

STUDY OF EXPERIMENTAL TECHNIQUES FOR VISIBLE FLAME LENGTH MEASUREMENT OF TURBULENT DIFFUSION FLAMES

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Abstract. *Optical visualizations of turbulent diffusion flames are used to estimate the visible average flame length. The paper presents a study of three different methods to measure the VFL using optical techniques. The effect on the image of the main optic parameters such as focus, exposure time and ISO sensibility are analyzed. The VFL obtained with images in low exposure time and long exposure time are compared with a third optical method that is based on the luminous intensity. Finally one method was used to characterize the behaviour of turbulent diffusion flames in function of the increment of the volumetric flow rate.*

Keywords: *Flame Length, Turbulent Flames, Measurement*

1. NOMENCLATURE

Symbols

d_b	Inner diameter burner, [mm];
F	Diaphragm aperture, [];
L_F	Average visible flame length, [mm];
$*L_F$	Normalized visible flame length, [];
$L_{F,i}$	Individual visible flame length, [mm];
Re	Dimensionless Reynolds number based on diameter, [];
t_{exp}	Shutter speed, [s];
n_j	Number of pictures

Abbreviations

NG	Natural gas;
CCD	Charge-coupled device;
MSE	Measurement by short or low exposure time
MLE	Measurement by long exposure time
MFP	Measurement by frequency photography
VFL	Visible Flame Length
SEM	Standard error of the mean

2. INTRODUCTION

Predicting models for turbulent diffusion flame lengths have important applications and have called the attention of many research groups. Since several studies use photographs to measure the flame length, with photographic parameters varying among authors, it is important to explore possible discrepancies among measurement techniques that could affect the results.

Chamberlin, D. and A. Rose, 1948 investigated the flickering in luminous flames. Using a photographic method was investigated the vibration motion of the flames. The flames were photographed using video films with an exposure time 1/55 s and speed of 32 frames per second. They did not use computers to examine their data.

Wohl, et. al, 1949, used two visual techniques to analyze the turbulence in diffusion flames. Direct photographs were used to measure the flame length and shadow photographs to analyze the internal structure of the turbulent flow at base of the flame. Photographic parameters were not defined. Posterior years the experimental data was used by Hottel, 1953 to propose a correlation as function of the flame properties.

Baker and Liang, 1978, provide general correlations of flame length, which were compared with experimental data where the flame length was judged visually by a trained observer. The tip was the highest and was the downstream point at which flame light was seen with an appreciable frequency.

Gautam T., 1984 performed a study about the factors that influence in the flame length for different hydrocarbons. The pictures were taken with an exposure time of 1/30 seconds, without more photographic parameters undefined. The flame length were defined how the average of individual flame length measured between the exit of the burner and the highest visible point of the flame. A second visual technique (Schlieren photography) measured the lift-off.

In the same decade, Zukosky, et al., 1985 investigated the behavior of diffusion flames for natural gas using video film with low exposure time. The images were extracted from the video and processed manually where the flame length was measured at the highest point of the boundaries marked by the visible zone or luminous region due to soot. The focus of the study was the flickering of the flame. The authors did not declare the photographic parameters.

Santos A. and Costa M., 2005 analyzed diffusion flames of propane and ethylene. The technique used to measure the flame length is based on the average of individual flame images. The minimal number of images required were defined in relation to Reynolds number Re . With an exposure time of 5 seconds, for Re greater than 8000 the number of images required was of 5, and for Re smaller than 8000 the images used were of 3.

Stratton, B. J., 2005 in his doctoral thesis describes a method of converting footage into a time-average 3-dimensional representation flame. The aim is to find a correlation between the flame volume and the heat release rate of the fire, as well as to determine the flame height and flame pulsation frequency. He used two digital video cameras at position orthogonal to the fire. Their photography parameters were auto adjusted by the cameras.

In the last years, the study performed by Kim, H. K., et al., 2007 investigated the flame length of oxy-fuel combustors for a wide range of fuel and oxidizer velocities. A digital camera was used to obtain the flame images with an exposure time 1/60 seconds at an aperture F2.0. The flame length was defined as the time-average value of the recorded flame length for a time interval of 2 minutes.

Zhang, X., et al., 2015 proposed a mathematical model for flame volume estimation based on flame length of turbulent diffusion flames. A digital camera were used to capture flame images with a quality of 3 Mpx. The images were extracted of a video film of 20 seconds with a speed of 25 frames per second. The images were processed digitally using the technique developed by Otsu, N., 1975 after that, the flame length and width were measured using the technique developed Orloff, L., 1981.

Hu, L., et al., 2015 applied the same method used for Zhang, X., et al., 2015 2015 to process images. The flames were sized to obtain the area and volume of the flames. He uses 750 images obtained from a video film of 30 seconds. Photographic parameters were not declared. At the same time, an infrared thermography camera (spectral range: of 8 - 14 μ m) was used to get the flame contour, based on the isotherm 800K.

This paper presents a study of three methods for measuring flame lengths using photographs. The methods are applied to natural gas turbulent diffusion flames. Previous tests were carried out to examine the effects of Exposure Time, Aperture and ISO number. With the objective of to have a diversity of flames, the fuel was mixed with CO₂. The addition of this inert gas produces a change on the luminosity of the flame due to reduction in the production of soot. Optimal parameters are proposed to obtain useful images in order to use them in a characterization process.

3. METHODOLOGY

The study will describe three methods to estimate the flame length. First the experimental workbench is described. Then, the photographic parameters are explored. Finally, the three methods are presented.

3.1. Experimental Setup

Figure 1 shows the experimental setup to measure the visual flame length. Aiming to reduce the disturbance from external flows, the flames were confined within a rectangular enclosure of steel screens (mesh 20) with the following dimensions: 1.5 m wide, 1.0 m long and 3.5 m high. The enclosure extended from the floor to an exhaust duct. The fuel was injected through a stainless steel burner of 7.55 mm inner diameter (d_b) and $30d_b$ long. The burner has a pre-chamber with glass spheres and screens to rectify the flow. The experimental ambient was kept in dark conditions to decrease the influence of the background. The visual flame length was investigated for natural gas flames varying the fuel flow rate and the dilution with CO₂. Two mass flow controllers measured the volumetric flow rate, one for the fuel (Bronkhorst) with an uncertainty of $\pm 0.4\%$ of the reading $\pm 0.1\%$ of the full scale and one for the diluent (Omega) with an uncertainty of $\pm 0.8\%$ of the reading $\pm 0.2\%$ of the full scale.

Two photographic cameras, Canon T5i and ProSX-5M were used to capture the pictures. These cameras have control over the photographic parameters that are explored in this study. Then, each image was processed by specialized software developed for each method.

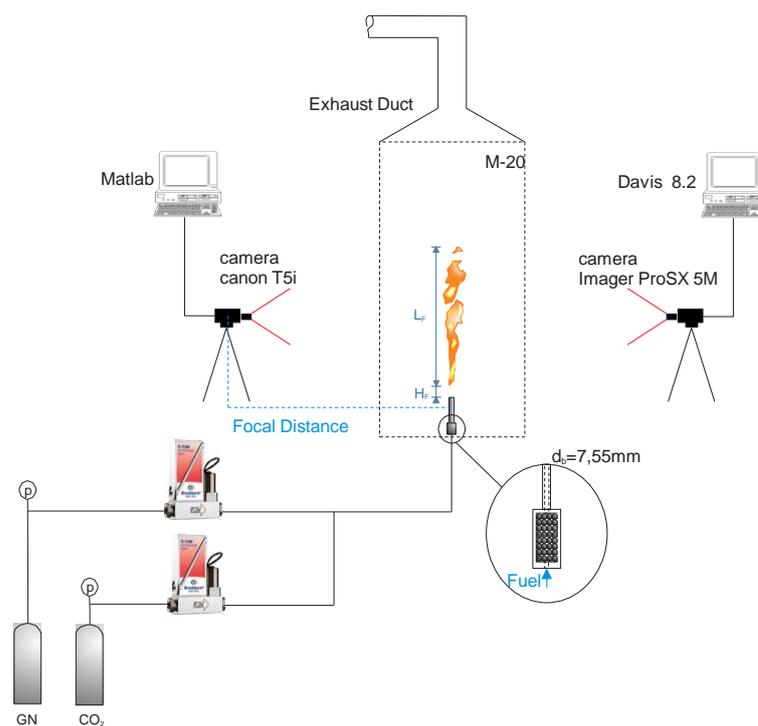


Figure 1. Experimental apparatus and schematic of experimental setup.

3.2. Optical Parameters

Photography parameters were analyzed in this section in order to get a representative image of a turbulent diffusion flame. A good photography can be taken with the correct set of parameters. The aperture, the exposure time and the ISO sensitivity are the main parameters of photography. The next subsections will describe how these parameters are specified and their effects over the flame images.

3.2.1. Aperture or F number

The aperture controls the amount the light that enters in the CCD sensor (for digital cameras) and is given in a scale represented as F -number. For a large F -number, the camera has a small aperture of the diaphragm, opposite situation occur for a low F -number. It works like the pupil of the eye, adjusting the visualization depending on ambient light. In condition of darkness, the pupil increases its size to allow more light to get in. It is also related too to the depth of field. The aperture adjusts the depth of field by blurring the background (large F -number) relative to the target that is in a focal distance from the sensor of the camera or bringing background and target into focus simultaneously (small F -number).

A digital camera used here has a lens 18-55mm which was setting in the condition with the greater possible field of view. This is important to correlate the number of pixels of the flame in the picture with the real dimension. A smaller focal distance will permit to have more pixels representing an object and the ratio mm/pixels will decrease. This characteristic is important during the digital process of a flame image and the uncertainty of the measurement. A greater number of pixels representing the flame image needs more time for processing, but will results in smaller uncertainties.

3.2.2. Exposure time

A second important parameter in photography is the exposure time. This is the time the sensor is exposed to the light and is inversely proportional to the shutter speed. The shutter is the device that keeps the camera sensor blocked until the camera fires. When there is motion in the scene to be registered, as in turbulent flames, the exposure time controls whether the image is an instantaneous or an integrated image. Thus, the exposure time have to be matched in each situation, depending on the velocity of the event to be captured and the type of image that is desired. For example, in a typical turbulent flame, it is possible to see small flame volumes disconnected from the main flame near the flame tip. For visual flame length measurements, it is important to capture these small flame volumes that are moving upwards. If the exposure time is low, these small flame volumes may not be captured, but if it is high, the image may be saturated. Thus, a compromise value have to be found.

3.2.3. ISO Sensitivity

The last parameter is the ISO sensitivity (or ISO number). In photography, ISO number determines how sensitive the sensor camera is to incoming light. It is analogous to the film sensitivity in traditional cameras. In digital cameras, the sensitivity depends on the kind of sensor (CMOS or CCD). Both work similarly, converting the light into electrons. The difference is how the sensitivity is adjusted, producing in some cases different quality of images with the same photography parameters. Usually, the higher ISO number the higher is the sensitivity and less light is required to produce an image.

3.2.4. Photography parameters and flame images

Previous examinations performed for a flame of high luminosity show that the first parameter to be defined is the ISO number. This is so, because it affects only the image saturation and can be used to produce a slight adjustment according to the variation of light coming from the flames. Hence, the ISO number was initially set to 3200, the middle value of the camera range.

A particular characteristic of turbulent jet diffusion flames is the liftoff of the base of the flame from a certain level of the volumetric flow rate. In these flames, the lower region has a bluish color and the downstream region has a yellowish luminosity from soot particles. With the increase of the volumetric flow rate, the proportion between the two regions changes and the total luminosity too. To avoid the excess of light, the ISO number was adjusted to 1600 for flames with high luminosity and to 6400 for flames with low luminosity.

The choice of the ISO number, within the above range, was found to slight affect the measurements of L_F , with maximum differences of 5%. For large changes of the ISO number, a new configuration of exposure time and aperture must be obtained, as will be discussed.

For the other two parameters, the Figure 2 presents the variation of the exposure time and aperture for an ISO number of 3200. It shows that some regions of the flame were not visualized in the image by the decrease of exposure time and by the increase of F-number. These low intensity images are concentrated in the bottom right corner of the figure. The opposite happens at the top left corner, where saturated images are formed due to large apertures and exposure times.

The combination of parameters to be used depend on the type of picture (instantaneous or integrated) and the flame luminosity. There is no single set of parameters that is able to give good pictures for all flames and different sets may result in equivalent flame pictures.

In this study, an instantaneous photograph of a turbulent flame is considered to be an image of the flame with sharp boundaries captured with the lower possible exposure time. An average photograph of a turbulent flame is an image of the flame captured with the longer exposure time possible without being saturated at the boundaries.

It is easy to see that two different combinations can result in similar images. For example, the one with exposure time equal to 1/125 s and aperture F11 and the other with exposure time equal to 1/320 s and aperture F3.5 are very similar. In this case, since we are interested in obtaining an instantaneous image, the criterion for selection was, arbitrarily, to use the lower possible exposure time.

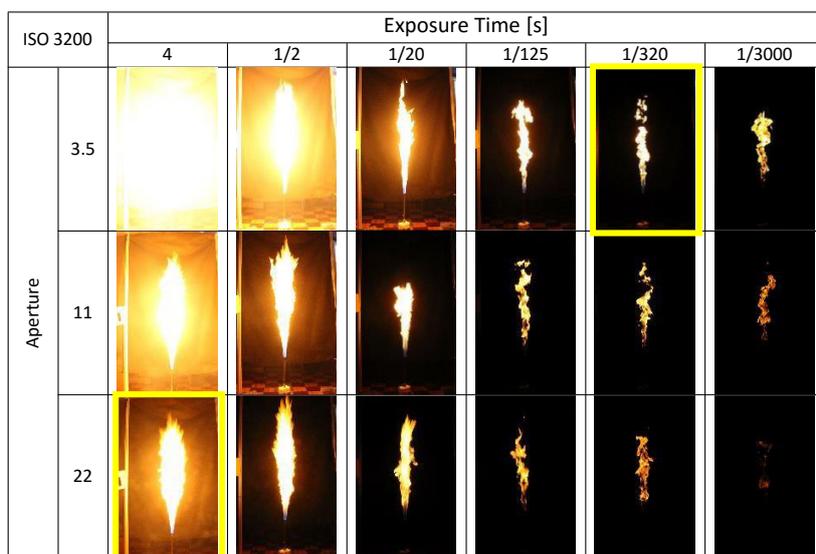


Figure 2. Variation of the exposure time and F-number (or aperture) for a constant ISO number using flames of NG. Volumetric flow 30 l/min. Focal distance in 2,45 m. Resolution: 15 Mpx.

3.3. Methods to measure the flame length

In the literature, it is possible to find several methods to measure the flame length. Here we will explore two methods described in the literature and a third method that is new.

In the first method, the visual flame length is computed by the average of a great number of instantaneous flame images, captured with low exposure time. In the second method, the visual flame length is computed by the average of few measurements of long exposure time flame images.

Finally, a third method is based on the analysis of image counts, a parameter that is related to the luminous intensity of each pixel.

3.3.1. Flame length measurement by short exposure time images, MSE

In the first measurement method, the L_F is the average of n_1 measurements of $L_{F,i}$ in images captured with low exposure time (MSE). In this method, each individual length is defined as the distance between the burner exit plane and the tip of the flame, from an image with exposure time of 1/320 s and aperture of F3.5.

Using the software Matlab®, a technique of images process was developed. First, the algorithm converts colored to gray scale images. Then, the output image is converted to a binary image; setting the value 1 (white) to pixels with luminance greater than a *predefined level*, and replacing all other pixels with the value 0 (black).

Then each region with circumscribed boundaries (flame pocket) is identified and their properties are evaluated: area, centroid and bounding box. After that, the requested points of interest: the highest and lowest point in a Cartesian coordinate system are used to compute the individual flame length $L_{F,i}$. Figure 3-b shows the final result of an instantaneous image. To guarantee the correct location of the exit burner, it was marked with the light of a laser pointer.

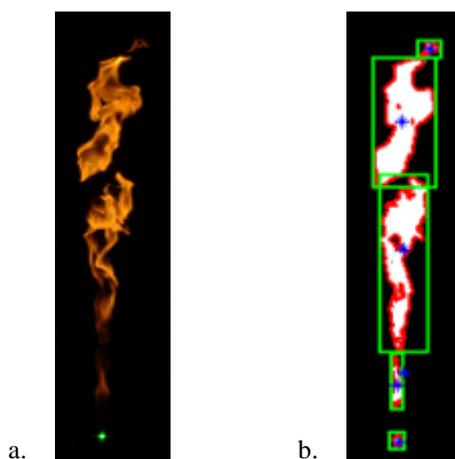


Figure 3. Measurement process of VFL from an instantaneous image of a flame of 30 l/min. Volumetric flow rate 30 l/min. t_{exp} : 1/320 s and aperture F3.5. Focal distance in 2,45 m. Resolution: 15 Mpx. ISO 3200

As mentioned, the liftoff of the flames can be also computed by this technique. Visual observations showed that the brightness at the base of the flame is quite weak in contrast with the principal flame volume. To measure this distance it is necessary to perform another measurement, focusing only on the base of the flame and thus reducing the excess of light. Figure 4 shows the measurement process of the lift off for a turbulent diffusion flame.

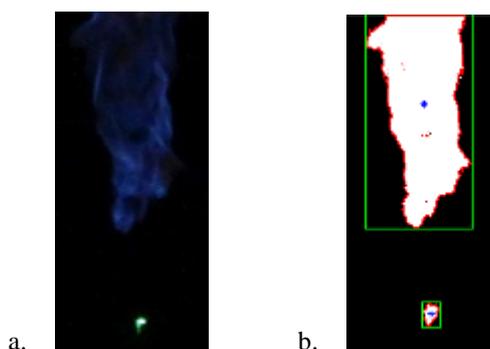


Figure 4. Measurement process of the base of the flame. Volumetric flow rate 30 l/min. t_{exp} : 1/320 s and aperture F3.5. Focal distance in 2,45 m. Resolution: 15 Mpx. ISO 3200

3.3.2. Flame length measurement by large exposure time images, MLE

The second measurement method, the L_F is the average of n_2 measurements of $L_{F,i}$ in images captured with large exposure time (MLE). Here, each individual length is defined as the distance between the burner exit plane and the middle point of the region of flame intermittency, $L_{F,i} = (L_{f,1} - L_{f,2})/2$, where $L_{f,1}$ is the upper limit of the flame (fading brightness region) and $L_{f,2}$ is the lower limit of the flame (region of intense brightness). Each image is captured with an exposure time of 3 s and aperture of F22.

The measurement process for this method was not performed digitally. To measure this kind of images is necessary to invert the colors of the picture with the aim having higher contrast between the required limits. The Figure 5-b shows a sample of a flame image with the inverted colors. The black region corresponds to the region with intense brightness. This technique helped in the identification of the measured points and to reduce the uncertainty of the measurement.

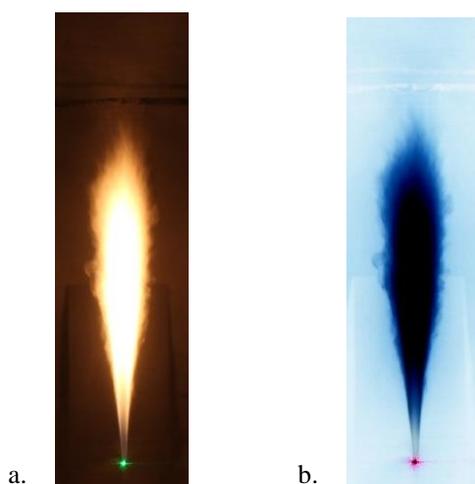


Figure 5. Measurement process converting from the color to inverted color images. Volumetric flow rate 30 l/min. Exposure time 3 s and aperture F22. Focal distance in 2,45 m. Resolution: 15 Mpx

3.3.3. Flame length measurement by image frequency analysis, MFE

The third measurement method is showed in Figure 6 in comparison to the other two. This method uses the software Davis 8.2® to determinate L_F . It is a commercial software that associates a scale of counts with the frequency with which the flame images are in a determined region. It counts the times that a region of flame occupies a pixel of a total of n_3 images. The visual flame length is defined as the distance between the burner exit plane and the middle point of the tips of the regions with low and high flame realization (1% and 99% of the images respectively), $L_F = (L_{f,0.01} - L_{f,0.99})/2$. The method uses images with short exposure time with the same photography parameters as first method.

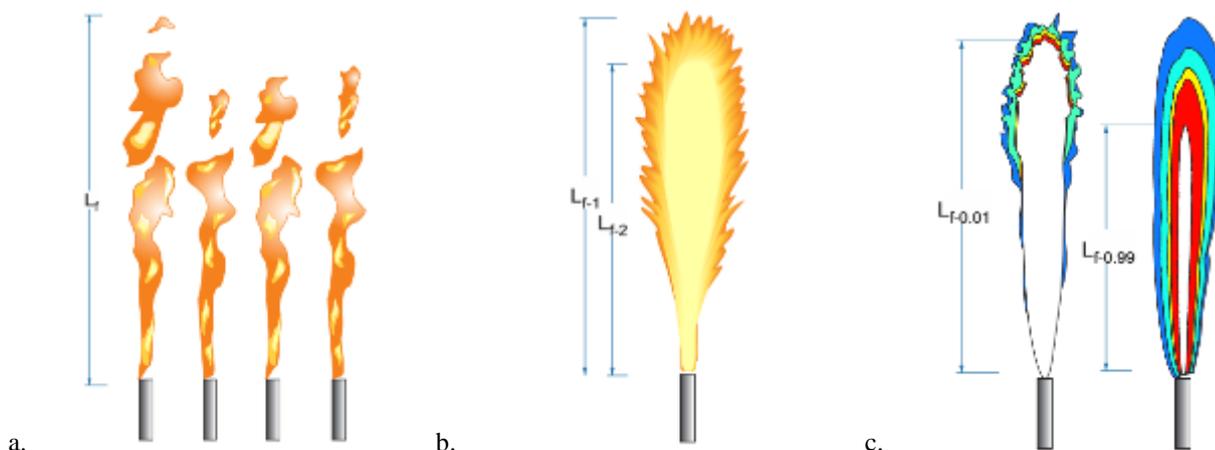


Figure 6. Measurement scheme. a. From instantaneous image. b. From average image c. From frequency image

Figure 7-a presents an image of a flame of 30 l/min, which shows the white area representing the region with frequency of 0.01 equivalent to a minimal of three occurrences of flame. Regions colored are sections of the flames

with less than three occurrences. Figure 7-b shows the same flame, but now the white area represents the intensity of 0.99, equivalent to a minimal of 297 occurrences of flame.

The advantage of this software is its ability to capture many pictures with low processing cost; therefore, the number of images could be more than those used in the MSE method. The software determines pixel by pixel the average and standard deviation of the flame intensity (given in a generic unity).

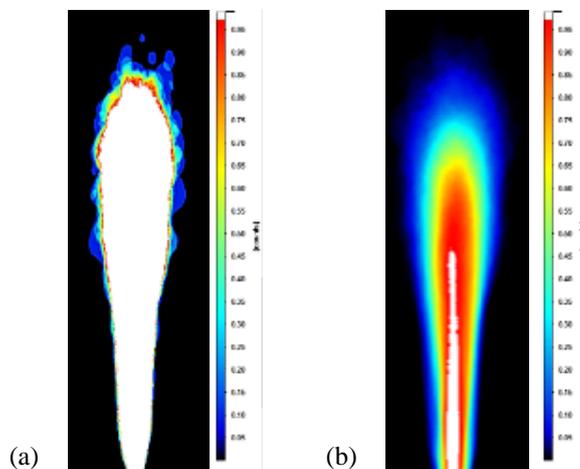


Figure 7. Color mapping of a turbulent flame of 30 l/min. a. Color mapping with intensity of 0.99 b. Color mapping with intensity of 0.01

3.3.4. Discrepancy due to variation of photographic parameters

¡Error! No se encuentra el origen de la referencia. shows measurements of L_F within the limits of low exposure time performed for a flame of 80 l/min, which presents high brightness. The method used to obtain L_F was the average of instantaneous images (MSE). For an easy interpretation, a new variable is defined, $*L_F$, as the normalized flame length relative to the smaller exposure time results ($t_{exp}=1/320$ s). The visual flame length values denote an increment of 6% for the highest exposure time used here, for which the image was still considered to be instantaneous. For an exposure time lower than 1/2000 s, the images are similar and could be used when the brightness of the flame is high.

Table 1. Influence of exposure time in the VFL, using instantaneous images. Volumetric flow rate 80 l/min. Aperture F3.5. Focal distance in 2,45 m. Resolution: 15 Mpx. ISO 3200.

t_{exp} (s)	L_F (mm)	$*L_F$
1/20	1312,5	1,06
1/40	1290,8	1,05
1/80	1277,7	1,04
1/125	1241	1,01
1/320	1233,3	1,00
1/2000	1230,1	1,00

In the Table 2, experimental evaluations of the photography parameters of the second measurement method showed small variation on the visual flame length, where only the ISO number was constant. With the variation of the exposure time between 0.5 to 10 s, the maximum discrepancy was 4.6 % in respect to the minimal value. With the variation of the aperture to F11, the flame images were quickly saturated hindering the measurements.

Table 2. Influence of exposure time in the VFL, using instantaneous images. Volumetric flow rate 80 l/min. Aperture F22. Focal distance in 2,45 m. Resolution: 15 Mpx. ISO 3200

t_{exp} (s)	$L_{F,1}$ (mm)	$L_{F,2}$ (mm)	$L_{F,3}$ (mm)	L_F (mm) Average	Relative variation
10	1487.9	1539.8	1519.0	1515.6	0.0415
6	1530.6	1535.8	1502.3	1522.9	0.0465
4	1535.2	1527.7	1506.3	1523.1	0.0466
2	1446.9	1444.0	1461.3	1450.8	0.0030
1	1355.2	1427.3	1375.4	1386.0	0.0476
0.5	1414.0	1474.0	1477.5	1455.2	0.0000

Finally, the minimal number of pictures is evaluated. Figure 8 shows the L_F as a function of the number of pictures. It demonstrates that the measurement by images with low exposure time requires a minimal of 200 images and for measurements by images with high exposure time require 8 images. How was mentioned, the method by image intensity analysis has the capacity to capture a great number of pictures with low cost of operation process, thus for this technique the minimal number used is of 300 images.

The standard error of the mean (SEM) was computed to compare the variation of the uncertainty in the measurement of L_F . The SEM estimates the variability among sample means, when it was taken from multiple samples from the same population. In contrast, the standard deviation measures the variability within a single sample. The SEM is usually computed by the standard deviation divided by the square root of the sample size. Therefore, it is easy to predict that the error will reduce with the increment of the sample size.

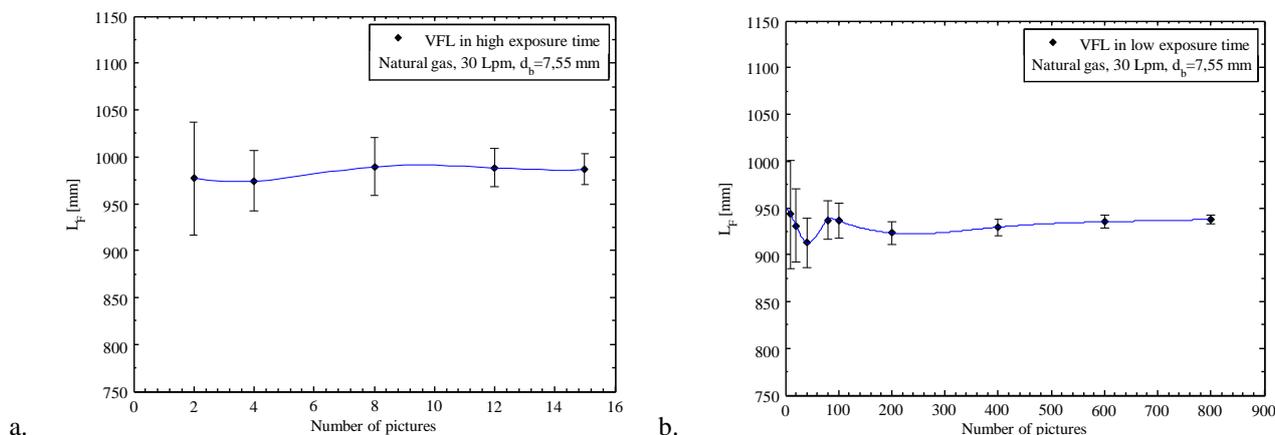


Figure 8. Variation of the VFL in function of the number of used pictures. a. VFL obtained on images with high exposure time. b. VFL obtained on images with low exposure time

4. RESULTS AND DISCUSSION

Figure 9 shows several turbulent flames measured by the three methods. The results are plotted in function of Reynolds number based on the burner diameter, $Re = ud_b/v$, where, u is the mean average velocity of the flow at the exit burner, d_b is the burner diameter and v is the kinematic viscosity.

The instantaneous image is the method less affected by the photographic parameters but needs a dark ambient to obtain reliable pictures. It is easier to determinate the individual flame length since it only needs to find the maximum point in each image. Other characteristic is the extra information obtained as the variation of the peak of the flame is related to the flame intermittency. The disadvantage is the large number of images required to obtain the average and the need of a specialized software to process them.

The measurement by integrated images is the most affected method by the photography parameters due to the quantity of light reaching the CCD sensor and thus, frequency producing an incorrect image (saturated). The advantage of this method is the reduced time required to compute the L_F . A principal disadvantage is the determination of $L_{f,2}$ because it depends on the definition of a boundary for which the light intensity is considered too low. In contrast to MSE method, it presents more uncertainty.

Several tests were performed with a repeatability of 3 times in each experiment, and usually, the two methods showed L_F values with a maximum difference of 10%. The MSE method is considered as the most reliable method due to its lower uncertainty.

The method of image intensity analysis is the method with more discrepancies. It was observed that L_F is lower than in MLE method, because the points $L_{f-0,01}$ and $L_{f-0,99}$ are dependent on the frequency of the flame occupying a specific region. The probability of obtaining a region with the 99% of the flames is low, thus, in some cases $L_{f-0,99}$ was reduced to $L_{f-0,70}$, producing a lower value of L_F .

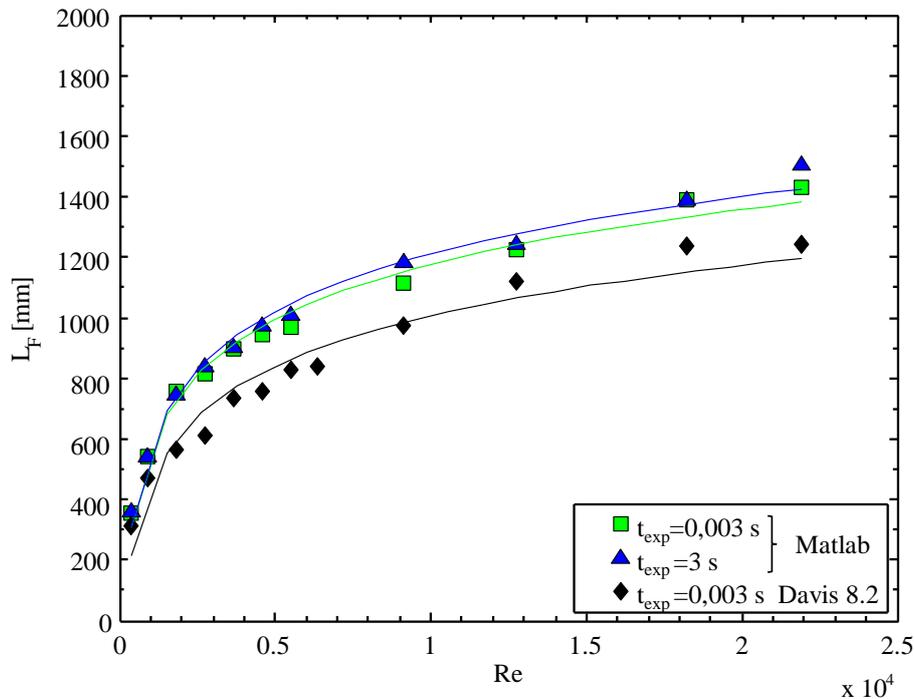


Figure 9. Progressive change of VFL with the increasing of Reynolds Number, analyzed from three measurement methods. Experimental data with Natural Gas as fuel.

Figure 10-a shows the experimental data of visual flame length obtained by the MSE method. For pure GN flames, the main characteristic is the increase of L_F in function of Reynolds number up to $Re=22500$ for a diameter $d_b=7,55$ mm. From $Re=22500$ to $Re=40165$ the L_F is approximately constant until their blowout was reached. The same qualitative behavior of visual flame length is found for flames diluted with CO_2 . For diluted flames, the visual flame length is lower and their blowout values are reached earlier compared to pure GN flames. Lower values of L_F are expected since there is less fuel in the mixture. The lower blowout limit is also expected since this limit is defined by a balance between the flow velocity at the flame base and the burning velocity in the same position (a premixed condition is reached due to air entrainment when the flame is lifted). Thus, since dilution with CO_2 decreases the burning velocity, the blowout limit is reached earlier.

Figure 10-b shows the average flame length L_F and its standard deviation for pure GN flames. Through the MSE method, it was possible to observe that the flame length fluctuations initially increase with Re and reach an equilibrium value in the asymptotic region. When the values of L_F are plotted in a frequency graph (not shown here), a normal distribution is obtained. Thus, the fluctuations of the flame length could be statistically related with the standard deviation. With a bilateral confidence interval of 95 % it was observed that the fluctuations are equivalent to 40 % of L_F in all cases.

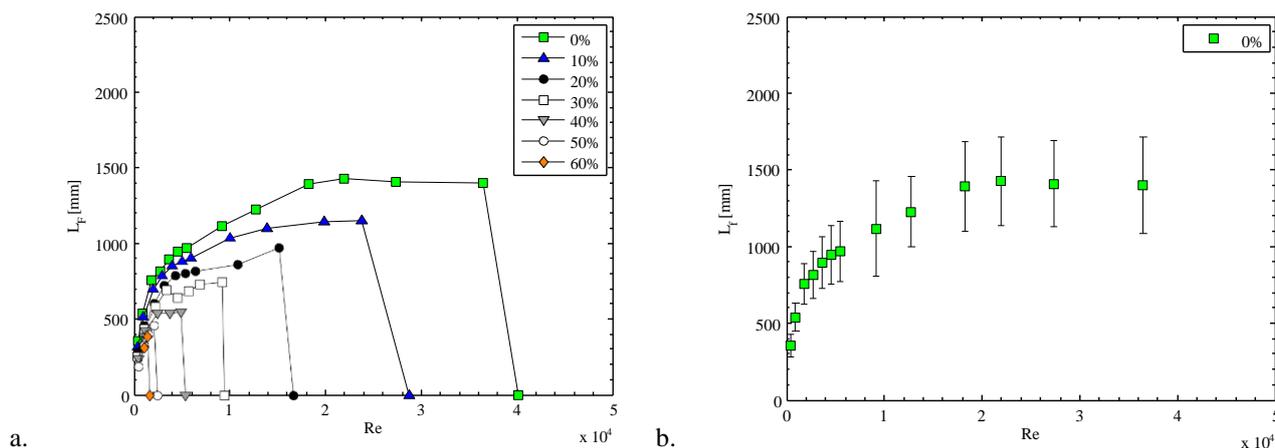


Figure 10. Progressive change of visual flame length with the increasing of Reynolds Number. a. Experimental data with Natural Gas as fuel diluted with CO_2 . b. Variation of L_F equivalent to 2σ

5. CONCLUSIONS

Three methods for measuring the visual flame length were studied and compared in this work: one method based on instantaneous images (MSE), one based in integrated images (MLE) and a method based on the analysis of pixel intensity.

The MSE is the method with smaller uncertainty, due to the larger number of pictures used to compute the average flame length. This method requires a high quality of instantaneous images, and thus, photographic parameters were explored and best choices are reported. The method was also able to define the flame tip statistical behavior.

The MLE method is a useful method to quickly estimate the flame average length. The experimental data showed a good estimation of the VFL, but it was necessary to have a reference VFL to calibrate the exposure time, aperture and ISO. Without these values, this method tends to give higher VFL values.

The frequency method was less suitable to compute the VFL. The flame variations brings the points of interest in the vertical axis to lower positions and thus, gives a smaller L_F than the other methods.

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