IMAGE PROCESSING OF INSTABILITIES IN DIFFUSION FLAMES PRODUCED BY ATOMIZATION OF FUEL OILS

Carlos Antonio Montalbán Caillaux, carlos.caillaux@poli.usp.br
Guenther Carlos Krieger Filho, guenther@usp.br
Natália Bernardi Ghisi, natalia.ghisi@poli.usp.br
Escola Politécnica da USP - Avenida Prof. Luciano Gualberto, travessa 3, 380 - CEP - 05508-900 - São Paulo - SP

Francisco Domingues Alves de Sousa, fdasousa@ipt.br
Instituto de Pesquisas Tecnológicas do Estado de São Paulo - Av. Prof. Almeida Prado 532 Cid. Universitaria. 05508-901 São Paulo - SP

Abstract. *The complex phenomenon of instabilities in fuel oil flames was studied experimentally in the present work. As indicators of stability limit, phenomenological observations, images produced by CCD cameras with interference filters and measurements of ultraviolet radiation intensity using an ultraviolet flame detector were used. The main objective of this work is to find out correlations between the flame stability and the following parameters: a) the ratio between the atomization steam flow rate and the fuel oil flow rate; b) the ratio between the primary air flow rate and the secondary air flow rate. The partial results obtained so far have shown strong influence of the primary air flow rate and the atomization steam flow rate on the flame stability. The use of values beyond the stable range can lead to blowout. With the stable limits identified at the present work, one can operate the investigated fuel oil burners more efficiently.*

Keywords: *Stabilization, blowout, burner.*

1. INTRODUCTION

Until the end of the twentieth century the criteria for sizing industrial burners were apparently well established by the constructors, under the point of view of the atomization nozzle and the air supplying velocities at the burner port. However, due to the increasing use of heavier fuel oils, in the three last decades, and the necessity of reduction of pollutant emissions (particulate material, CO and NO_x), such criteria will need to be reviewed. As far as NO_x emissions are concerned, the trend today is to use more than one air flux (primary, secondary and some times tertiary) supplied with low speeds or, in other words, with lesser momentum and, generally, with greater radial distances of the spray. With regard to CO and particulate material emissions, the trend it is to increase the efficiency of the atomization devices. The most immediate method to reduce the average droplet diameter in devices that use auxiliary atomization fluids, compressed air or steam, is to increase the ratio between atomization fluid and fuel oil (RAL). In fact, experiments performed in spray test devices, shown that the increase of the parameter RAL reduces the average diameter of the droplets, what within some limits, reduces the emission rates of pollutants.

However, when the value of the ratio RAL is already high, further increase causes only small reductions of the average diameter, ie., the curve of the average diameter of droplets is asymptotic to the axis "atomization fluid/fuel oil - RAL". This can produce flame instabilities, leading to its complete blowout. A number of important physical parameters are expected to influence the flame characteristics in a burner close to blowout condition. To understand the basic mechanism of flame stabilization and blowout at a fundamental level, the problem of a diffusion flame formed by a fuel jet in an oxidizing atmosphere has been studied (Lee and Chung, 1997) and stands out as an useful model in a simple geometry. Three distinct mechanisms have been proposed regarding the blowout of turbulent diffusion flames:1) premixed flame propagation, 2) large scale mixing and 3) flame instability.

Early investigators, such as Vanquickenborne et al. (1966) and Kalghatgi (1981), proposed expressions for blowout velocity based on premixed flame considerations, suggesting that blowout occurs when the local reactant flow velocity exceeds the maximum premixed turbulent burning velocity. These predictions showed qualitative agreement with measurements for most hydrocarbon fuel mixtures.

In a laminar jet diffusion flame, if the mass flow rate exceeds a critical value, the base of the diffusion flame lifts off from the burner tip and remains suspended at a certain distance above the burner. This phenomenon is known as "lift-off" or "blow-off". A further increase in the mass flow rate of the jet causes the lift-off height to increase until the base of the diffusion flame approaches the flame tip at which point the flame blows out. If the flame extinguishes directly from the burner tip without a stable lifted position, the phenomenon is called "blowout". Hysteresis effects are seen, that is, flame lift-off and reattachment do not happen at the same value of the mass flow rate. However, blowout always occurs at a fixed mass flow rate for a given fuel in the burner. Near blowout conditions, a complex time-dependent behavior is observed where the flame jumps back and forth between the lifted and attached configurations.

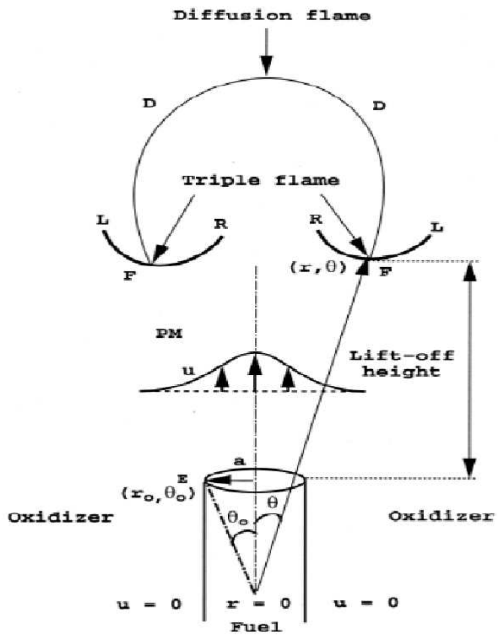


Figure 1. Schematic of the triple flame in a laminar lifted diffusion flame over a round jet (Ghosal and Vervisch, 2001).

The lifted diffusion flame is stabilized by a triple flame in the far field of the jet. Triple flames (Figure 1), observed by Chung (2006), are a characteristic flame structure that appears in partially premixed flames. The fuel and oxidizer undergo partial premixing in the zone "PM". The mixture then burns in two branches, the fuel rich branch, "FR" and the fuel lean branch "FL". Behind these two flame zones the hot streams of unburned fuel and oxidizer come together and burn as a trailing diffusion flame, "DF" along the stoichiometric surface. The structure consisting of the three branches FR, FL and DF is collectively known as the triple flame. The triple flame has a characteristic propagation speed determined by the local environment. The flame is stabilized at the point where the flame propagation speed with respect to the fuel/oxidizer matches the flow speed on the stoichiometric line.

Broadwell et al., (1994) suggest an alternate theory for explaining blowout based on Large Scale Mixing. They suggest that flame stabilization occurs when hot gases, which have been expelled to the edge of the jet by earlier large scale turbulent structures, are reentrained and ignite fresh mixture eddies within the jet. If the mixing time of the reentrained gases is too short, the gases cool down rapidly and ignition becomes impossible, leading to blowout. Thus, blowout takes place when the reaction time cannot keep pace with changes in mixing time. Experimental laser imaging by Muniz and Mungal, (1997) provides support for the role of the large-scale structures in the flame stabilization and extinction processes.

Recently, a flame-front instability model (Chao et al., 2000) has also been proposed to explain blowout, which states that intrinsic flame-front instability causes pulsations and plays a role in leading to the blowout. To conclude can be said that although premixed flame concepts can explain most aspects of blowout in diffusion flames, recent works suggest that coherent structures, high strain rates, heat losses and entrainment play an important role in the flame stability.

The flame, as it approaches blowout from a statically stable operating condition, exhibits enhanced unsteadiness. Often, temporary flame losses and re-ignitions are also seen close to blowout. These result in global and local changes in heat release rates in the combustion zone, producing chemiluminescence and radiation emissions, in addition to the change in flame temperatures. Such emissions can be detected by readily available sensors and can be used to characterize the blowout process in a combustor. Some researchers have found such unsteady flame dynamics in combustors prior to blowout. Roquemore et al. (1991) observed longitudinal oscillations in a non-premixed, gas turbine combustor simulator just prior to blowout. They found the flame to lift off from the base of the combustor as equivalence ratio was reduced to near blowout values. This was one of the earliest flame dynamics observed in a realistic engine. Venkataraman et al. (1999) conducted a parametric study to investigate combustion stability in a coaxial, premixed bluffbody- stabilized dump combustor. Using CH^* chemiluminescence images, they were able to capture repeated detaching and reattaching of the flame from the centerbody close to blowout. De Zilwa et al. (2000) similarly investigated flame dynamics close to blowout in dump stabilized combustors with and without swirl. They noticed very low frequency (around 3-12 Hz) oscillations as the blowout was approached.

The main objective of the present work is to find out correlations between the flame stability and the following parameters: a) the ratio between the atomization steam flow rate and the fuel oil flow rate; b) the ratio between the primary air flow rate and the secondary air flow rate. In order to investigate the stability map of a specific oil burner, an experimental setup was built and measurements were carried out, as explained in the following sections.

2. EXPERIMENTAL SETUP

The experimental setup used in this work is shown schematically in Figure 2. This study employed one 800 - 900 kW dual-fuel burner, showed in Figure 3, provided of an oil gun with a nozzle fuel injector 31.8 mm in diameter and 50° degree angle between sprays. The furnace has inlet diameter $1.45\ m$ and height of $4.0\ m$ in which the burner is connected.

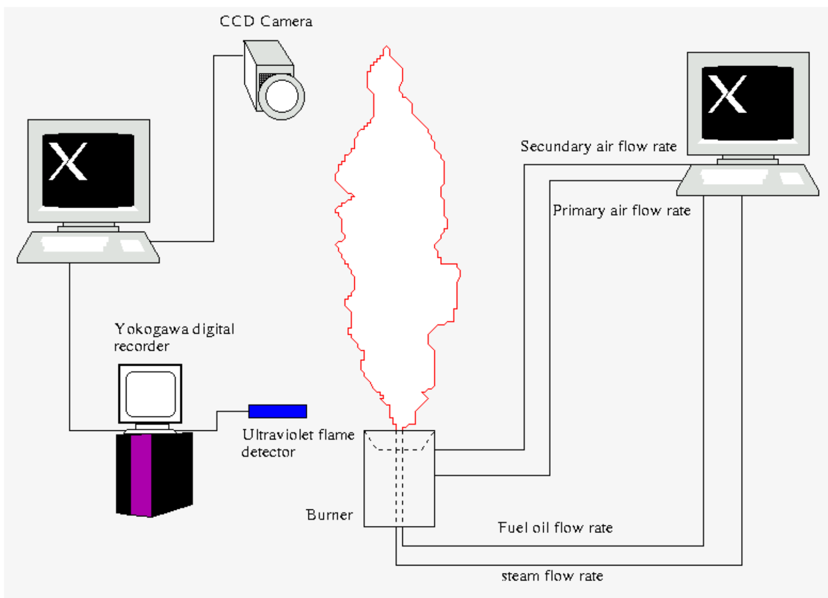


Figure 2. Experimental setup.

An optical set composed by interference filter ($800\ nm$), made by Corion, a pinhole zoom lens with manual adjustments for focus, type $V - ZLP12$, made by Marshall and monochromatic CCD camera, type $V - 1070$, made by Marshall were used. This set was lodged into a cooled device as shown in figure 4 and is composed by: a set of wires for the camera power supply and for the signal conduction from it up to the acquisition board which was installed into the computer, the frame acquisition and dispatching board, made by Coreco Imaging.

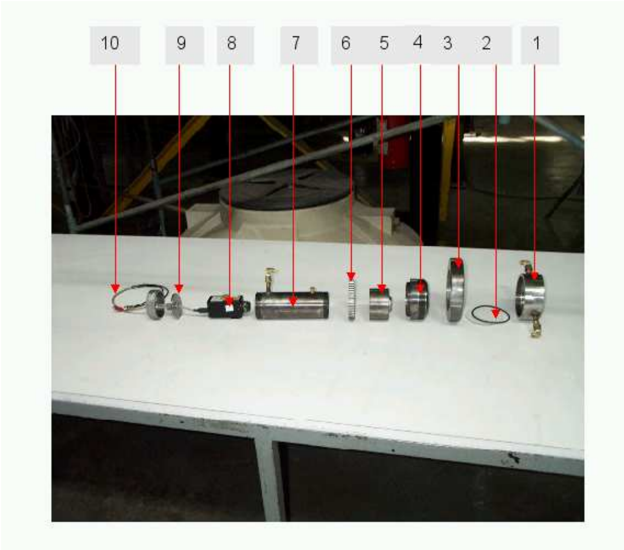
A in house developed computer program for automatic visual inspection, called SCIVA, developed by IPT, provided with a large tool menu for acquisition, storage in BITMAP file and treatment of images was used to image processing. Additionally an ultraviolet flame detector, made by Honeywell, model $C7027A1049$, in series to an impedance, connected to a Yokogawa digital recorder - scale $0 - 6\ V$ with data register frequency $1\ Hz$ were used for monitoring UV radiation intensities emitted by the near nozzle flame region.

During the tests the following variables had been monitored and stored in electronic files: fuel oil flow rate, fuel oil inlet temperature to the burner, water flow rate, steam flow rate, used as atomization fluid, oxygen content in the chimney gases, measured by continuous analyzer. The fuel oil used was $1B$ type, viscosity $1334\ cST\ @\ 50°C$, density $1.01\ g/cm^3\ @\ 50°C$ and higher heating value $41.9\ MJ/kg$.

The table 1 shows the parameters of tests performed in the present work. For all this cases, the oxygen mole fraction at the exit of the furnace was 3%. All data of mass flow rate (Q) are given in Kg/h. The results shown in this work were acquired for a fixed fuel oil mass flow rate of $60\ kg/h$. Therefore, the overall equivalence ratio of the burner was kept constant. The case 1 is the baseline for the evaluation of the flame stability. This case represents the normal and safety operational condition of the burner. The other cases were investigated in order to find out the extreme conditions of the burner, without blow out.

The image processing was based on the concept of gray tons. A gray scale digital image is an image in which the value of each pixel is a single sample. Displayed images of this sort are typically composed of tons of gray, varying from

Figure 3. Dual-fuel burner whit its oil gun.



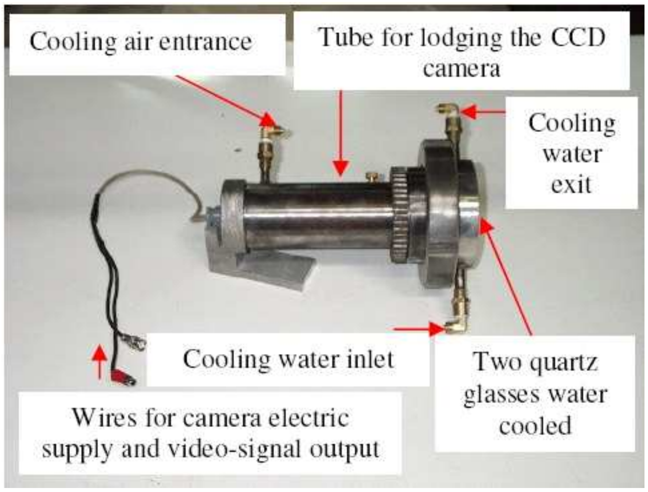


Figure 4. Exploded view of the optical set, 1) hatchway for lodging quartz glasses 2) quartz glasses and tighting ring 3) screw-nut for fixing the hatchway to the furnace wall 4) device for tighting the quartz glasses 5) device for lodging the interference filter 6) screw-nut for fixing the camera tube lodging to the hatchway 7) camera tube-lodging 8) CCD camera 9) optical set rear-closing device 10) wires for electrical camera supply and signal output.

black at the weakest intensity to white at the strongest, though in principle the samples could be displayed as tons of any color, or even coded with various colors for different intensities. Gray scale images are distinct from black-and-white images, which in the context of computer imaging are images with only two colors, black and white; grayscale images have many tons of gray in between. Gray scale images are often the result of measuring the intensity of light at each pixel in a single band of the electromagnetic spectrum (for example visible light). Gray scale images intended for visual display are typically stored with 8 bits per sampled pixel, which allows 256 intensities that is tons of gray (see Figure 5), to be recorded, typically on a non-linear scale. The accuracy provided by this format is barely sufficient to avoid visible banding artifacts, but very convenient for programming (Russ, 2006).

The histogram is an important tool for image analysis, which plots the number of pixels as a function of their brightness values. The histogram is well spread out over the available 256 brightness levels. Many images do not have a brightness range that covers the full dynamic range of the digitizer. The result is an image whose histogram covers only a portion of the available values for storage or for display.

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Table 1. Operating conditions of the investigated cases.

Case	$Q_{primary\ air}$ $[kg/h]$	$Q_{secondary\ air}$ $[kg/h]$	Q_{steam} $[kg/h]$
1	500	500	20.13
2	500	500	37.35
3	500	500	3.02
4	600	400	20.92
5	600	400	24
6	600	400	7.83
7	400	600	20.57
8	400	600	37.74
9	400	600	2.34

Figure 5. Gray scale with 256 gray tons

3. RESULTS AND DISCUSSION

As said above, the baseline operational conditions for the studied burner were: $20\ kg/h$ of atomizing steam to $60\ kg/h$ of fuel oil, $500\ kg/h$ of primary air mass flow rate and $500\ kg/h$ of secondary air mass flow rate (Case 1). For this condition, 3% oxygen content in the chimney gases was obtained. Figure 6 shows the output signal of the flame detector for the Case 1. The average value of the tension is $1.0328\ V$ and its variance is 0.13408.

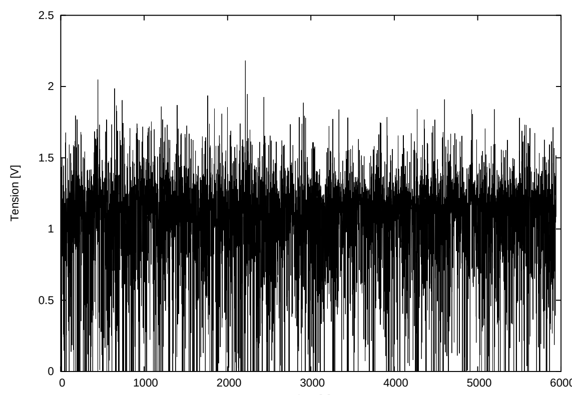


Figure 6. flame detector tension for the baseline operation condition - Case 1.

In figure 7, where the atomizing steam flow rate is increased to $37.35\ kg/h$ (Case 2), it is observed that the average value (Table 2) of tension of the flame detector diminished to $0.80181\ V$ and the value of the variance increased to 0.37473.

When the atomizing steam flow rate is reduced to $3.02\ kg/h$ (Case 3), the average tension value is $0.1390\ V$ (Figure 8) and the variance is 0.24352.

For all operating condition 50 instantaneous images were taken from the flame at intervals of 2 minutes each one ($8.33\ mHz$). Each image is composed of 307200 very small areas, called "pixels", distributed in 480 lines and 640 columns. From these images the histogram area of gray tones was obtained and used as indicator of flame instability. In the Figure 9 one can observe the variation of the histogram areas, for each image. For this first condition (baseline case), the average value of these areas is $3761\ pixels$ and the difference between the maximum and minimum value is $1361\ pixels$.

For the operating condition 2, the mass flow rate of steam is increased to $37.35\ kg/h$ with a pressure of $4.85\ kgf/cm^2$. For this condition the values of the histogram areas are shown in the Figure 10, the average value of these areas is $3185.3\ pixels$ and the difference between the maximum and minimum value is $873\ pixels$. The output signal of the flame detector for this operating condition is shown in Figure 7. The average value of the tension is $0.80181\ V$ and the variance is $0.37473\ V$.

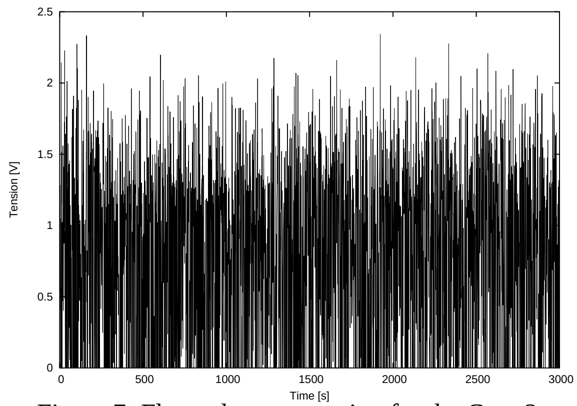


Figure 7. Flame detector tension for the Case 2.

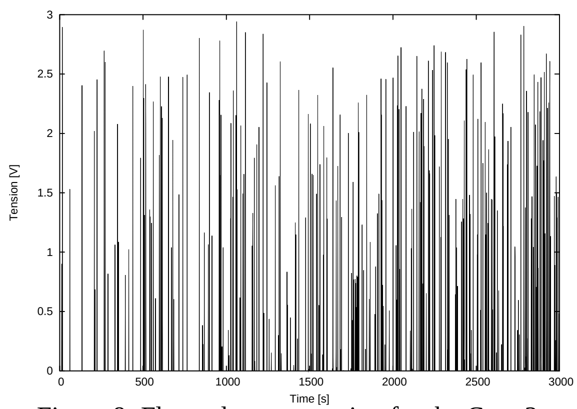


Figure 8. Flame detector tension for the Case 3.

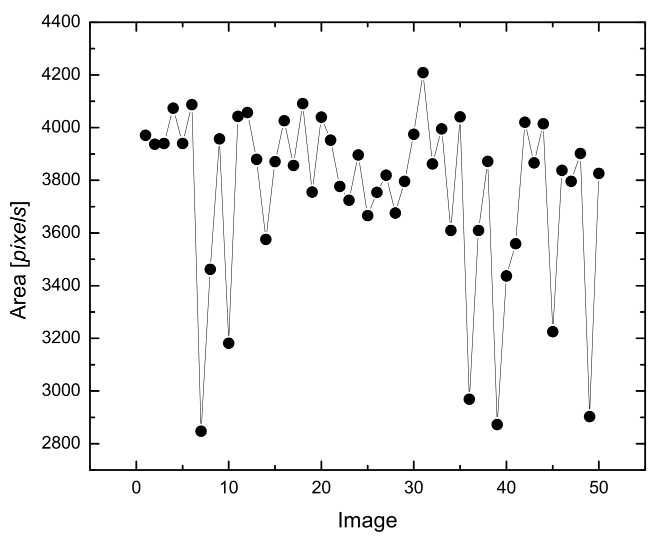


Figure 9. Histogram areas of gray tons for the condition $500\ kg/h$ of primary air mass flow rate and $500\ kg/h$ secondary air mass flow rate, $20.13\ kg/h$ steam mass flow rate.

For the Case 3, the steam mass flow rate is decreased to $3.02\ kg/h$ with a pressure of $0.9\ kgf/cm^2$. Figure 11 shows the values of the histogram areas, in which the average value is $2809.3\ pixels$ and the difference between the maximum and minimum value is $687\ pixels$. Figure 8 shows the output signal of the flame detector, the average value is $0.1390\ V$ and the variance is 0.24352.

From these results one can see that the tension values of the flame detector vary with the appearance of the events that lead to blowout. The variance was the statistical tool that shows greater sensibility to the changes of condition in the

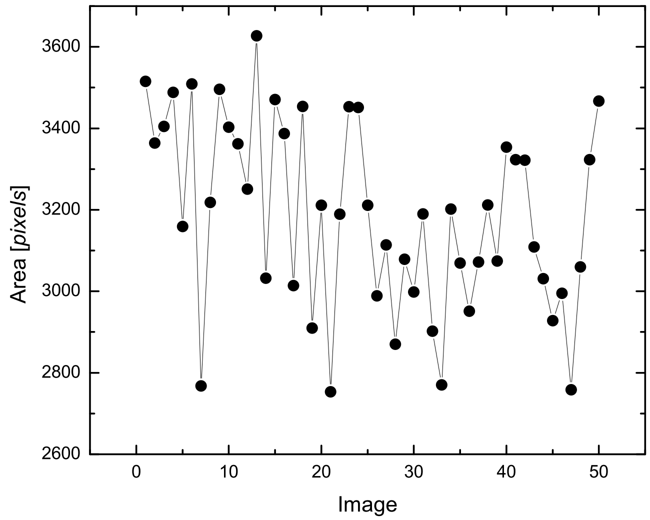


Figure 10. Histogram areas of gray tons for the condition $500\ kg/h$ of primary air mass flow rate and $500\ kg/h$ secondary air mass flow rate, $37.35\ kg/h$ steam mass flow rate.

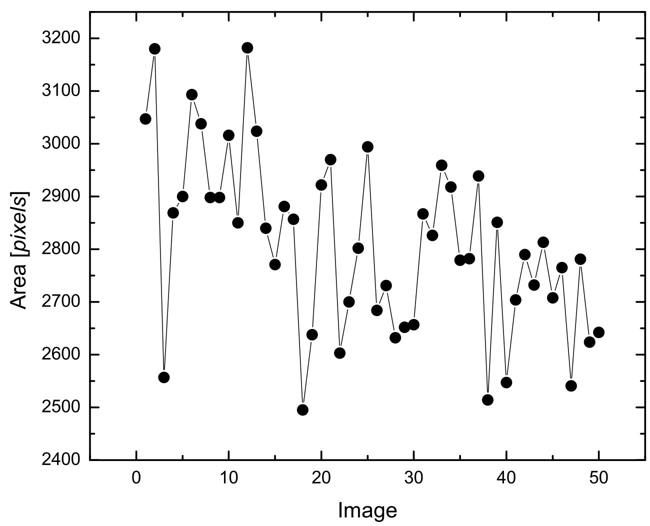


Figure 11. Histogram areas of gray tons for the condition $500\ kg/h$ of primary air mass flow rate and $500\ kg/h$ secondary air mass flow rate, $3.02\ kg/h$ steam mass flow rate.

vicinity of these events. Figure 12 shows the variance values for these three operating conditions.
Figure 12 shows the tendency of the variance when the flame begins to behave instable. The Case 1 it is a "stable" operating condition and shows the lower value of the variance, meanwhile the variation in the steam mass flow rate make increase this value. Same behavior can be observed for the other cases, with exception of the case 6 in which one the value of the tension was 0 therefore the variance also will be 0.

Figure 13 shows how the average histogram areas of gray tons varies. In this figure it is possible to observe that the mean value of the histogram areas, for the Case 1, is the greatest if compared to the mean value for the Cases 2 and 3. This behavior is visible comparing the images taken from the flame is these conditions, see figure 3.

The experimental results for the investigated cases are summarized in the Table 2. The influence of the air supply on the stability of the flame was investigated in the Cases 4 to 9. For the Cases 4 to 6, where the primary air flow rate was increased, limits of the steam flow rate both higher and lower were narrowed. This can be reinforced by the results for mean valuer of the flame detector tension and mean value of the histogram areas of gray tons, which were both decreased. The Cases 7 to 9, where the primary air flow rate was diminished and the secondary air was increased, no flame blow out was observed. With these results, it can be concluded that the information contained in the flame detector tension and in

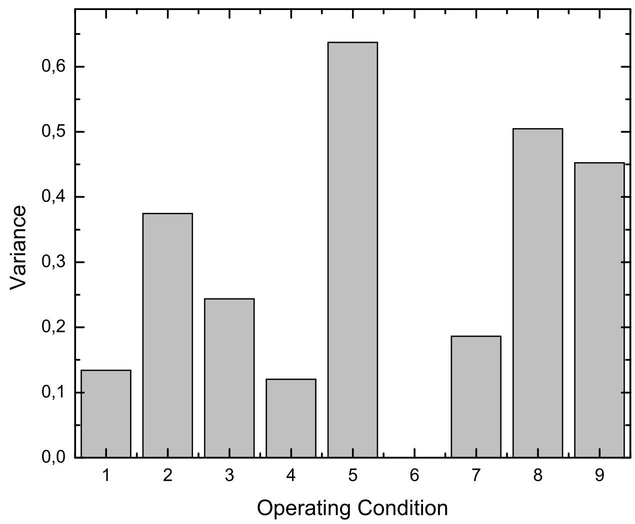


Figure 12. Variance values of the flame detector signal for all cases.

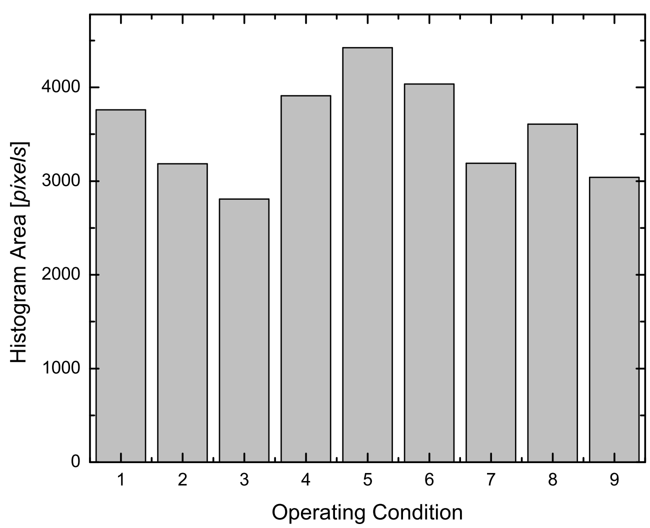
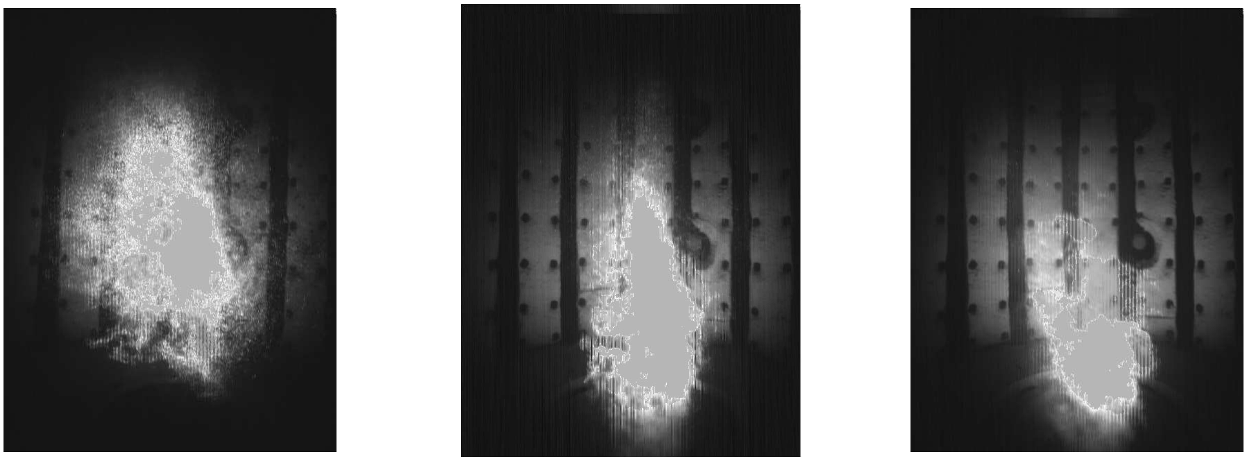


Figure 13. Mean values of the histogram areas for all cases.

the histogram areas of gray tons could be used as indicator of the flame instability.

In addition, exist other image characteristics that can help us in the identification of situations in which the burner is not operating in optimal conditions (excess of air, poor atomization, liftoff, etc.), characteristics such as the area, the perimeter, the aspect ratio (width/height) and the number of objects, can also be related with the conditions of non-optimal burner operation. The table 3 shown this values. Values such as the number of objects along with the area or the gray ton along with the area or the perimeter of flame image can give us more and better indicators of bad operation of the burner or flame instabilities. These values will be used for automatic monitoring of flames in industrial burners.



a) b) c)

Figure 14. Sequence of images of three operating conditions,a) Case 3; b) Case 1; c) Case 2.

Table 2. Results of each one of the cases

Case	Mean value of the histogram areas of gray tons (Pixels)	Mean value of the Flame detector tension (V)	Variance values of the flame detector signal
1	3761	1.0328	0.13408
2	3185.3	0.80181	0.37473
3	2809.3	0.1390	0.24352
4	3910.7	0.0857	0.12033
5	4424.36	0.05058	0.063727
6	4036.42	0.0	0.0
7	3189.6	0.97463	0.18639
8	3608.8	0.73576	0.50454
9	3040.9	0.37233	0.45249

Table 3. Characteristic Dimensions of Flame for all cases.

Case	Area	Perimeter	Aspect Ratio (width/height)	Object Number	Mean Gray tons
1	38295	6490	2,39	234	61,10
2	37649	6386	1,90	176	59,13
3	57317	8855	1,61	503	72,25
4	31581	9782	2,18	420	55,01
5	30113	4569	1,88	779	48,81
6	38479	10057	1,85	1149	43,25
7	36745	4008	2,57	202	65,93
8	37312	4131	2,52	195	60,61
9	55002	7871	1,46	457	69,85

4. CONCLUSION

The optical measurements carried out for the studied burner have shown that the flame is sensible to changes in the primary air mass flow rate and in the steam mass flow rate. The conditions in which the primary air flow rate was increased and the secondary air flow rate was reduced were the most unstable conditions. All of the unstable conditions lead to flame blowout. In the conditions when the primary air flow rate was diminished and the secondary air flow rate was increased, flame blowout was not observed. The reduction of the atomization steam flow rate/fuel oil flow rate ratio, nevertheless presents instabilities, does not lead to the flame blowout. The increase of this ratio increases the instability and, over certain value, leads to the flame blowout.

For the conditions of minimum steam flow rate, the formation of coke in the nozzle was observed, with the obstruction of the exit of the steam/fuel oil. The coke formation is a well known indicator of poor atomization. It was observed that the maximum values of the tension of the flame detector decrease and its variance increases. Concerning the image processing, the average values of the gray tons histogram diminishes with the beginning of the instabilities. This tendency continues throughout all tests. So it can be said, that both techniques are useful to detect the proximity of the instabilities.

In future works, the authors will evaluate new variables such as the angle between sprays and the addition of swirl in the primary air. With such additional information, the complete stability map of the oil burner will be determined.

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