively. The experiments were performed in an enclosure room with a temperature of approximately $20°\mathrm{C}$ and relative air humidity of 73%.

3.1 Case 1: candle with wick length $L_w = 4.9\,\mathrm{mm}$

Table 2 shows the measurements results performed in the experimental apparatus using the candle with wick length $L_w = 4.9\,\mathrm{mm}$. At every $5\,\mathrm{mm}$ confinement depth, L, a photograph was taken to determine the length, L_f, and the maximum diameter, D_f, of the candle flame, through the ImageJ program. These flame dimensions were obtained by relating the scales to defined pixels in the photograph taken with the scale in millimeters of the ruler. To allow an interpretation in terms of the flame volume confined within the tube, the flame volume $\mho_f$ was calculated by considering its shape as being equal to that of an ellipsoid.

In this experiment for the candle with $L_w = 4.9\,\mathrm{mm}$, it was observed that with the confinement depth increase, L, the flame suffered small oscillations (instabilities), related to gas diffusion and convection phenomena. However, these oscillations were not significant for the flame extinction. The gases released by combustion ascend vertically by convection. As the flame enters the tube, this ascending vertical flow of combustion gases tends to hinder the oxidant arrival by convection and, in addition, the oxidant diffusion to the flame region will be slowing with increasing confinement depth. This is due to the fact that the dimensionless rate of fuel feed, M, depends on the confinement depth, L, and influences the magnitude of the convective terms in relation to the diffusion terms defined in Eqs. (1) to (3). In addition, the confinement depth, L, also influences the dimensionless rate of fuel consumption, R.

Figure 3 illustrates three distinct positions of confinement depth, L, with respect to the tube for the candle with $L_w = 4.9\,\mathrm{mm}$, the data of which are shown in Tab. 2: a) $L = 0\,\mathrm{mm}$ (not confined); b) $L = 35\,\mathrm{mm}$; c) $L = 70\,\mathrm{mm}$. It is observed in the photographs that the flame volume is relatively small, reducing the amount of the combustion gases released, allowing the oxidant arrival to the flame with little difficulty. Despite the instabilities, the flame was not extinguished, even at the maximum allowable confinement depth.

Table 2. Measurements of the length, diameter, and volume of a diffusion flame, produced by a candle with wick length $L_w = 4.9\,\text{mm}$ (Case 1), as a function of the confinement depth.

L / [mm]	L_f / [mm]	D_f / [mm]	$\mho_f$ / [mm^3]
0.0	13.0	5.5	205.9
5.0	13.7	5.4	209.2
10.0	13.2	5.3	194.1
20.0	12.9	6.3	268.1
25.0	13.3	6.3	276.4
30.0	13.9	6.3	288.9
35.0	13.1	5.5	207.5
40.0	12.2	7.9	398.7
45.0	13.8	6.2	277.8
50.0	11.2	6.4	240.2
55.0	10.7	6.1	208.5
60.0	10.1	8.1	347.0
65.0	11.7	5.9	213.2
70.0	13.4	8.0	449.0
Average	13.1	6.3	254.1
Standard deviation	1.2	1.0	78.6

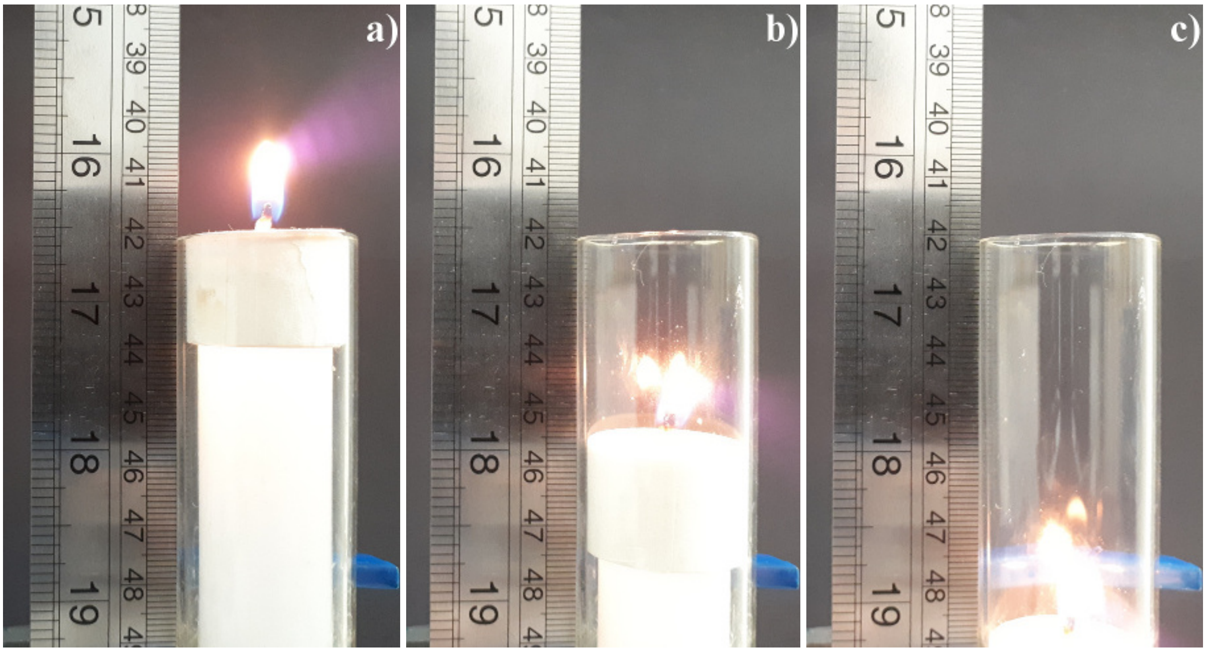

Figure 3. Photographs of the candle with wick length $L_w = 4.9\,\text{mm}$ (Case 1) taken at three different confinement depths: a) $L = 0\,\text{mm}$; b) $L = 35\,\text{mm}$; c) $L = 70\,\text{mm}$.

3.2 Case 2: candle with wick length $L_w = 9.4\,\text{mm}$

Table 3 shows the measurements results performed in the experimental apparatus using the candle with wick length $L_w = 9.4\,\text{mm}$. As in case 1, at every $5\,\text{mm}$ of confinement depth, L, a photograph was taken to determine the length, L_f, and the maximum diameter, D_f, of the flame, as well as to calculate the flame volume $\mho_f$. In this experiment for the candle with $L_w = 9.4\,\text{mm}$, it was also observed that with the increase of the confinement depth, L, the flame suffered small oscillations (instabilities), related to the gas diffusion and convection phenomena. However, these oscillations were significant so that flame extinction occurred at a confinement depth $L = 48\,\text{mm}$.

Figure 4 illustrates three distinct positions of confinement depth, L, with respect to the tube for the candle with $L_w = 9.4\,\text{mm}$, the data of which are shown in Tab. 3: a) $L = 0\,\text{mm}$ (not confined); b) $L = 25\,\text{mm}$; c) $L = 48\,\text{mm}$ (extinction). It is observed in the photographs that the flame volume is more significant than in case 1, releasing a more substantial quantity of combustion gases, which in turn make it difficult for the oxidant to reach the flame. As a consequence, the flame was extinguished when it reached a confinement depth $L = 48\,\text{mm}$, as observed in Fig. 4c.

Table 3. Measurements of the length, diameter, and volume of a diffusion flame, produced by a candle with wick length $L_w = 9.4\,\mathrm{mm}$ (Case 2), as a function of the confinement depth.

L / [mm]	L_f / [mm]	D_f / [mm]	$\mho_f$ / [mm^3]
0.0	22.8	6.5	504.4
5.0	23.4	6.3	486.3
10.0	24.8	6.5	548.6
15.0	26.1	8.8	1058.3
20.0	25.5	7.5	751.0
25.0	22.5	8.8	912.3
30.0	26.7	7.9	872.5
35.0	28.3	8.5	1070.6
40.0	25.3	8.9	1049.3
45.0	26.7	7.7	828.9
48.0	Extinction	Extinction	Extinction
Average	25.4	7.8	850.7
Standard deviation	1.9	1.0	228.9

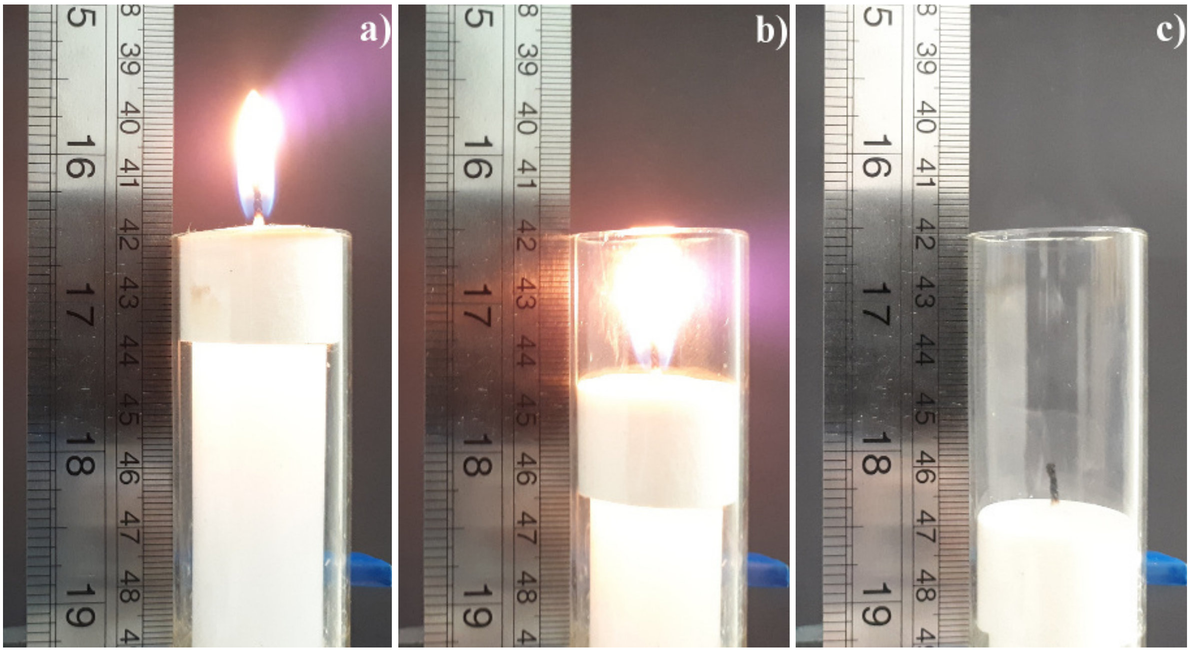

Figure 4. Photographs of the candle with wick length $L_w = 9.4\,\mathrm{mm}$ (Case 2) taken at three different confinement depths: a) $L = 0\,\mathrm{mm}$; b) $L = 25\,\mathrm{mm}$; c) $L = 48\,\mathrm{mm}$.

In order to observe the temperature distribution, as well as to show the occurrence of a flow of the gases released by the combustion of the candle flame, two photographs are shown in Fig. 5, for the candle with $L_w = 9.4\,\mathrm{mm}$: a) normal image and b) thermal image.

In Figure 5b, it is possible to visualize the gases resulting from the candle flame combustion, which by convection tend to ascend. Due to higher temperatures than surrounding ambient air, the combustion gases can be seen in the thermographic image shown in Fig. 5b. As discussed previously, the combustion gases rise through the tube when the candle is confined hinders the oxidant diffusion into the flame. Similar results can be observed for the candle with $L_w = 4.9\,\mathrm{mm}$ analyzed in case 1.

4. CONCLUSIONS

In the present work, an experimental analysis was carried out regarding the diffusion flames instability. For this analysis, normal and thermal photographs were taken for two candles with different wick lengths, but as same diameter. In this analysis, the influence of the candle wick length in the flame extinction process was observed, due to the increase of the flame confinement depth inside a glass tube. The confinement depth and the flame dimensions were obtained using an image processing program.

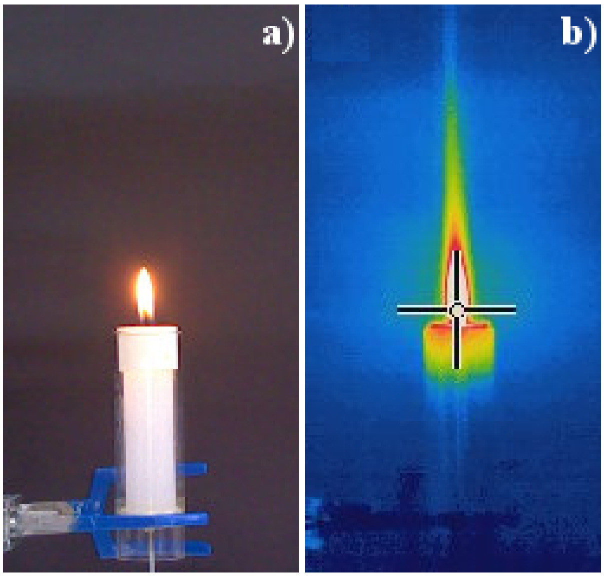

Figure 5. Photographs of the candle with wick length $L_w = 9.4\,\mathrm{mm}$ (Case 2), by using the FLIR T-440 thermographic camera: a) normal image; b) thermal image.

The results obtained in this analysis demonstrate that the increase in wick length increases the vaporized fuel rate, increasing the flame volume, which in turn produces a larger amount of combustion gases. These combustion gases difficult the oxidant arrival in the confined flame and together with the increase of the confinement depth, influence the magnitudes of the diffusion and convective terms of the governing equations of the combustion process, due to variations in the rates of fuel feed and consumption.

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