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A NEW METHOD TO PREDICT JET FLAMES PROPERTIES THROUGH GEOMETRICAL MODELS

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Adrian de Jesus Jano Fong

156074

Joseph Nahim Ramirez Castelan

159215

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Advisor: Adriana Palacios Rosas, Ph.D.

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Signature sheet

Scientific Article that to complete the requirements of the Honors Program present the students **Adrian de Jesus Jano Fong, ID: 156074 and Joseph Nahim Ramirez Castelan, ID: 159215.**

Advisor

_____

Adriana Palacios Rosas, Ph.D.

President

_____

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A NEW METHOD TO PREDICT JET FLAMES PROPERTIES THROUGH GEOMETRICAL MODELS

A. Palacios[1*], A. Jano[1], J. Ramirez[1]

[1] *Universidad de las Americas Puebla, Departamento de Ingenieria Quimica, Alimentos y Ambiental. Santa Catarina Martir, San Andres Cholula, Puebla. C.P. 72810. Mexico.*

Abstract

The study of jet fire types and nature represents a step forward in the chemical industry safety This article proposes a new method with MATLAB® to automatically read jet fire images and obtain the flame properties. Determining values of volume, height, lift off, and width of the flames. Also, the method implements theoretical models for estimating flame volume as geometric ellipsoid, geometric kite, regression model, image processing and a new proposed model by Jano & Ramirez.

Furthermore, the results obtained are compared with the data reported by Garcia and Palacios, who analyzed the same flame images by regression model. It was concluded that the proposed method is more precise, efficient, and faster compared to the method used by Garcia and Palacios. The method for jet fires images, achieves an average speed processing of 6.2 images per second, under different conditions of pressure or methane volumetric flow.

Keywords: Jet fire; flame shape; flame height, automate method; MATLAB®.

Resumen

El estudio de los tipos de *jet fires* y su naturaleza representa un paso adelante para la seguridad en la industria química. Este artículo propone un nuevo método con MATLAB® para leer automáticamente imágenes de *jet fire* y obtener propiedades de la llama; volumen, altura, *lift off* y ancho de la llama. Además, el método implementa modelos teóricos para

* *Corresponding author. E-mail: adriana.palacios@udlap.mx*

estimar el volumen de la llama como elipsoide geométrico, cometa geométrico, modelo de regresión, procesamiento de imágenes y un nuevo modelo propuesto por Jano & Ramírez.

Además, los resultados obtenidos se comparan con los datos reportados por García y Palacios, quienes analizaron las mismas imágenes de llama mediante modelos de regresión, lo que llevó a la conclusión de que el método propuesto es más preciso, eficiente y rápido en comparación con los métodos utilizados por García. y Palacios. Este método para imágenes de *jet fires* logra una velocidad promedio de procesamiento de 6.2 imágenes por segundo, bajo diferentes condiciones de presión o flujo volumétrico de metano.

Palabras clave: Dardos de fuego, forma de flama, altura de flama, metodología automática, MATLAB®.

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1. Introduction

Accidents in the Chemical Industry have resulted in substantial economic losses, environmental damage, and human casualties (Casal, 2017). Therefore, the safe production, storage and distribution of chemical products is of utmost importance and the center of a large body of research (Casal, 2017).

An industrial accident could be caused by different circumstances, but fire accidents have proved to be an important factor in increasing the impact of the accidents due to the domino effect associated with fire accidents, such as BLEVE (Boling Liquid Expanding Vapor Explosion). One example of the dangerous combination of Jet fires and BLEVE is the accident of San Juanico, where approximately 500 human lives were lost (Hemmatian *et al*, 2015). Consequently, several actions and systems have been developed and implemented in order to improve fire safety (Casal, 2017).

Examples of efforts are the DOW´S Fire & Explosion Index Hazard Classification Guide and the SFPE Handbook of fire Protection Engineering (AIChE, 2016; Hurley *et al*, 2015), which are valuable safety references. Both references analyze key factors like material factors, economic values (AIChE, 1994), the reliability and computer simulations (Hurley *et al*, 2015) in order to prevent accidents and domino effects in chemical industries.

Jet fires property analysis history dates to 1948, with the first studies of flame length (Hottel, & Hawthorne, 1948) and diffusion flames (Wohl, & Gazley, 1948). Later, in 1978, it was assumed that unstable flame analyses were senseless due to the unsteady flame state over time (Annushkin & Sverdlov, 1978), therefore, the focus changed to the analyses of stable flames and visible flame length in vertical jet flames diffusion (Becker, & Liang, 1978). By 1984, the concepts of lift-off heights and visible vertical turbulent jet diffusion flames lengths were formally introduced in the literature (Kalaghatigi, 1984) and different solution methods were explored.

The fire computer simulation methods aim to analyze possible fire scenarios to obtain fire property data; nevertheless, the mathematical models and computational power to analyze all the fire scenarios have been limited, therefore, different approaches and models can be explored in order to predict fire property data (McDermott *et al*., 2008). In this context, authors have proposed some geometrical models to characterize the flame and stated how flame properties data could be calculated. Some examples of geometrical models include: the ellipsoid (Baron, 1954), the cylindrical ascendent disks (Orloff, 1981), the cone (Chamberlain, 1987), the rectangle (Palacios, A. 2011) and the kite (Zhou, 2016).

Flame properties can be also analyzed from mathematical approach, through regression analysis as it is proposed by Palacios *et al* (2017) and further explored by Garcia (2019). Nevertheless, the flame properties data obtained by this method consumes a considerable amount of time, as in both references, the estimated time was almost three years.

Moreover, computer simulation and flame modelling depend on the physics characteristics of the flame such as lift off, width, height, and area, but the volume depends on the model use to measure it (geometric or mathematical) that is being consider for its calculations

In this work, an efficient and optimized computational method using a MATLAB® code is proposed, as part of a new method for the flame properties calculus. The MATLAB® code can analyze and compute some of the physical flames properties and the flame volume considering four models: Zhang (2015a), Orloff (1981), Zhou (2016), and Jano & Ramirez (2021).

The present work analyzes 8 methane flame conditions, classified into two groups (P flames and V flames) of four flame conditions. The P flames were obtained from a constant volumetric flow of 10.24 L/min, at 0.7, 0.8, 0.9 and 1 atm. The P flames have been previously tested and evaluated by Garcia (2019). The V flames were obtained at constant pressure of 1 atm, at volumetric flows of 7, 8, 9 and 10 L/min). V flames have been also analyzed, by Palacios *et al* (2017).

The experiments carried out in the present study were obtained from a collaborative research work between UDLAP and University of Science and Technology of China (USTC), financially supported by the Royal Society, UK (UDLAP *et al*, 2014).

2. Experimental design

Experimental methane jet fires were carried out in the Laboratory of Fire Science and Technology of the USTC. Figure 1 depicts an outline of the experimental set-up, consisting of a flow supply system, with a 2 m long pipe, a stainless-steel nozzle, and a low air pressure chamber of 3 m (width) x 2 m (length) x 2 m (height). The ambient pressure inside the chamber was regulated and maintained by a vacuum pump and controlled by a pressure sensor. As the ambient pressure decreased, other parameters affecting the jet fires development also decreased: the amount of oxygen per unit volume, the fuel the mass flow rate of the gas released through the orifice. Each test began when the pressure inside the sealed chamber was stable for a period of about 5 min after pumping fresh air into the low-pressure chamber to replace previous air. The duration of each experimental test was 2 min.

Table 1. Experimental conditions of the partially premixed methane-air jet flames.

Fuel (L/min)	**Air (L/min)**	**Air supplied (%)**
7	0-2.92	0-29
8	0-2.9	0-27
9	0-3	0-25
10.24	0-3.2	0-24

During all the tests, the following parameters remained constant: an ambient temperature of 25 ºC, a relative humidity of 35%, and a nozzle diameter of 3 mm. Through a flow rate meter, the fuel supply rates and hence fuel jet exit velocities at the nozzle were controlled.

For the P flames, it was obtained the geometrical characteristics of the vertical subsonic flames at normal and sub-atmospheric pressures of 1.0, 0.9, 0.8, & 0.7 atm at constant volumetric methane flow rate of $\dot{V}_{or} = 1.71 \cdot 10^{-4}\, m^3/s$. For the second set, V flames, it was under the same conditions, just varying the volumetric methane flow rate to 7, 8, 9 and 10 L/min at constant atmospheric pressure P = 1 atm.

A charged-coupled device (CCD) digital camera of sensor size 8.5 mm and an image size of 320 x 240 pixels was used to film the jet fire experiments. Each methane flame condition had an average of 750 images captured.

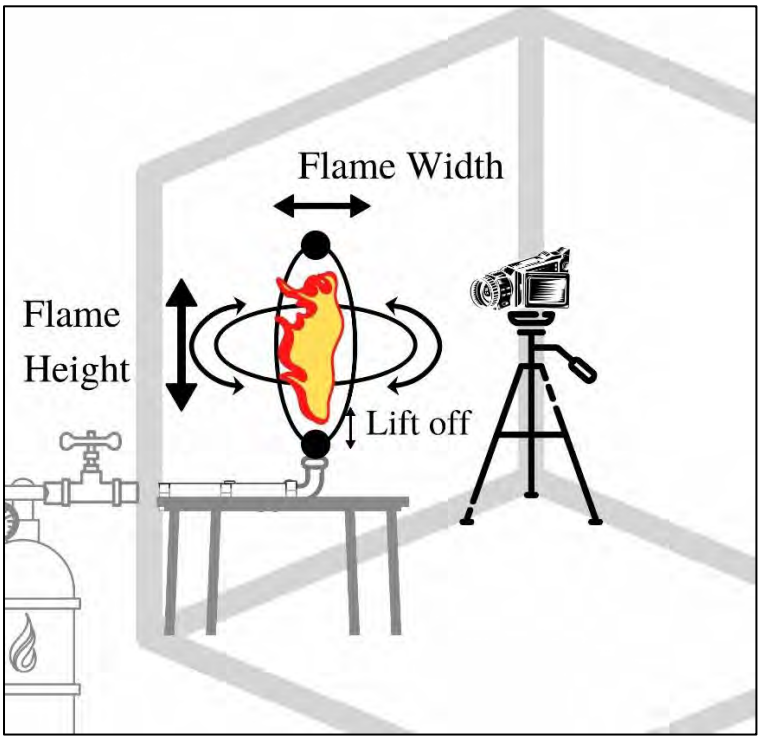


Figure 1: Representative Set-Up diagram of the experiments conducted at the labs of the University of Science and Technology of China. (Jano & Ramirez, 2021)

3. Methodology

This work methodology is divided in two main ideas. The first part points out the general process of the computational method used to read and calculate the jet fires properties, explaining how it was implemented and the flame properties obtained. The second part describes the models used for the flame volume estimations.

3.1 Flame image processing method

The method proposed in this work aimed to read and process images of any fuel jet fires recorded. The main idea is to achieve a fast and precise obtention of the flame properties, to calculate the volume of the flame with different models. All the mentioned above with the intention of automatize the study of jet fires and their properties.

3.1.1 Properties obtention

Flame images are load as a database into MATLAB® and the image type of the flame is specified. These images undergo a process of qualification, in which the spectrum of the flame is split into red, green, and blue masks. The green mask is filtered, since flames mostly round in the blue and yellow colors, the wavelength of blue color is around 450 nm and for yellow color is 550 nm. According to Shefer *et al* (2009) and Frank *et al* (2000) the jet fire electromagnetic spectrum is mostly presented between 375 to 540 nm. And more specific, the laminar flow of methane combustion spectrum, according to the work of Shefer (2009) lies between 410 and 450 nm, which can be appreciated in the blue flame, Figure 2.

The binarization of the image is performed accordingly with the intensity of the flame. Due to the refraction of the photons at the time of capturing the flame images, the brightness of the frames constantly varies. That is why the code automatically calibrates the intensity of the flame with an adaptive threshold, allowing a smooth reading of the flame structure in the frames.

After the color selectivity, the clearing of the shape is done by homogenizing the interior of the flame, as it is shown in Figure 2. The binarization process is performed in a custom cropped image to increase the clarity of the flame and avoid the misread of some highlights

or flashes outside the flame due to the reflex that the flame causes. Figure 2 shows a process of reading, binarize and clear the image of a flame.

Figure 2: Image binarization process. (Jano & Ramirez, 2021)

Once there is a clear image of the flame, Figure 3, the pixel coordinates of the flame are used in order to obtain the following flame properties in pixels: the height (h_f) width (w_f), lift off (s) and vertical area (A_f), for more detail see Annex B. The data provided by these flame properties in pixels is used to calculate the flame volume for the four different geometric models accordingly with each model equation.

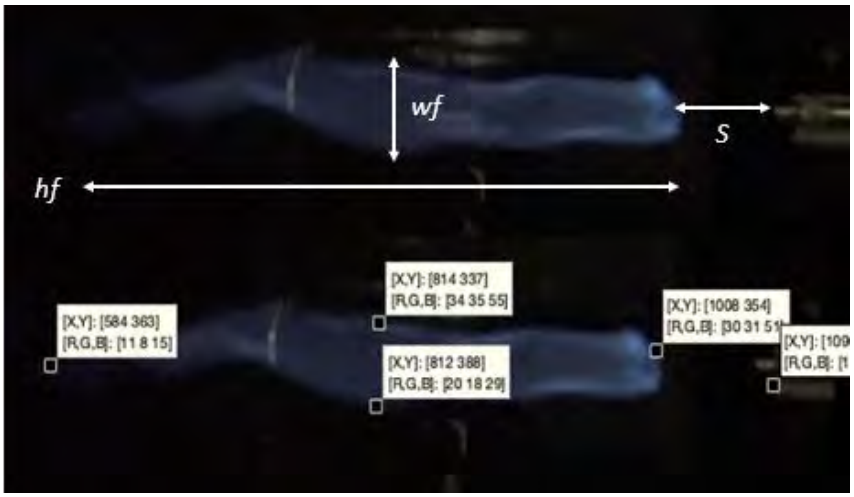


Figure 3: Pixel properties obtention. (Jano & Ramirez, 2021)

It must be clarified that at this point, the flame properties are expressed as pixels, therefore a pixel-meter ratio (P2M) was used. The P2M is a conversion factor from pixel to meters that was used for this method and is strictly related to the experiment dimensions used in the

laboratory. The P2M value change between P flames and V flames because the camera angle between each experimentation was changed, leading to a P2M values of 800 [pixel/meter] for P flames and 700 [pixel/meter] for V flames. For more details on the calculation of the P2M see Annex A.

After obtaining the flame properties required (h_f, w_f, A_f, s) the program calculates the flame volumes by Zhang (2015a) model ($V_{f,\ ellipse}$), Orloff (1981) model ($V_{f,\ Orloff}$), Zhou (2016) model ($V_{f,\ kite}$) and the proposed circular base model (V_f) (Jano & Ramirez, 2021). These models are explained with more detail in section 3.2.

The results obtained in MATLAB® are stored in a Microsoft Excel® file, to calculate the average values for: lift off; flame height; flame width; and the flame volumes for the four different geometric models considered. All the previous calculus is done for each methane flame condition. Likewise, it is calculated a flame lecture stability (f_s) for the jet fires.

The flame lecture stability is a proposed property that measures the flame lecture regularity of the method along each methane flame condition. It uses the average volume of the methane flame condition and compares it against each image (k), evaluating from 0 to n, where n is the last image, Eq. (1). Then an average flame lecture stability is obtained by applying an average theorem in all the results of Eq. (1).

$$f_s = \overline{\left(\frac{V_k - \bar{V}}{\bar{V}}\right), k\Big|_0^n} \tag{1}$$

At higher flame lecture stability values, then the lecture of the jet flame may be classified as irregular, but at lower flame lecture stability values, the jet flame lecture of the method can be classified as stable.

3.2 Flame properties models

Several models have been proposed to estimate flames properties such as height, lift off, width, and volume. Geometric figures have been proposed, such as, prolate spheroid by Zhang (2015a) based on the ellipse of Baron (1945), or kite geometry by Zhou (2016). Likewise, there are mathematical models proposed, such as Garcia's regression model (2019), which suggests the calculation of the flame volume using a polynomial formula.

Other research used film images and proposed methods to compute flame properties, such as the cylindrical disks from Orloff (1981). This research follows the last approach proposing a method based on MATLAB® code to analyze binary images.

Even though, there are many other important different models to predict jet flames properties, most of them are more focused on the thermal radiation than the geometry. For example, Palacios *et al* (2012) proposed a solid flame model, which describes the flame radiation emission as a frustum cone. Lowesmith (2007) proposed a one-point radiation model. Ekoto (2014) described a multipoint source radiation model. And Zhou (2015) a line source radiation model, later integrated with the Kite model (Zhou, 2016).

For this study, the aim is to compare visual properties as volume, and the other properties already mentioned. The experimental results did not include thermal radiation data; thus, the radiation models were not considered. However, according to Zhou (2015), the kite model describes better the radiation emittance, and is the one used for the Kite model (Zhou, 2016). Hence, kite's model is the only one which was considered from all the radiation models mentioned.

3.2.1 Geometric volume approach

In the case of geometric models, the objective is to adapt the geometric figure to the flame to calculate a flame volume. Therefore, different geometrical figures have been proposed (Section 3). For the purpose of this article, the geometric figures of a Kite (Zhou, 2016) an ellipsoid (Baron, 1954; Zhang, 2015a) and the circular base model proposed (Jano & Ramirez, 2021) were considered, calculated, and compared. The reason why these geometries were considered is because they have shown accuracy to predict thermal radiation in different works (Zhou, 2016) (Zhang, 2015a).

3.2.1.1 Ellipsoid Geometry

Baron's (1954) jet fire figure proposed an ellipse form using the height of the flame (h_f). Based on this geometry, Zhang *et al* (2015a) proposed a mathematical model to obtain the flame volume, using h_f as geometrical parameter, to study the combustion characteristics during gaseous fuels energy conversions. The experimentation consisted in turbulent gaseous

propane jet flames produced by different diameter nozzles at 64 kPa, which lead to two types of ellipse analyses (Figure 4).

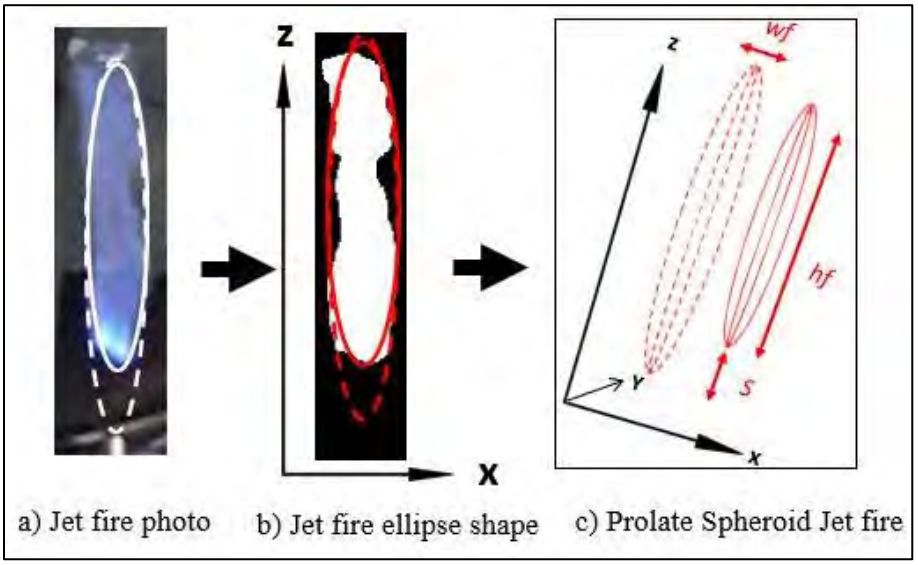


Figure 4: Baron (1954) ellipse and Zhang (2015a) prolate spheroid volume estimation. The dotted line considers the lift off (s) and the solid line does not. (Jano & Ramirez, 2021)

Consequently, Eq. (3) is proposed to estimate the volume of the flame, in which b is a constant that depends on the fluid pressure. According to Baron (1954), for flows at normal pressure, b must be equal 0.29, and for sub-atmospheric flows b must be equal to 0.2.

$$V_{f,ellipse} = \begin{cases} \frac{\pi}{36} b^2 h_f^2 & s = 0 \\ \frac{\pi}{36} b^2 h_f^2 + \frac{\pi}{12} b^2 h_f^2 s + \frac{\pi}{12} b^2 h_f s^2 - \frac{\pi}{12} b^2 s^2 \ln\left(\frac{h_f+s}{s}\right) & s > 0 \end{cases} \quad (2)$$

3.2.1.2 Kite Geometry

Zhou *et al* (2016) explained that the heat transfer of the jet fire is adjusted to a kite (Figure 5) experimenting with vertical and horizontal propane flames of up to 5 m length with different flow rates between 390 kg/h and 100 kg/h, and a release pressure of 7.5 atm. This geometry considers most of the flame shape, Figure 5, meaning that the calculus of volume estimation significantly contemplates the full real flame volume. Also, the model from Zhou *et al* (2016) acknowledges the lift off and discriminates the volume below it.

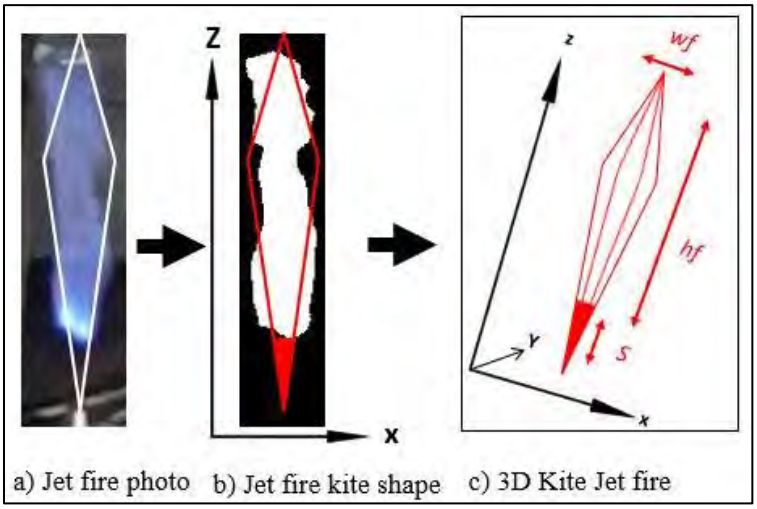


Figure 5: Zhou (2016) kite volume estimation. (Jano & Ramirez, 2021)

Remarkably, Zhou *et al* (2016) compared radiation predictions from different flame shapes models (Lowesmith 2007; Ekoto 2014; & Palacios 2012) and furthermore, proposed a thermal model based on a kite jet flame shape. Therefore, Zhou *et al*. (2016) does not calculate the flame volume directly. Hence, to integrate Zhou *et al*. (2016) model for comparison purposes in this work, Eq. (3) was developed to represent the volume obtained (Figure 5c), as suggested by Zhou *et al* (2016).

$$V_{f,kite} = \left[\frac{({w_f}^2 * (h_f + s)}{3}\right] - \frac{\left(\frac{w_f * s}{2(\propto h_f + s)}\right)^2 * s}{3} \tag{3}$$

Despite looking like a geometry that could not predict better the jet fire than the Baron's ellipse (1954), the work of Zhou *et al* (2016) demonstrated that the kite geometry predicts more accurately the thermal radiation. Nevertheless, both geometries are included in the comparison.

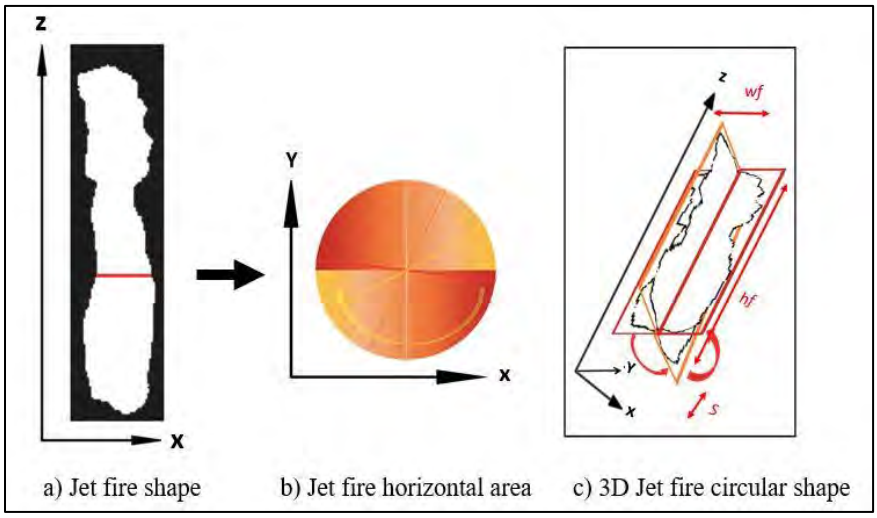
3.2.1.3 Circular Base Proposed Model

It is proposed to use the real vertical area x-z axis (A_f) of the jet fire obtained by the computer and MATLAB®, and estimate the volume from it, rotating the area and obtaining a more precise volume without limitations imposed by fixed geometries (Figure 7). The model assumes that the base on the x-y axis is circular (Figure 7b). The main reason of that assumption is because the geometry of a sphere has been studied and accepted for jet fires by several researchers. Dietrich *et al* (1995), and Zhang *et al* (2015b) worked with

253 microgravity combustion, obtaining a spherical shape for the flame at microgravity
254 atmospheres. Sunderland *et al* (1999), Dietrich *et al* (2000), and Кузнецов *et al* (2020)
255 studied laminar jets at non buoyancy atmospheres, getting spherical geometries as well. In
256 Figure 6 it can be more appreciated the shape described.

257

258 Figure 6: Laminar jet fire of C_2H_4 at microgravity conditions. (Zhang *et al*, 2015b)



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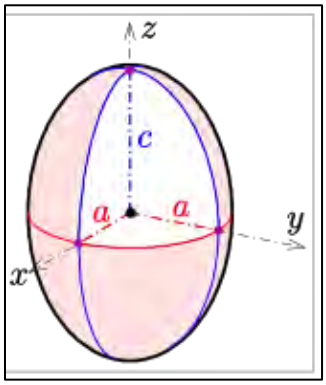
260 Figure 7: Circular base proposed model. (Jano & Ramirez, 2021)

261 The flame volume was calculated adapting the theoretical volume of a prolate spheroid,
262 Figure 8.



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264 Figure 8: Theoretical volume of prolate spheroid. (Ag2gaeh, 2015)

Eq. (4) was used to obtain the vertical area of the prolate spheroid (x-z axis), and Eq. (5) for the volume of the prolate spheroid. (Zwillinger, 2011):

$$A_e = \pi * a_e * c_e \tag{4}$$

$$V_e = \frac{4}{3} * \pi * a_e^2 * c_e \tag{5}$$

The main idea of the model is to calculate a volume (V_e) from the vertical area (A_e).

$$V_e = \frac{4}{3} * a_e * A_e \tag{6}$$

Finally, the volume was modelled in terms of the area *V(A)*, using Eq. (4) and (5), Eq. (6) was obtained. In terms of the jet fire, the radio on the z axis (c_e) represents the half of the height of the flame (h_f) then $c_e = h_f/2$. The width of the fire is represented by twice the radio on the x axis $2a_e = w_f$. And the vertical area (A_e) represents the vertical area of the jet fire, obtained by the computer $A_e = A_f$. Then it is obtained Eq. (7), representing Figure 7c.

$$V_f = \frac{2}{3} * w_f * A_f \tag{7}$$

3.2.2 Mathematical volume approach

The flame volume of a jet fire can also be estimated using a mathematical approach (Palacios, 2017; Garcia, 2019). These methods do not correlate the volume to a specific geometric shape, instead, try to describe the flame volume with a mathematical behavior. To add these mathematical methods to the comparison, the models of Garcia (2019) and Palacios (2017) have been included.

3.1.2.1 Regression Model

Palacios (2017), and later Garcia (2019), proposed a method on flame images using Paint® and Microsoft Excel® to define the lift off , the height of the flame, and 10 diameters of the flame, each at every 10% of the height along the z axis, Figure 9a. The objective was to stablish a relation, between the flame and a regression model, to calculate the flame volume.

After manually obtaining the properties (h_f, w_f, s), the diameters were used to develop a regression equation that calculated the flame volume. Garcia (2019) and Palacios (2017)

assumed a square perimeter, Figure 9b, to calculate an area for each measured diameter, Figure 9a. Then, the areas were tabulated in Excel® to obtain a behavior expressed in a polynomial function. Finally, the polynomial function was integrated along the flame height to obtain the volume of the flame (Figure 9).

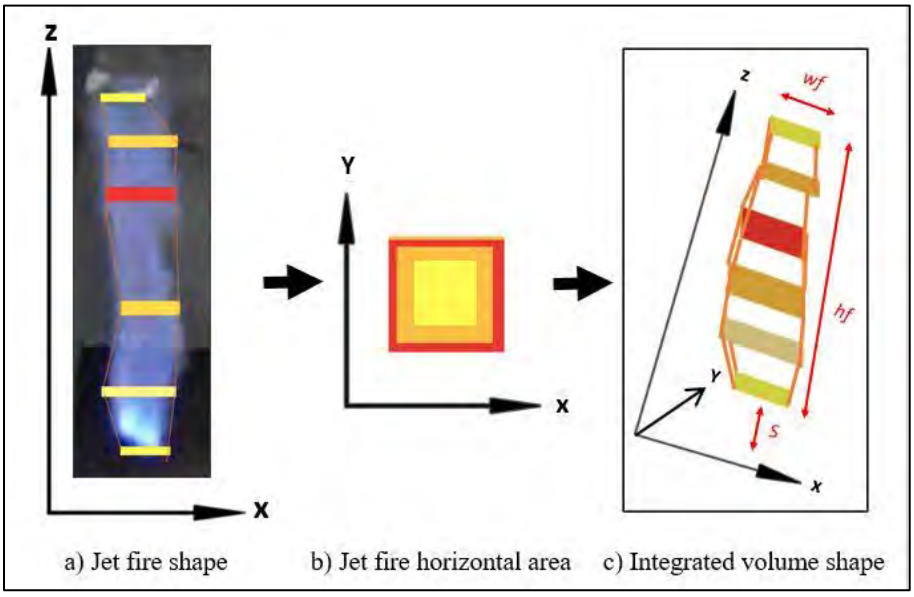


Figure 9: Regression model used by Garcia (2019) and Palacios (2017). (Jano & Ramirez, 2021)

3.2.3 Flames image properties obtention

Orloff (1981) was the first to conceive the use of use image processing to study fire properties but lacked the tools to do it efficiently. Nowadays, image processing effectively implemented in the study of jet fires is already possible (e.g., Garcia, 2019; Shen *et al*, 2017).

3.2.3.1 Cylindrical ascendent disks (Orloff)

In 1981, Orloff proposed a method to obtain the volume of the flame from a two-dimension image (x-z axis), arguing that the flame can be conceived as stacked disks. Hence, the volume of the flame can be calculated by integrating the volume of the stacked disks (defined by the product of the horizontal length and circular area x-y axis, Figure 10.

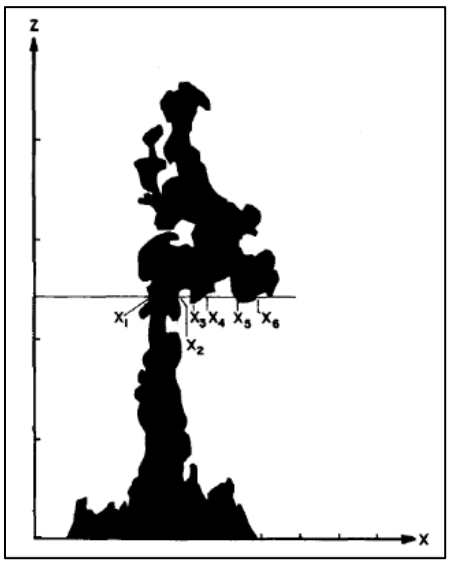


Figure 10: Orloff model image processing. (Orloff, 1981)

4. Results and Discussions

All the images of the 8 methane flame conditions (P and V flames) were analysed by the proposed method, obtaining results for each volume estimation model. Average flame volume results are compared graphically. Furthermore, results are compared against Garcia (P flames) and Palacios (V flames) results, in order to analyse the proposed method flame lecture accuracy and contrast the image processing speed of Palacios and Garcia's method against the proposed method.

4.1 Analysis of flame properties from proposed method

4.1.1 Vertical subsonic methane jet flames at constant volumetric flow (10.24 L/min) at different pressures (P flames).

The flame volume behaviour patterns, obtained by Garcia method and the proposed method, are that at sub-atmospheric pressure if there is less pressure then the greater the volume is, nonetheless the flame volume at atmospheric conditions has a bigger volume than the 0.8 atm and 0.9 atm volume but it is smaller compared to the 0.7 atm flame volume (Figure 10).

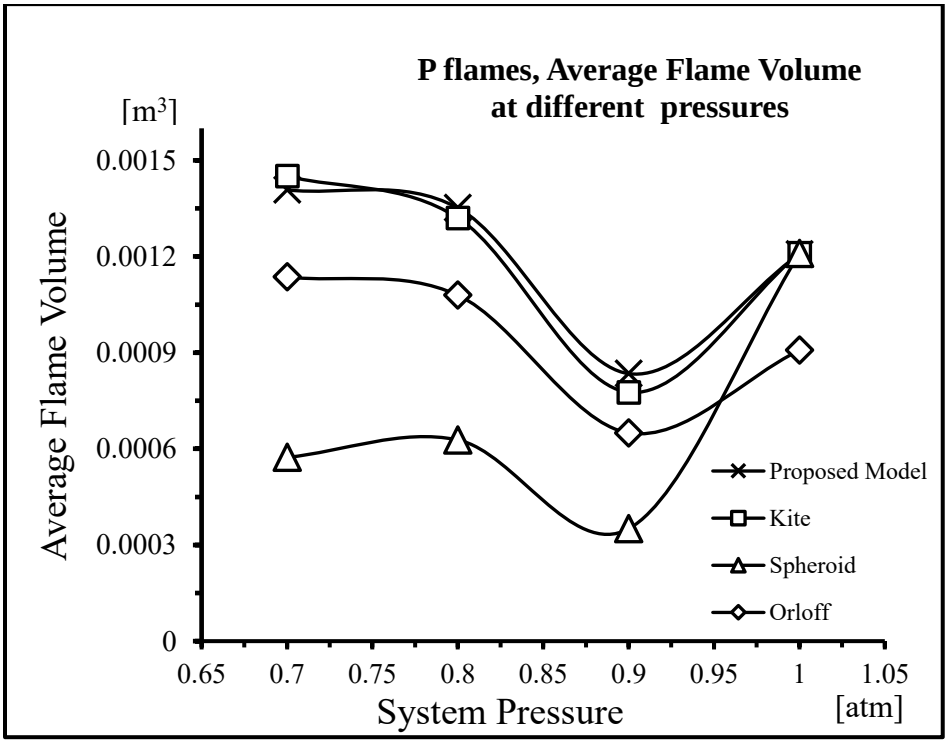


Figure 10: P flames Average Flame Volume at 10.24 L/min. (Jano & Ramirez, 2021)

Regarding the comparison with the results from Garcia (2019), it is determined that in 0.7 atm and 0.8 atm the flame volume results are very similar with the proposed model and the Kite geometric model. Also, the behaviours of Garcia´s results are the same as the one obtained in the proposed method. Despite existing a difference in the results at 0.9 atm, it could be explained due to the main differences in the flame volume estimation. (Figure 10).

4.1.1.1 Flame Lift off

The flame lift off behaviour pattern of P flames can be observed in Figure 11a, at a lower pressure the biggest lift off is obtained. Nonetheless, the lift off behaviour pattern reported in Garcia (2019) is similar to the behaviour pattern obtained by the proposed method, meaning that there exists a proper flame lecture in the proposed method, as a matter of fact, the values of 0.9 atm and 1 atm are very much similar, 0.049 m and 0 m respectively.

4.1.1.2 Flame width

The flame width behaviour pattern is analogous to the pattern of volume, Figure 11b. The width values of Garcia (2019) and the calculated in the proposed method have the same behaviour pattern, however, the range results do not coincide. The discrepancy in the proper values could be occasioned because of the use of a different P2M, or the accuracy on the

measure of the program against the manual obtention used by Garcia. Anyhow, the closeness on the results is high, just differing 1 mm at most.

4.1.1.3 Flame height

The flame height behaviour calculated with the proposed method shows an increasing and decreasing pattern, because the 0.7 atm and the 0.9 atm flame height are smaller than the 0.8 atm flame height, but 0.8 atm has a smaller flame height than at 1 atm, Figure 11c. On the other hand, Garcia (2019) flame height behaviour pattern increases at sub atmospheric pressure near the atmospheric pressure, but once the flame reaches the atmospheric pressure the flame height decreases a little. discussion

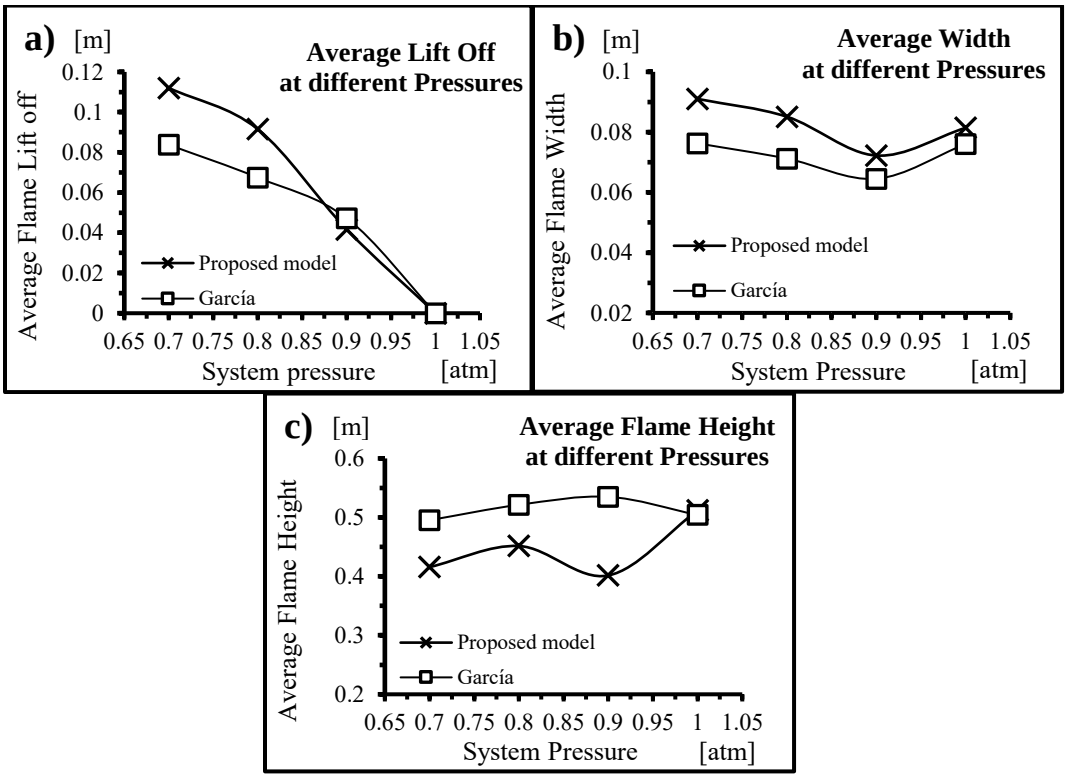


Figure 11: Constant Volumetric Flow 10.24 L/min at different Pressure comparison. a) Average Flame Lift off, b) Average Flame Width, c) Average Flame Height. (Jano & Ramirez, 2021)

4.1.1.4 Flame lecture stability

The flame lecture stability of the P flames volume values from Garcia method and the proposed method are shown in Table 2. The average flame lecture stability of all the data is 17.22%, the highest is at 0.9 atm from the Garcia Regression model and the lowest is 10.83% at 1 atm from the Orloff (1981) model, meaning that there exists a small unsteady

methane flame along in the time, but a general behaviour pattern can be pointed out, which allow us to understand the methane flame behaviour at the specified conditions.

Table 2. Flame lecture stability. Constant Volumetric flow (10.24 L/min) at different Atmospheric Pressure (0.7, 0.8,0.9, 1 atm).

Data	Pressure [atm]	Proposed Model	Kite (Zhou)	Ellipsoid (Baron)	(Orloff)	Regression Model (Garcia)
Flame lecture stability	0.7	14%	20%	19%	11%	16%
	0.8	15%	20%	21%	14%	16%
	0.9	16%	21%	23%	14%	23%
	1	12%	18%	22%	11%	19%

The P flame volume reported in Garcia and the one obtained by the proposed method have similar results. Furthermore, Zhang *et al* (2015a) reported propane flame volume values, at 100kPa and 64 kPa and volumetric flow of 0.01 m^3/h (1.666 L/min), are between 0.0012 m^3 and 0.0066 m^3, in which the maximum volume values are at 100kPa and the lower values are at 64kPa, giving an average flame volume around 0.003 m^3, meaning that P flames volumes are inside the volume range of literature data for sub-atmospheric pressure.

4.1.2 Vertical subsonic methane jet flames at constant atmospheric pressure at different volumetric flow (V flames).

The V flames average volume obtained by the proposed method, states an increasing behaviour pattern along with the volumetric flow, Figure 12a, meaning that at constant pressure, the methane flame volume will increment if the volumetric flow increases. The increasing behaviour is relatively constant for the Kite, Ellipsoid and Orloff model but the proposed model had a significant increment from 9L/min to 10L/min. The reason of this is that the proposed model depends on the flame width in order to calculate its volume and at these conditions, the average width value is greater than the increasing average flame width, occasioning that the circular base proposed model could be over-sizing the flame at this point.

On the other hand, the average flame volume results from Palacios's method stated a decreasing pattern and that the average flame volume is much bigger than the one calculated

with the proposed method, Figure 12b. This volume difference could be explained by a different set of factors, which will be discussed later (section 4.1.2.5).

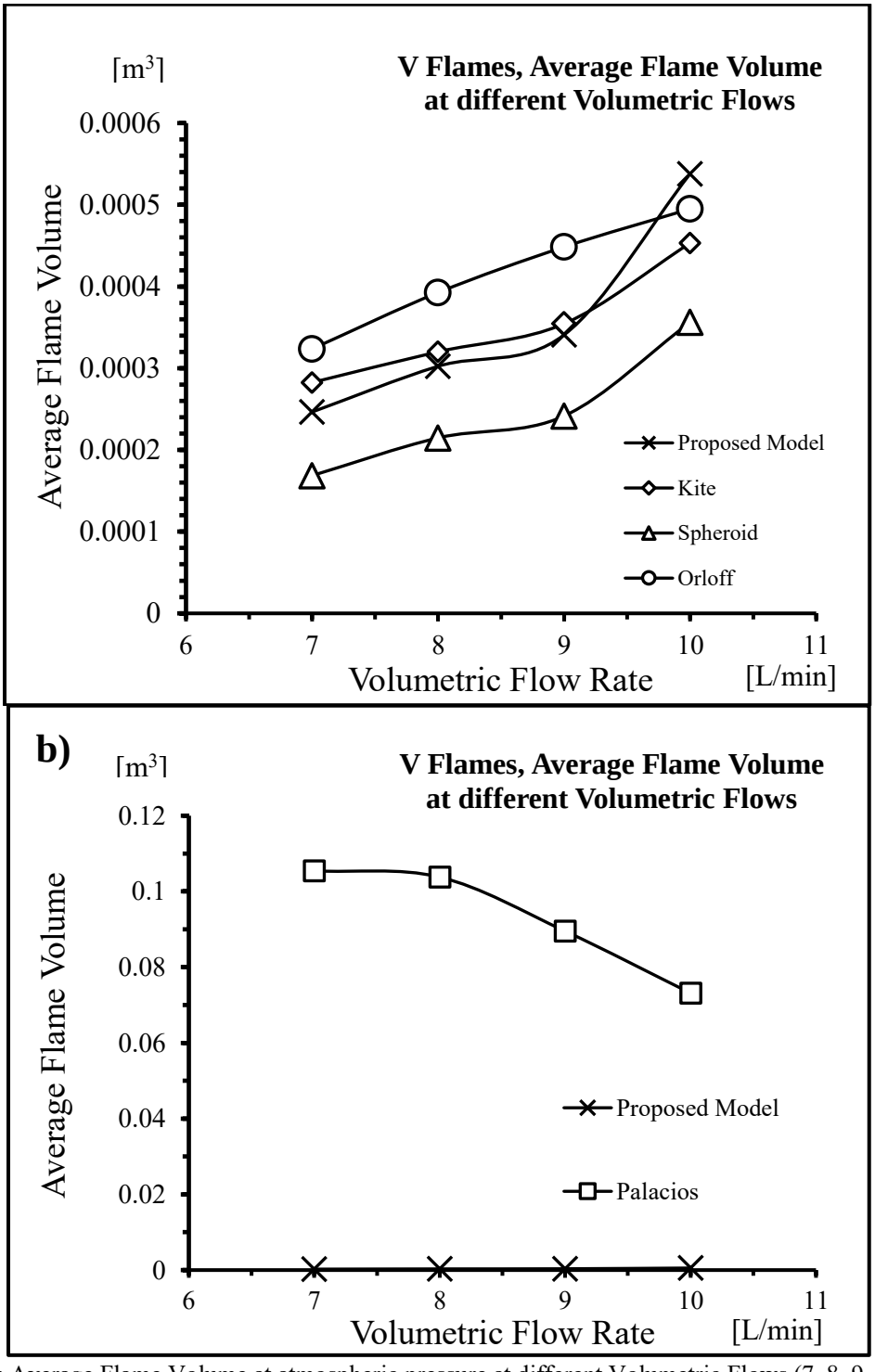
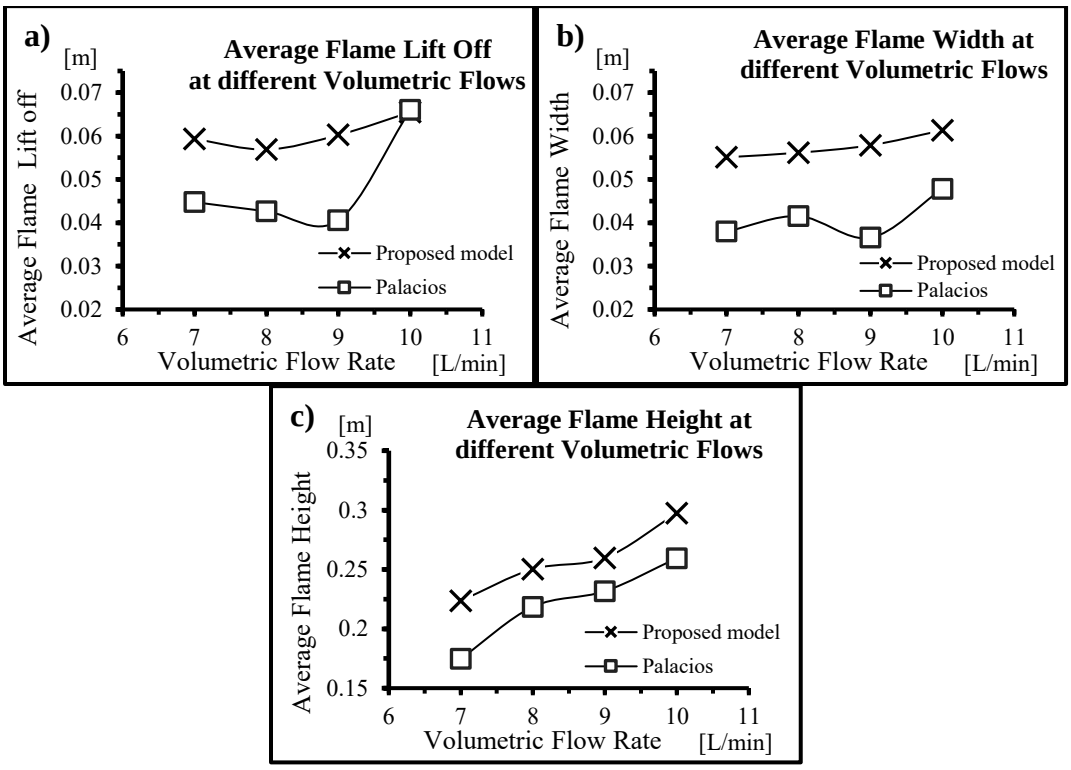


Figure 12: Average Flame Volume at atmospheric pressure at different Volumetric Flows (7, 8, 9, 10 L/min) comparison. a) Literature models b) Palacios model. (Jano & Ramirez, 2021)

389
390
391 4.1.2.1 Flame Lift off
392 The flame lift off behaviour pattern calculated with the proposed method (Figure13a), states
393 that the lift off of 8 L/min is smaller than the 7 L/min, but there is an increasing lift-off pattern
394 from 8 L/min to 10 L/min. Differently, from the lift off results by Palacios (2017), it could
395 be observed that the increasing pattern started at 9 L/min. Figure 13a graphically shows that
396 the data calculated from Palacios and the proposed method have a different range of values.
397 While Palacios lift off values are between 0.04 m and 0.065 m, the proposed method lift off
398 values are in a 0.055 m to 0.065 m range. However, the lift off value at 10 L/min is practically
399 0.65 m in both analyses.
400 4.1.2.2 Flame width
401 The flame width behaviour pattern obtained by the proposed method suggest that the width
402 of the flame should increase along with the volumetric flow, this pattern behaviour can be
403 seen in Figure 13b, but in Palacios's analysis exists an irregularity at 9 L/min that does not
404 fit the increasing width pattern observed in the proposed method results. Moreover, the width
405 values range are slightly different, for Palacios values the range is between 0.036 m to 0.047
406 m, while the proposed method width range is from 0.055 m to 0.062 m
407 4.1.2.3 Flame height
408 The flame height behaviour pattern observed from the values of the proposed method is an
409 increasing pattern which also agrees with the values reported in Palacios's method (Figure
410 13c), as a matter of fact, the results are similar with each other, which means that at a higher
411 volumetric flow a higher flame height will be obtain if the pressure remains constant.
412



Figures 13: Average Flame Height at atmospheric pressure at different Volumetric Flows (7, 8, 9 ,10 L /min) comparison. a) Average Flame Lift off, b) Average Flame Width, c) Average Flame Height. (Jano & Ramirez, 2021)

4.1.2.4 Flame lecture stability

The flame lecture stability results of the image processing, which are reported in Table 3, states an average flame lecture stability of 12.36%, in which the maximum value is 22.43% at 7 L/min from the Ellipsoid geometric model and the minimum value is 8.24% at 7 L/min from Orloff's approach but the flame lecture stability of Palacios's method is 75.35%, in which the maximum value is 81.12% at 10 L/min and the minimum is 72.10% at 7 L/min. These results can be explained due to two scenarios: the methane flame is very irregular at every system evaluation or there exists some irregularities in the methane flame property data calculations.

Consequently, from the flame lecture stability values of the proposed method and the methane flame videos can be stated that the methane flames behaviour pattern is not that irregular, therefore, the expected flame lecture stability should not have high values. Palacios (2017) method converts some negative flame volume values in positive by applying the absolute value, thus affecting the flame volume calculations which affects the flame lecture stability values.

Table 3 . Flame lecture stability. Constant Atmospheric Pressure (1 atm) at different Volumetric flow (7, 8, 9, 10 L/min)

Data	Vol. Flow [L/min]	Proposed Model	Kite (Zhou)	Ellipsoid (Baron)	(Orloff)	Regression Model (Palacios)
f_s	7	9%	11%	22%	8%	72%
	8	9%	10%	17%	9%	74%
	9	9%	10%	15%	9%	74%
	10	12%	15%	21%	11%	81%

4.1.2.5 Volume inconsistency at V flames discussion

There are three important factors to consider for explaining the volume difference between Palacios's method and the proposed method, the flame lecture stability, the P2M parameter, and the absolute values of the volume obtained in Palacios's method.

The flame properties lecture (in pixels) in Palacio's method and the one proposed are quite similar, as it is shown in Table 4. Even though some of the properties slightly differ, the tendency of the properties is similar in both methods, that is why the flame lecture stability is not consider a critical factor explaining the volume differences.

Table 4. V flame properties values obtained by Palacios and proposed method.

	Method	Height (pixel)	Lift off (pixel)	Width (pixel)
7 L/min	Palacios (2017)	154.4	39.5	27.9
	Proposed	156.5	41.5	32.7
8 L/min	Palacios (2017)	193.1	37.7	30.5
	Proposed	175.2	39.8	36.7
9 L/min	Palacios (2017)	204.6	35.8	26.9
	Proposed	181.8	42.2	39.2
10 L/min	Palacios (2017)	229.3	59.6	35.2

Proposed	236.9	52.2	53.6

Since the camara vision angle change from P flames to V flames, a new P2M parameter must be calculated, Palacios P2M value used was 883.5 [pixel/metro] and for the proposed method the P2M value is 700 [pixel/metro]. However, both values are similar, which means that the P2M parameter is not a critical factor.

Therefore, the final factor is how the volume is calculated. In the regression equations calculated by Palacios (2017), several negative values were obtained and convert into positive values by using an absolute value, which can significantly impact the average flame volume of the methane flame condition. On the other hand, as it was previously stablished, the P volume values veracity is between literature volume data range, according to Garcia (2019) and the reported values by Zhang *et al* (*2015a*). Considering the fact that both, P and V flames, are analysed by the same method, it can be assumed that the V flames volumes have certain veracity.

On the other hand, in the experimental room at the Laboratory of Fire Science and Technology of USTC behind the flame, there was an unknown material that reflects the luminosity of the flame and MATLAB® recognized this reflection as part of the flame, affecting, thus, a proper binarization of the flame. This reflection problem was mostly solved by cropping the image before binarization to a size where the actual maximal flame could be recognized reducing the reflection to a minimum. Unfortunately, the luminosity of the room where the flames were recorded, was not constant. The changes of the luminosity can affect the reading of the flame in the image, which could lead to wrong calculus. Therefore, five different versions of the code were done, in which the binarization section of each code was programmed more specific to obtain a better lecture of the flame.

Despite all, the true reason of the flame volume differences between Palacio's method and the proposed method is unknown, the previously explained factors may affect the final calculate flame volume value.

4.2 Image processing speed

476 Finally, one of the most remarkable advantages of the new method is the time required to
477 obtain and analyse the properties of the jet fire. The times utilized by Palacios (2017) and
478 Garcia (2019) were compared against the time used by this method.

479 The speed is represented in number of images processed per second (image/sec). That, with
480 the intention of contrast the capability of frame treatment from both methodologies, Table 5.

481 Table 5. Average processing time.

	Image set	Proposed Method [Image / s]	Regression Method [Image / s]
Average Image Processing	7 L/min	5.3	-
	8 L/min	5.5	-
	9 L/min	5.3	-
	10 L/min	5.4	-
	0.7 atm	4.9	-
	0.8 atm	5.6	-
	0.9 atm	11.9	-
	1 atm	5.6	-
	General	6.2	3.74×10^{-5}

482

483 According to Garcia (2019), his method and processing speed for P flames was three years,
484 which is 3.74×10^{-5} image per second, while the one proposed, for analyzing the same images,
485 was 6.8 image per second, which represents a huge productivity increment. Moreover, the
486 average image processing of Palacios (2017) was three years too, and the average image
487 processing speed of the MATLAB® code is 5.4 image per second. Generally, the new method
488 has a 6.2 image per second speed which clearly can be interpreted as fast.

489

490 Even though, the time given by Palacios and Garcia (3 years each) is not the exact time
491 expended computing the images. These 3 years represent the time expended on manually
492 computing each image of P flames or V flames and capturing the properties of the flame.
493 Also, it involves the time required to input the data in Excel®, making graphs and obtaining
494 the regression equation, integrating that equation, and then calculating the volume, all that

for each image. Moreover, it could take more time if it were required the same accuracy, which is not the case, as discussed before (Section 4.1).

While the Garcia (2019) and Palacios (2017) methods required a huge amount of human effort, the one proposed was made based on computational work. Despite needing human effort for developing the code, the time used (120 hours) can be neglected compared to the number of images that can be processed.

One of the important aspects on the speed processing is the number of images per second (6 images), which connotates it achieved a speed fast enough to measure a proper behavior of the jet fire. Nevertheless, the speed processing may be faster if the Matlab® code is more optimize in order to consume less computational work or if the compute hardware specifications are upgraded, because the CPU, the graphic memory, and the RAM memory influence on the computational work efficiency, in this work an Intel Core 5-9400F CPU, a GeForce GTX 1650 graphic card and 16 Gb of RAM are used.

However, being able to properly measure the behavior of a jet fire in a short period of time is important, the true impact of this method on the chemical industry relies on fire safety procedures, because if we are able to predict jet fire properties at different conditions, then we could be able to dimension undesired but probably jet fire accidents which could be mitigated by accurately plant design, on the other hand due to the processing speed, this method could be implemented in the chemical industry, for example the petrochemical sector, as a flame control indicator in which the jet fire properties could be specified for the desire process conditions and alarm the employees if the jet fire properties are off desired jet fire properties range.

5. Conclusions

The proposed method shows low flame lecture stability values due to a precise flame analysis, meaning that the computer analysis is constant and accurate for the lecture and calculus of methane flame properties. The method is an efficient alternative for the study of flames, also it is very flexible and editable for the application of new geometrical /mathematical models. The proposed method represents a next step in the flames research because of the amount of data that can be processed. It could be beneficial in terms of time and could accelerate the study of jet fires. At the end of this work, it has been possible to read and analyse around 6000 flame images in 17 minutes.

The flame lecture stability for the proposed method was 14.61%, for Garcia (2019) method was 18.64%, and for Palacios (2017) method was 75.35%, which means that the most stable lecture was the proposed method. The average image processing speed of Garcia (2019) and Palacios (2017) method was 3.74×10^{-5} images per second and for the proposed method was 6.2 image per second.

5.1 P flames analysis

The results for the average volume and width of P flames presented a decreasing pattern at the evaluated sub-atmospheric pressures, but this pattern was broken at atmospheric pressure. The lift off of the flame decreased and become zero once the atmospheric pressure was reached, and the height of the flame showed an irregular behaviour. The comparison analysis of the P flames properties (v_f, w_f, h_f, s) between the proposed method and Garcia´s results had very similar patterns each other. Nonetheless, the height analysis at Garcia´s results suggested a decreasing curve which maximum was at 0.9 atm and the proposed method results suggested an irregular behaviour. Even though the results were not the same, they were in a certain range of similarity. Hence, it was concluded that difference happened because of each method nature.

5.2 V flames analysis

The results for the V flames volume showed an increasing pattern along with the increment of methane volumetric flow, the lift off showed an increasing curve with a minimum at 8 L/min. Nevertheless, the comparison analysis of the V flames between the proposed method and Palacios (2017) showed that they were not similar at the flame volume analysis but at the lift off, width and height flame properties, a similarity could be seen. Both methods have read the same flames and had relative similar values between each other, but due to the three factors discussed (flame lecture stability, P2M parameter, and absolute volume values) the flame volume discrepancy existed.

It was observed that Palacios (2017) results suggested a decreasing behaviour pattern along with the volumetric flow increasing and the proposed method results suggested an increasing behaviour pattern in all the geometric models. Additionally, the proposed method results were compared against literature values and it was resolved that there was a close similarity.

However, it was determined that the main reason of the flame volume values discrepancies between both methods remains unknown.

5.3 Future work

The proposed method along with the proposed geometric flame approach represents an accurate, efficient, and quick tool for flames studies due to its programmable nature, the image processing speed will help reduce the physical flame properties calculation and the optimizing binarization parameters will help to analyse the flame lecture stability accuracy. However, this method could be improved by performing the experiments in a dark environment and keeping a stable camara angle along all the experiments which will benefit the P2M factor calculation and therefore more accurate flame results could be obtained.

All the mentioned above will contribute to the flame knowledge and research. It is aware that a future improvement could be optimizing the code to performed live-flame calculations, which could help the chemical industry such as petrochemical, thermoelectric plants, among others, to monitor flame properties at real time and leading them to take better decisions regarding safety or operational issues. Although, a basic camera normally can capture between 16 to 32 frames per second, pointing out that the actual process speed (6.2) is not far from reaching a capability to treat fires in a *quasi-real* time, granting possibility to develop tools for provide better control in the future industry.

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Nomenclature

a_e	ellipsoid radius on the x-axis (m)
A_e	ellipse area (m^2)
A_f	flame vertical area (m^2)
b	constant in Eq. (2)
b_e	ellipsoid radius on the y-axis (m)
c_e	ellipsoid radius on the z-axis (m)
f_s	flame lecture stability
h_f	flame height (m)
s	flame lift off length (m)
$P2M$	pixel to meter ratio
V	flame volume
$\bar{V}$	flame volume average
V_e	ellipse volume
V_f	flame volume obtained by proposed method (m^3)
$V_{f,\ Palacios}$	flame volume obtained by Palacios method (m^3)
$V_{f,\ Ellipse}$	flame volume obtained by Baron method (m^3)
$V_{f,\ Orloff}$	flame volume obtained by Orloff method (m^3)
$V_{f,\ Garcia}$	flame volume obtained by Garcia method (m^3)
$V_{f,\ Kite}$	flame volume obtained by Zhou method (m^3)
w_f	flame width (m)
Greek symbols	
α	length ratio of lower flame to whole flame (non-dimensional)

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704

705

Annex A

For the pixel to meter ratio used (P2M), it was used a metal bar already measure in centimetre units. Figure 15 represents the bar used; it is shown the equivalent in centimetres to the indicated section of the bar. In figure 16, it can be appreciated that a photo of the metal bar was taken, to measure the ratio between pixel and meters. MATLAB® is able to count the number of pixels that are equivalent to the 5 cm of the metal bar.

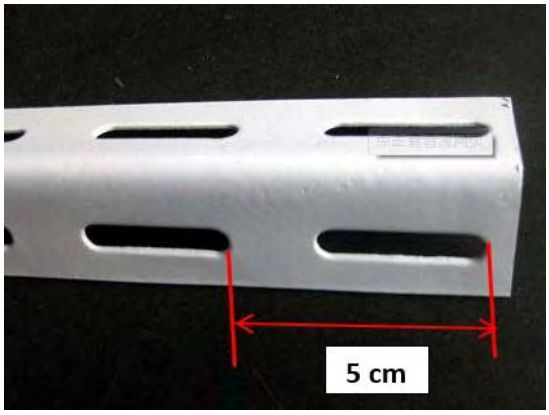
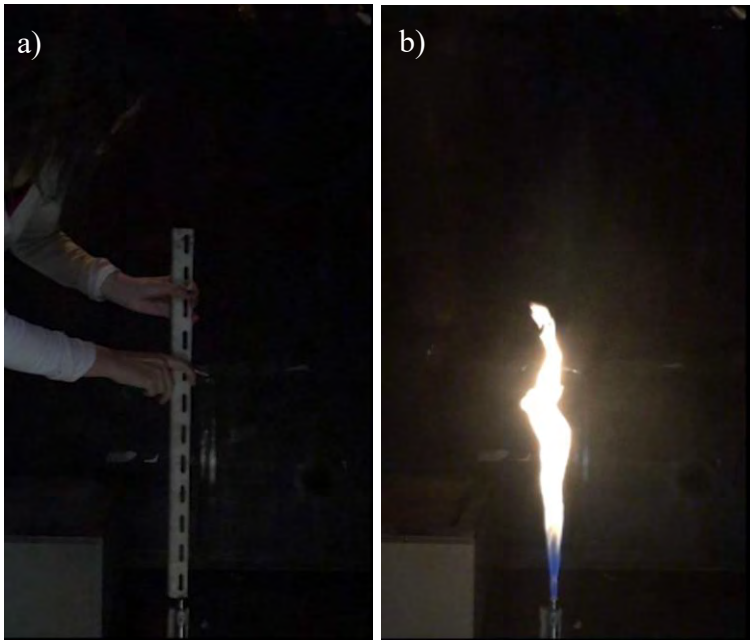


Figure 15: Metal bar size. (UDLAP *et al,* 2014)



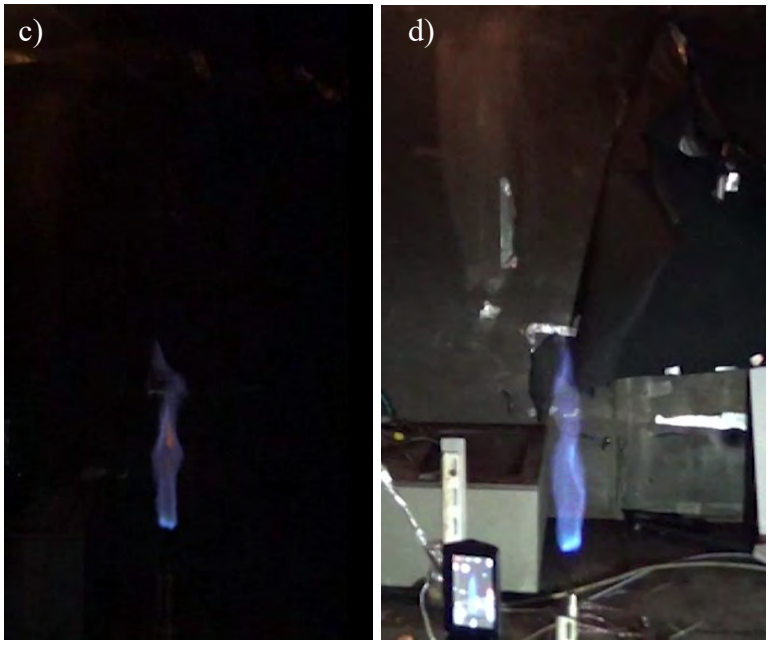


Figure 16: a) Metal bar in experiment room b) 1 atm pressure Jet fire photo c) 10 L/min methane jet fire photo d) 9L L/min jet fire photo. (UDLAP *et al,* 2014)

As it can be seen, there are different photos taken in different angles. That was a problem to obtain a proper P2M ratio. The directly P2M ratio obtained was for P flames, Figure 15b, due to the image has the same angle as Figure 15a. For the other photos changed of angle, Figure 15c and 15d, it was correlated a P2M according to some structures in the images. However, the P2M for Figure 15c, was the hardest and possibly the least accurate. Luckily, Figure 15c just represents the 10 L/min methane flame images.

Anyway, the experiments were not based or planned to execute this method proposed. For further experiments, it is recommended to don´t change the camera angle or zoom and have a homogeneous color background.

Annex B

For the obtention of the flame properties with MATLAB®, the image is read, and the jet fire is filtered, as already explained (Section 3.1). Parting from a localized flame, the code obtains some coordinates, Figure 9, and measure the distance between them.

In Figure 17, it can be appreciated 5 points. Point 1, is the highest point along the z axis, representing the peak of the jet fire. Point 2 is the lowest point in the flame, representing the base of the fire. The height of the flame is calculated measuring the pixel distance between point 1 and 2.

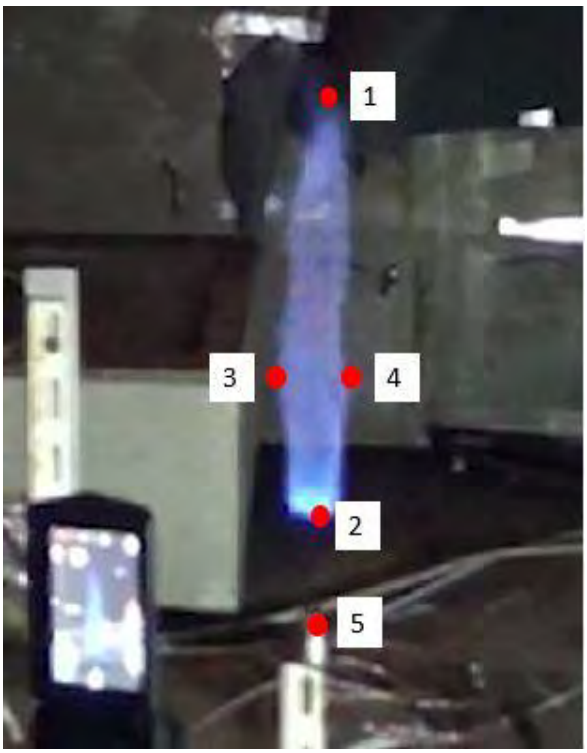


Figure 17: Important coordinates of the frame. (UDLAP *et al,* 2014)

The pixel distance between point 3 and 4, represents the maximum diameter of the flame. Because of the nature of the flame and its instability, the maximum diameter changes every frame. Anyway, the code is able to read al the diameters of the flame along the z axis and decide the maximum diameter of each frame.

Finally, the point 5, Figure 17, is situated at the nozzle and outside of the methane flow. The lift off is measured with the distance between point 5 and 2, where combustion starts.