Infrared Imaging Software for Jet Fire Analysis

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Jet fires, often originated by the ignition of hydrocarbon sonic jets, are characterized by a high momentum jet flame lifted from the outlet orifice. The high thermal flux released, especially if there is flames impingement on a given equipment, can lead to a domino effect. Therefore, predicting its size and shape is quite interesting in order to foresee the possibility of this effect on a given equipment.

Several mathematical models have been proposed to predict jet fires main features, some of them based on experimental data. However, the analysis of jet flames can be sometimes difficult. In this communication, an in-house infrared imaging software for jet fire analysis is presented, which allows the calculation of different flame-geometry descriptors. A set of capabilities are included in a graphical user-friendly interface that can help users to easily obtain fire metrics. The tool also provides options to export the results for a post-processing analysis useful for risk prevention, such as preventive design and calculation, and emergency protocols design.

1. Introduction

Jet fires are usually associated to the high speed release hydrocarbon (sonic velocities are reached when the pressure in the container is higher than 1.9 bar abs). Due to the strong turbulence, air is entrained by the jet and, thus, the combustion is much better than that found in a pool fire. Due to this good combustion in the case of a gas jet, it is difficult to define the flame contour; if the jet is fed by two-phase flow, then the combustion is poorer and due to the existence of burning soot particles the flame is much more bright and visible (Casal, 2018). In both cases, the analysis of experimental images can be improved by applying an in-house infrared imaging software based on previous contributions. In order to improve the knowledge about the jet fire dynamics, experiments of vertical propane jet fires in open environments were carried out (Gomez-Mares et al., 2008; Palacios et al, 2008, 2012). Sonic and sub-sonic regimes were achieved and different measuring devices were used to register the flame size and temperature and the thermal radiation intensity reaching a given target. In such experimental work, one of the most important tasks is to manage and analyse the thermal data obtained. There is a considerable literature describing experimental and theoretical studies of thermal radiation from flames (Zhou, 2015), such as surface emissive power (SEP).

In-house algorithms have been used to process these IR images, hence allowing the determination of semi-empirical correlations related to the flame geometry and the thermal radiation. According to the results obtained from IR experiments from previous contributions, no software or graphical user interface was issued. Consequently, a further jet fire experiments with IR cameras would be required for the development of new post-processing techniques. The novelty work is presented as a new software, in this case, for jet fire analysis which allows the calculation of different flame-geometry descriptors (flame area, flame length and width, tilt angle orientation, and lift-off distance), as well as the thermal properties such as the surface emissive power. All these capabilities have been included in a graphical user-friendly interface that can help users to easily obtain fire metrics. A set of these post-processing tools were implemented in this tool which also provides results in spreadsheets data useful for risk prevention, such as preventive design calculations and safety and emergency protocols design. Furthermore, one of the goals of this paper is providing to the user a useful application to manage, acquire and analyse fire detection in IR images. A brief description of the experimental

set-up and procedures, the measurements implemented in the software, the implementation of the design features and a case-use example based on the experimental set-up are presented.

2. Experimental set-up and procedures

The Center for Technological Risk Studies (CERTEC) performed experiments of vertical propane jet fires in open environment at a relatively large scale (Gomez-Mares et al., 2008; Palacios et al, 2008, 2012). An infrared thermographic camera was located at a certain distance to register the flames temperature distribution; several radiometers were also located at different distances. Here, the experimental data provided by the thermal infrared camera has been used to test the implementation of the proposed application.

The IR camera, Thermovision from FLIR system, works as well as a radiometer composed by a set of bidirectional sensors. The signal produced by each sensor is proportional to the irradiation of heat. The signal is transformed into temperature through emissivity and the distance of the object. The IR camera specifications are depicted in Table 1. This camera possesses lenses of 24º and minimal focal distance of 0.5 m. Moreover, a Focal Plane Array (FPA) is supported extracting a set of images with a definition of 320x240 pixels. The temperature range used is between 500 ºC and 1500 ºC.

Table 1: IR camera specifications

IR Camera Specifications	Description
Model	Agema Thermovision 570 Infrared Camera
Detector type	Focal plane array, uncooled 320x240 pixel
Field of view (FOV)	24º horizontal, 18º vertical
Spatial resolution (IFOV)	1.3 mrad
Measurement range	500-1500ºC
Digital output	14-bit real-time serial digital video
Thermal sensitivity	<0.15ºC

A pre-process step was in charge of capturing the IR images stored in a private project file. In order to extract all the images in a useful format, an exportation part was also implemented, according to the frame rate selected by the case. Two different software programs (ThermaCAM Researcher® and Matlab 2017b ®) and specially-developed ad-hoc algorithms were used for image processing. Since the accuracy of the measurements with the IR camera depended on the spectral range of the thermal radiation from the fire, the emissivity of the flames had to be adequately adjusted in order to minimize the error.

It is important to remark that the IR images used for this experimental data have an emissivity coefficient (ε) equal to 0.2. The pixel dimensions are calculated according to the size of the horizontal and vertical vision of the camera compared with the distance of the object. The camera was located at 30 m of distance to the flame, therefore the pixel area was 0.00160 m^2. The gas outlet orifice diameter was 15 mm. The mass loss rate used was 0.23 kg/s, with an ambient temperature equal to 298 K. A text file with the entire frame names list with the IR images was created. The Matlab file contained a temperature matrix corresponding to the IR image. The matrix size was the same as the original image. In addition to the temperatures, information related to the parameters of the camera was also exported; this is important in order to calculate the correct scale of temperatures used to obtain the IR image.

3. Measurements implemented

According to the experimental data obtained with large vertical propane jet fires, the flame-geometry descriptors have been determined. The jet flame surface was defined according to the isotherm of 800 K (Palacios et al., 2012). Then, the area occupied by the flame corresponds to the sum of those pixels with at least 800 K.

The flame reach (flame length plus lift-off) was determined as the maximum distance between the gas outlet orifice and the highest pixel element at a minimum temperature of 800K. The implementation was based on getting all the coordinates of the boundary flame using a binary image with the purpose of finding the first and the last coordinate point. Then, after a manual selection of the base point of the flame (see Figure 1a), a vector between the first point and the base point was obtained. Taking the first point in x-axis with the base point on the y-axis, a perpendicular line is calculated. With these measurements, the flame length and height can be obtained. Similarly, the tilt angle orientation was obtained using the inverse tangent of the length and height.

Moreover, the lift-off distance (*S*) is defined as the centerline distance from the gas release point to the start of the detached and stabilized flame. In the tool, the lift-off is obtained from an empirical equation similar to that obtained by Schuller et al. (1983). In an attempt to find a valid expression for the sonic flow, the lift-off was obtained as a function of the orifice's Reynolds number *(Re)* (Palacios et al., 2012). The relationship between *S* and *Re* is expressed in the following equation:

$$S = 6 \times 10^{-4} \cdot Re^{0.5} \tag{1}$$

Another measurement implemented in this tool has been the surface emissive power (SEP), which concerns the radiative heat emitted per unit area of the flame surface. It was calculated from the mean flame temperature matrix as follows:

$$\overline{SEP} = \begin{cases} \frac{\varepsilon \cdot \sigma \cdot \Sigma_i \cdot \Sigma_j \, \overline{E}_{i,j}^4 a_x}{\Sigma_i \cdot \Sigma_j a_x} \; \forall \; T_{i,j} \geq 800 \text{ K} \\ 0 \; \forall \qquad T_{i,j} < 0 \end{cases} \tag{2}$$

where $\overline{T}_{i,j}$ is the mean temperature (K) of a cell element, i and j indicate the position of the cell, $\overline{SEP}$ is the mean surface emissive power (kW·m^{-2}) of the pixel element, ε is the emissivity, σ is the Stefan-Boltzmann constant (kW·K^{-4}·m^{-2}), and a_x is the area of a grid cell (m^2).

4. Results and implementation design

The implementation of the in-house infrared imaging software was done according to the measurements previously described. A graphical interface, developed in MATLAB 2017b ®, was implemented. Notice that in this example, all the images were segmented with a threshold of 800 K according to the proposed experimental set-up (experiment of 116 images).

The interface design is depicted in Figure 1. The first step is to define the path definition workspace. Users should select the folder containing all the segmented images (highlighted on the blue box 1 in Figure 1). It is important to select a correct source data (previously segmented or pre-processed), due to the fact that the main geometric parameters of flames are occasionally very difficult to analyze. Next step is to set the configuration set-up in order to calculate the geometric-flame descriptors focused on jet fire parameters (highlighted on the red box 2). Remember that the IR Camera provides these parameters and they are specific according the hardware configuration used. If these parameters are not correct, then the results will be wrong. The recommendation for users is to collect and verify previously the required information before calculating the measurements. Additionally, users can decide if these measurements are applied to all the set of images or select just a range. Sometimes, it is not necessary to analyze all the set of images, but just focus on a small part of the experiment. For this reason, there it is another visualization option to improve the efficiency of the analysis.

Once all the parameters and options have been uploaded, the "Calculate" button should be pressed and immediately a pop-up window to select the base point of the flame is displayed (see Figure 2). This is a required parameter because all the measurements are calculated according to this base point. Automatically, a visualization panel that contains the temperature range, flame geometry, surface emissive power contour and histogram is displayed (highlighted on orange box 3 of the graphical interface). By default, the obtained results of the first image are shown. However, users can use a slider bar in order to change images (back or next forward). In addition, there is an option to display the measurements of a specific image by selecting the corresponding index value.

Another feature design included in the software is the displaying of the log information box. This allows knowing the status of each action (highlighted on green box 4 in Figure 1). It is very useful for users, because it is possible to check the status of the computing process or a detailed information in case that the calculating process detect some error or missing step. Furthermore, this graphical interface offers some options to manage the configuration state of the project in two different ways (copy/paste). When managing a large amount of data and doing multiple tests, it is very useful to save a configuration of the actual state like a checkpoint. Then, it is possible to come back to the checkpoint by pressing a "paste state" button or reset the actual configuration.
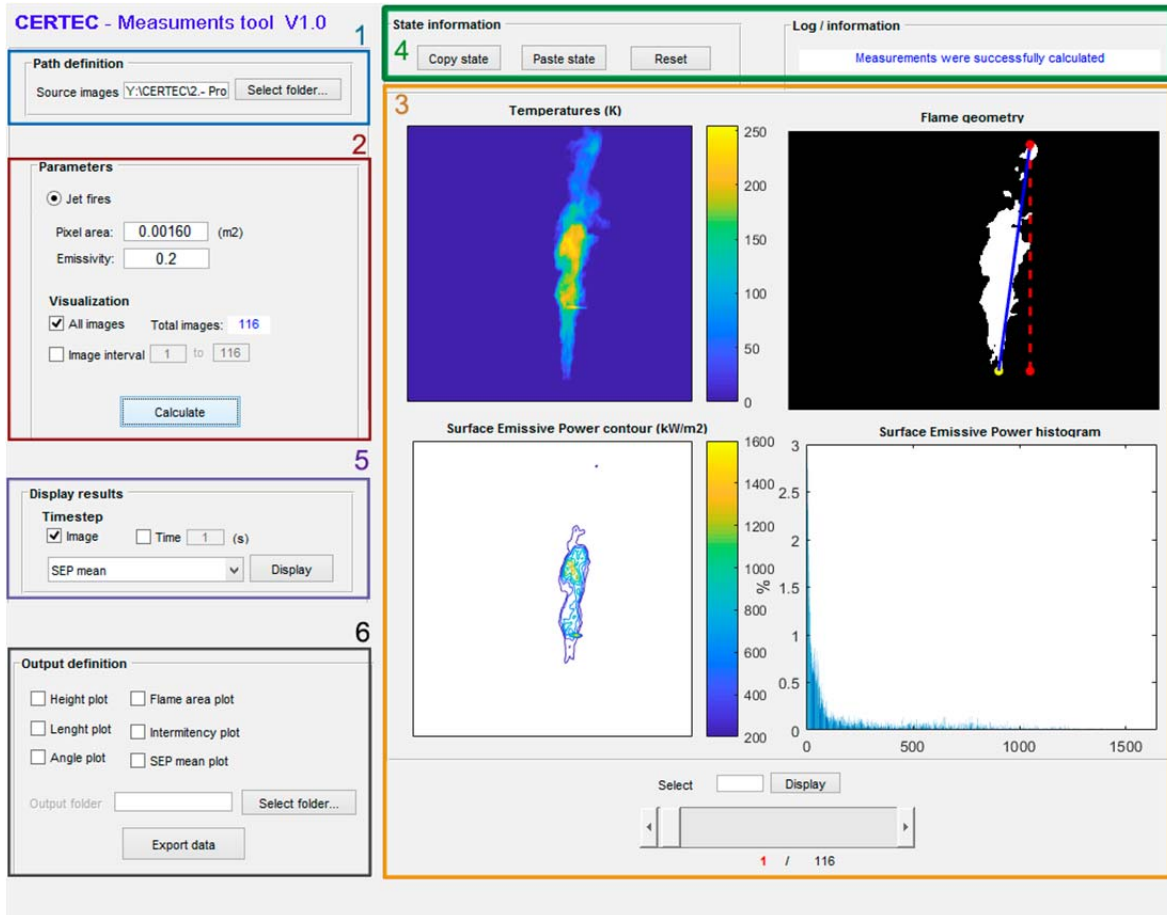
Figure 1: Example of the graphical interface design: the interface of the software containing a set of visualization panels with the obtained results.
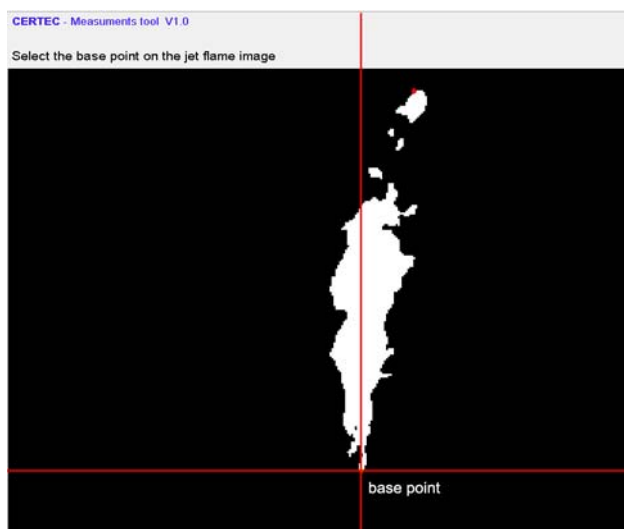

Figure 2: Example of the pop-up window to select the base point of the jet fire image. This base point is a required value in order to calculate the jet fire analysis.
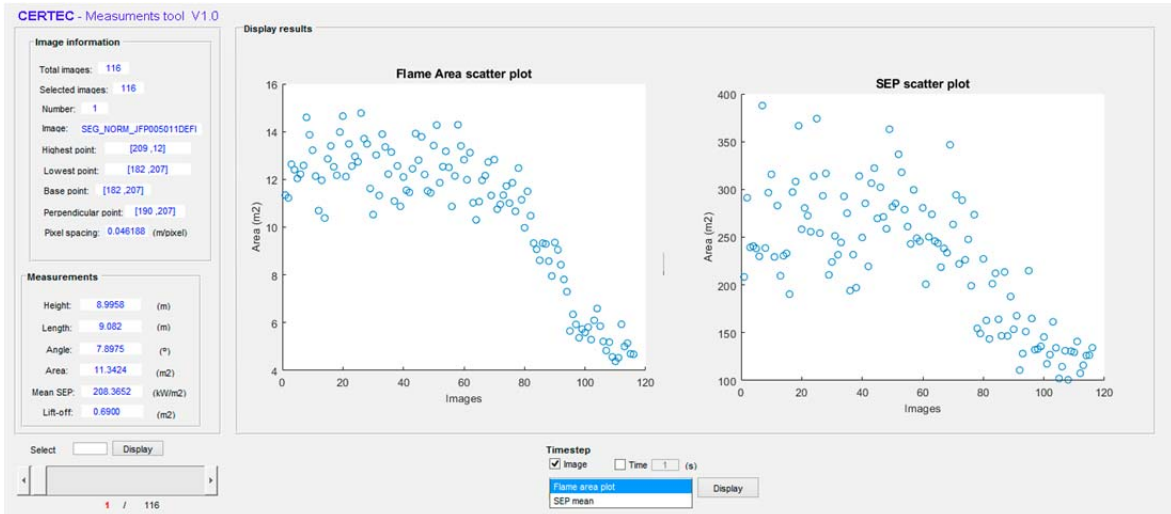
Figure 3: Example of the display options to represent the results. The measurements obtained with the flame area and SEP scatter plots of all the set of images are displayed.
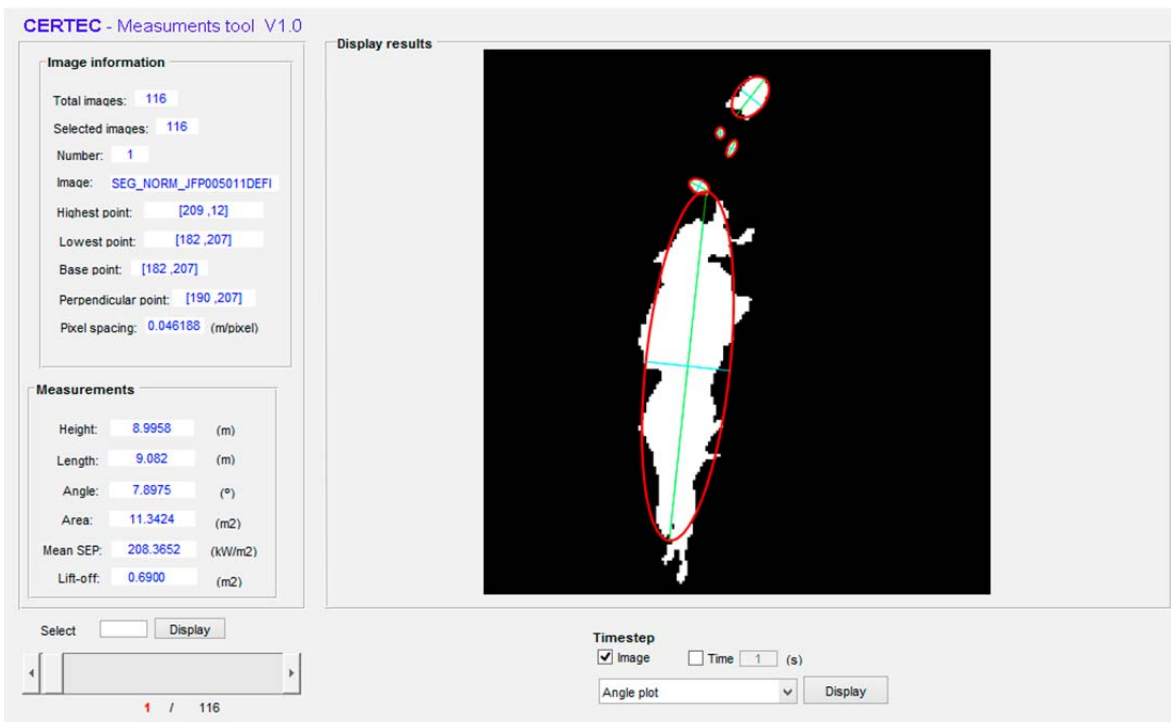

Figure 4: Example of the display options to represent the results. The measurements obtained with the tilt orientation angle plot.

Concerning the visualization, different options have been implemented to display the results by plots according to specific measures (highlighted on purple box 5 in Figure 1). Users should select a plot combo that contains the results according to the flame area and SEP mean. Once the option is selected, the "Display" button should be pressed and a new pop-up window will appear with the corresponding scatter plot. In the example, a flame area scatter and SEP plot are shown. In this case, both calculations used all the set of images. A difference respect the results displayed in Figure 1, which have been calculated individually, is that in this case, both calculations are based on all the sets of images corresponding with the experiment (i.e., 116 images). Then Figure 3 shows an example of these two scatter plots and the numerical results of the geometric-flame descriptors such as height and length of the flame, tilt angle orientation, flame area, mean

SEP and lift-off distance. Furthermore, Figure 4 shows an example of the angle orientation obtained by pressing the angle orientation option from the plot combo.

Finally, an important feature of the graphical interface is that it allows exporting the results in spreadsheets data (highlighted on black box 6 in Figure 1). Users should select on the output definition panel the folder to export this file. In this sense, the height, length, angle orientation, flame area and SEP mean corresponding to the scatter plots could be exported in different spreadsheets files. One of the purposes of this tool is providing facilities for users from the risk prevention field. In this sense, these data could be useful for preventive design calculations, safety and emergency protocols design.

5. Conclusions

An infrared imaging software for jet fire analysis is presented. This application allows the calculation of different jet fire flame-geometry descriptors (flame area, flame length and height, tilt angle orientation, and lift-off distance), as well as the thermal properties such as the surface emissive power. One of the main objectives to use this software is provide to users create a repository of IR experiments. A set of capabilities are included in a graphical user-friendly interface that can help users to easily obtain fire metrics. This information can be used to determine the separation distances required between structures and equipment and a potential jet fire source, in order to avoid flame impingement, which could scale-up the accident. For industrial field could be useful for risk prevention, such as preventive design and calculation, and emergency protocols design. As a further work, this software can be improved by adding new functionalities according to the requirements of the users. In this sense, a graphical interface could become a full application to be used for another image format and modalities such as pool fires domain. Furthermore, more implementation focused on time-evolution statistics or real time flow could be included. In this sense, it can allow users to perform direct characterization and analysis flame intermittency and pulsation frequency.

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