35th HEAT TRANSFER and FLUID MECHANICS INSTITUTE

MAY 29-30, 1997

PROCEEDINGS

Edited by Frederick H. Reardon
and Ngo Dinh Thinh

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PROCEEDINGS of the 35th HEAT TRANSFER and FLUID MECHANICS INSTITUTE

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PREFACE

This volume contains the papers presented at the 35th Heat Transfer and Fluid Mechanics Institute, which was held at California State University, Sacramento on May 29-30, 1997

The Heat Transfer and Fluid Mechanics Institute (HTFMI) was originally organized by a group of west coast universities in 1948 to provide a regional forum for the presentation and discussion of scientific and technical work in heat transfer and fluid dynamics. Over the years, the Institute has become an international forum. The papers presented at each meeting are published in a bound volume of Proceedings, which is distributed throughout the world.

HTFMI meetings were held annually until 1968; since that time they have been held biennially, except that there was a three-year gap between the 28th and 29th meetings. Until 1982, the meetings were rotated among the sponsoring universities. Beginning with the 28th Institute (1982), California State University, Sacramento has been the host, as well as the publisher of the Proceedings.

This 35th Institute carried on the HTFMI tradition of variety in both approach and subject matter. The meeting opened with a presentation of an artificial vision system for three-dimensional characterization of industrial flames. In the following sessions, the topics ranged from flow and heat transfer in ducts and over fins to a water supply system for the city of Cusco, Peru. Computer modeling techniques were central to nearly half of the presentations; experimental results were presented in another seven papers.

The editors are grateful to the authors for the high quality of the papers submitted and for their cooperation in meeting publication deadlines. It is a pleasure to acknowledge the support and encouragement of Dean Braja Das, of the School of Engineering and Computer Science. Thanks are also due to the Mechanical Engineering faculty and staff, especially to Ms. Jessie Richburg and Ms. Kay Carling-Smith, whose efforts contributed greatly to the success of the 35th HTFMI.

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TABLE OF CONTENTS

AN ARTIFICIAL VISION SYSTEM FOR THE 3-D RECONSTRUCTION AND THE DYNAMICAL CHARACTERIZATION OF INDUSTRIAL FLAMES

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Abstract.

The relationship between the phenomenology of the combustion (i.e. the shapes of the flames and their motion) and the combustion settings is easly seen but is not well understood; this is primarly because of the lack of idoneous measuring systems.

This article describes the development of a system for the 3–D reconstruction and the dynamical–morfological characterization of industrial flames.

The system is able to reconstruct a three dimensional geometric model of the flame by taking tree (or more) simultaneous pictures of the flame.

The images taken are processed in order to extract the contours of the flame, then the contours are interpolated by a reconstruction algorithm to produce the 3–D model of the flame.

Once the geometric model is obtained it is possible to measure several morphological parameters that may be used to characterize the combustion process.

The system described has applications both in research (analysis of turbulent flames phenomenology or characterization of industrial burners) and industrial applications (automatic systems for the control and regulation of industrial sites).

Introduction.

Combustion was (and probably will be) the principal mean for the production of energy for a long time. Todays' research looks towards both to an industrial development compatible with the enviromental issues and to the progressive exaustion of non–renewable combustibiles.

A sound understanding of the physical, chemical and dynamical processes involved in the combustion is necessary for the reduction of the pollutants and for the increasing of efficency.

Unfortunately combustion processes are extremely complex and there's not yet a comprehensive theory or modellization on the subject. In this perspective is useful to develop and diversificate the measuring systems that may contribute to gain insight in the phenomenology of combustion processes [1], [2], [3], [4], [5], [6], [7], [8].

Here we present a system for the 3–D reconstruction of a natural gas diffusive flame. Once obtained, the model of the flame may be used to measure several geometrical and morphological parameters (e.g. volume or surface area) that aren't easily measured with traditional techniques [9].

Acquisition Setup.

Experimental tests have been carried out using the 30 kW version of a series of diffusive natural gas burners of analogus technology [10], [11] produced by the IFRF (International Flame Research Foundation).

The burner is schematically shown in figure 1. The air is feed through a manifold from which six ducts lead the air in the *swirler* that gives a tangential component to the air velocity. The principal flux of the gas is feeded by a cylindrical duct with a series of holes on one end that inject the gas normally to the flux of the air coming from the swirler. The burner has also the option of a secondary gas feeding and a duct for flue gas recirculation.

The swirl number, defined as:

$$S = \frac{G_\theta}{G_x R}, \tag{1}$$

where

- $G_\theta = \int_0^\infty (\rho u w + \overline{\rho u' w'}) r^2 dr$ is the axial flux of the tangential momentum (counting also the turbulent contribute),
- $G_x = \int_0^\infty \left[\rho u^2 - \overline{\rho u'^2} + (p - p_\infty)\right] r dr$ is the axial flux of the axial momentum couting the turbulent stress and the term of axial dynamic pressure,

is adjustable and can be varied between 0 and 1 by means of a mobile knob; the regulation is calibrated by the manufacturer. Table 1 reports some of the principal characteristics of the burner.

In order to enhance the flame brightness and hence the image quality, the air–gas mixture was inseminated with a solution of water and sodium cloride (N_aCl): this turns the flame in a bright yellow/orange colour thus allowing for better images to be taken.

To acquire the data needed for the 3–D reconstruction, several simultaneous images of the flame must be taken from different points of view. We employed three CCD cameras; however the number of cameras is arbitrary: the software has been developed to deal with

Thermal input	30 kW
Natural gas flow rate	2.5 kg/h
Combustion air flow rate	43 kg/h
Mean Combustion Air Velocity	28 m/s
D_0 – Burner insert inned diameter	27 mm
D_g – Gentral gun outer diameter	18 mm
Number and diameter of holes on central gas injector	$24 \cdot \oslash 0.5$ mm
Number and diameter of pipes on secondary gas injector	$8 \cdot \oslash 0.75$ mm
Reynolds number	16300

Table 1: Burner characteristics.

any number of cameras; the increase of the number of sensors causes an improvement of the quality of the reconstruction.

The position of the cameras in space was chosen to cover as much of the surface of the flame as possible: optical axes of the cameras lie on the same plane, meet in a point that is chosen as the origin of the reference system and are 120 degrees apart (see figure 2).

To have and idea of the order of magnitude of the frequencies needed to record the whole dynamics of the phenomenon a preliminary acquisition was made using a high–speed camera capable of acquiring at frequencies ranging from 60 to 1000 frames per second (see figure 3). The detailed structure and dynamics of the flames appear to require acquisition rates of approximately $250 \div 750$ frames per second; assuming a resolution of 128×128 pixel and using 8 bits/pixel this sums up to a required bandwidth of $3 \times (128 \times 128) \times 500 = 24576000$ ($\approx$ 23 Mb/s) that is obtainable only with a dedicated hardware. It was then decided to employ three CCIR standard commercial CCD cameras (Sony XC–77RR–CE) equipped with an inline transfer CCD of 8.8×6.6 mm and 756×581 pixels. The cameras mounted 12.5 mm optics.

Since the major issues were a 3–D model of the flame and a time history of the morphological parameters, it was important to have a sequence of sincronized images. To obtain them the b/w signals from the three cameras were forwarded to a frame grabber (mounted on a PC) that "sees" them as a composite RGB signal, then saved to disk. This technique enforces the sincronicity of the signals and hence of the images.

Image analysis.

Once that the images have been recorded it is necessary to process them in order to extract the information needed for the 3–D reconstruction.

The images of the flames lack the surface features such as edges or textures which are the base for many reconstruction algorithms (see figure 3 and 4 for some examples of typical images): the main (and nearly the only) feature is represented by the "silhouette" of the flame, that is, its contour. Moreover in the hypothesis of an employment of the sistem on an industrial site gives the additional constrain of possibly degraded images and/or short processing times; due to this characteristics many reconstruction algorithm such as reconstruction from projection [13] or stereoscopic algorithms [14], [15], [16], [17], [20], [18], are not applicable to the images of the flames. The contour extraction algorithms, instead, may be made quite fast and robust [19].

In order to extract the contours of an object it is necessary to choose a threshold value to partition the pixels of the image as belonging to the subject or to the background; usually this value is chosen from the examination of the histogram of the gray levels of the image. In the case of the flame images the istograms of different pictures taken with different burner setting weren't sufficiently homogeneous (see figure 5), so it was not possible to use a single threshold value: the problem has been solved using an adaptive algorithm to choose the best threshold value: for each image the peak of the histogram representing the background was assumed to have a Gaussian shape; the mean and the standard deviation of the peak were used to select an optimal threshold value:

$$t_h = x_m + \gamma\sigma \tag{2}$$

where t_h is the threshold value, x_m is the mean and σ is the standard deviation of the peak; γ is an adjustable parameter that was tuned on the flame images.

After choosing a threshold, a contour following algorithm extracts the contour of the flame by succesively classifying adiacent pixels.

Often the images of the flames have low contrast, that is, the transition from the background to the flame is smooth, this could be a source of errors for the contour extraction algorithm.

To avoid problems arising from the low contrast, the images have been preprocessed by means of a customly developed enhancement filter that sharpens the edges of the flame. The filter behaviour is to increase the difference between the value of a pixel and the mean value of his neighborhood: if the pixel is in an homogeneous region its value is not changed much; otherwise if the pixel is in a dishomogeneous region (i.e. an edge) its value will undergo a significant change. The filter computes the output image $O_{i,j}$:

$$O_{i,j} = (f+1)\, I_{i,j} - f \sum_{m=-\frac{N-1}{2}}^{\frac{N-1}{2}} \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} K_{m,n} I_{i+m,j+n} \tag{3}$$

where $I_{i,j}$ is the input image, $K_{m,n}$ a mean kernel and f a varying parameter. The overall effect is an enhancement of the edges.

The extracted contours are coarse because of the noise present on the images so they are smoothed using an algorithm based on the Freeman *chain code* [12] representation.

The data of the contours have been finally organized in a tree–like structure (called the *tree* of the flame); this structure is both efficient in the reconstruction phase and gives an interesting *syntactic* description of the flame. The analysis of the tree of the flame gives several information on the flame morphology: for example the number and the size of the "branchings", their time dynamics, the space or time correlation between two points, etc..

3–D Reconstruction.

The reconstruction method is based on an innovative algorithm that rely on the information given by the contours of the flames.

From the geometrical point of view the contour of an object can be seen in the projection of the object on the plane of the image. Moreover the projection defines a sub–space containing the object: in the case of a perspective projection we have a *generalized cone*, in which the base is the plane region individuated by the contour and the vertice is given by the viewpoint; conversely, in the case of an orthogonal projection, we have a *generalized cylinder*[1].

When more viewpoints (or more images) are available there will be more sub–spaces each one containing the whole object. If the number of the viewpoint (i.e. the sub–spaces) goes to infinity, the points of the sub–space given as the intersection of all the sub–spaces define the *visual hull* [21] of the object (see figure 7).

Of course the volume of an object and the one defined by its visual hull don't coincide in all the cases (see figure 7) and in most pratical cases it is not possible to have a very large number of points of view; anyway if the object is not very complex and it does not have many concavities it is reasonable to approximate the volume of the object with the one defined by the intersection of the given *generalized cones.*

[1]Note that the case of the ortogonal projection may be derived from the perspective one when the viewpoint goes to ∞

For the reconstruction of the flame we have implemented a 2–D variation of the algorithm. The contour of the flame was "sliced" by a set of parallel planes (see figure 8). Each plane contains one or more sections of the flame: in this case each viewpoint "sees" a series of segments. The intersection of the angles coming out of the viewpoints defines a polygon; the set of all the polygons approximates the volume of the flame.

The algorithm computes, for each plane, the coordinates of the vertices of the polygons: consider the simplest case in which there is only one slice of the flame (figure 9); we see that the slice is represented, on the plane, by a segment on a line of equation

$$y = -\frac{x_t}{y_t}x \tag{4}$$

where (x_t, y_t) are the coordinate of the viewing point. The line of equation (4) passes through the origin and is at right angles with the line through the viewing point and the origin.

The coordinates of A and B are given by:

$$\begin{cases} x_A = \pm\frac{d_A y_c}{\sqrt{x_c^2+y_c^2}} \\ y_A = \mp\frac{d_A x_c}{\sqrt{x_c^2+y_c^2}} \end{cases} \tag{5}$$

and

$$\begin{cases} x_B = \pm\frac{d_B y_c}{\sqrt{x_c^2+y_c^2}} \\ y_B = \mp\frac{d_B x_c}{\sqrt{x_c^2+y_c+2}} \end{cases} \tag{6}$$

where

$$d_{A,B} = x_m \mp \frac{d}{2} \tag{7}$$

The slice of the flame lies between the lines passing through (x_c, y_c) and $(x_{A,B}, y_{A,B})$. Note that each line defines a couple of half–planes one that contains the segment $\bar{AB}$ and one that does not; note also that if a line l has equation:

$$ax + by + c = 0 \tag{8}$$

two points in the same half–plane both verify or don't verify the disequation:

$$ax + by + c > 0 \tag{9}$$

so the equation (9) represent a simple condition to decide if two points belong to the same half–plane; this relation is very useful in computing the vertices of the polygons..

To compute the vertices of the polygon we have to consider the

$$N_p = \frac{(2N)!}{2!(2N-2)!}$$

points given by all the intesection of N couples of lines, where N is the number of points of view. The vertices of the polygon that approximates the slice of the flame are those that verify equation (9) for every line.

The N_p vertices of coordinates (x_i, y_i) so computed will not be ordered, but we need to order them in order to obtain the convex polygon we need for the 3–D reconstruction; to order the vertices we compute the baricenter

$$\begin{cases} x_B &= \sum_{i=1\cdots N} \frac{x_i}{N} \\ y_B &= \sum_{i=1\cdots N} \frac{y_i}{N} \end{cases} \tag{10}$$

and the angle α between the x axis and the vector from (x_B, y_B) to (x, y) for every point. Sorting the points with respect to α orders the points: sequentially linking the now ordered vertices yields the convex polygon.

The case in which are present more sections of the flame is dealt considering separately every section; in this way the algorithm is able to resolve complex morphologies characterized by "branchings" that hide each other from the sensors (see figure 10).

Rendering.

The reconstruction algorithm yields a set of points in 3–D space. The points must then be used to build a solid model representing the surface of the flame.

The points we have are the vertices of the polygons approximating the sections of the flame one approach in building the model is to render a series of prisms that have the polygons as base and the distance between adjacent slices as height. Due to the small number of points in each polygon (3 to 6 with three cameras) the model apperance is quite angolous. One way to minimize this visually disturbing effect is to modify the normal vectors of the surface.

The rendering softaware computes the image representing the model by simulating both the surfaces properties and the effects of the illumination, in particular the way the light bounces off the surface. In the calculation the vectors normal to the surface are used to determine the direction of the outgoing light. On the edges of the prisms the normals have a discontinuity, this causes the edges to appear angular when the model is rendered. If, instead of the "true" normals, one computes an averaged normal the rendering software doesn't "see" the discontinuity and the rendered model *appears* to be smoother (see figure 11).

Another approach is to build a Delanuay triangulation out of the set of vertices. In this way the model is no more build on a per slice basis but a triangualtion algorithm computes a series of triangles from the vertices. This, together with the normals interpolation gives an even more realistic model (see figure 12).

The 3–D model of the flame can be viewed by means of a customly developed interactive program that enables the user to navigate around the model and examine it from different points of view. Moreover, since we recoderd a sequence of images the user can also move throught the different frames of the sequence examining thus the dynamics of the flame. This can be very useful for a phenomenological analysis of the shape of the flames and of the combustion processes.

Finally, from the 3–D model of the flame is possible to compute geometrical, such as the volume, the lenght, the surface etc. or morphological parameters such as form coefficients [22]. Since the parameters can be computed for each frame it is possible to build a time sequence that records the dynamics of the evolution of the parameter. This dynamics can be then analyzed by means of traditional signal analysis (e.g. Fourier transform) or using non–linear and chaotic techniques.

The individuation of the most significative parameters and their correlation to the combustion conditions needs a detailed theoretical study and a vast experimental campaign.

Results.

The experimentation and test of the various algorithms has been carried out in several combustion settings (see table 2) varying the swirl number, the flow rate of air and gas; the different acquisitions summed up to approximately 4200 images.

The analysis has been performed on two different configurations of the parameters of the adaptive threshoding algorithm (γ) and of the enhancement filter (f and N). The contour extraction algorithm is seen to behave quite well: the error rate was as low as 0.5% (see table 3). Note also that the algorithms have a low sensitivity to the variation of the parameters that means that the system may be used in different operanting situation and is suited for employment both in research laboratories and industial plants.

As an example of the potentiality of the method several geometrical parameters have computed. Graph 1 shows the time history of the volume of a flame with different burner settings and graph 2 the volume of an extinguishing flame, obtained by reducing progressively

Air (lt/min)	Gas (lt/min)	*Swirl* number
420	60	0.029
		0.487
		1.215
	80	0.029
		0.487
		1.215
560	60	0.029
		0.487
		1.215
	80	0.029
		0.487
		1.215
700$^{(*)}$	60$^{(*)}$	0.029$^{(*)}$
		0.487$^{(*)}$
		1.215$^{(*)}$
	80$^{(*)}$	0.029$^{(*)}$
		0.487$^{(*)}$
		1.215$^{(*)}$

Table 2: Values for the flow–rate of air, gas and for the *swirl number* used in experimental tests. Values marked with $^{(*)}$ refer to instable flames: the images corresponding to this values have not been recorded.

Algorithm Parameters	Number of frames	Number of errors	Error (%)
$\gamma = 1.3$ $f = 2.3$ $N = 11$	3600	23	0.638
$\gamma = 2.0$ $f = 3.0$ $N = 9$	3600	19	0.527

Table 3: Results of the recontruction.

the gas flow. This data can be used in the study of the relationships between dynamics of the flame and burner setting or in the investigation of stability mechanisms.

Graph 3 shows the plot of the volume versus an adimensional form coefficent defined as:

$$C = \frac{S^{3/2}}{V} \tag{11}$$

note that the points for every conbustion setting form a distinct cloud; this method can be used, in conjunction with pattern recognition techniques, to classify different operating conditions of a burner, for example in an industrial monitoring system.

Figures 11, 12 show examples of the reconstruction using the prism or the triangle approach; note the presence of the "branches" that have been succesfully reconstructed. Figure 13 shows several frames of sequence. The sequence was obtained using the navigation program; of course is possible to obtain a movie or to interactively view the model in real time; on our WWW page (`http://erg055.casaccia.enea.it/imglab/flames.html`) there are some examples of movies and 3–D models.

Conclusions.

This paper presented a system for the 3–D reconstruction of industial flames. The system is able to reconstruct a tridimensional geometrical model from three (or more) syncronous images taken from different points of view. The innovative algorithms implemented use an adaptive metodology thus allowing their use on images taken in different ambiental conditions thanks to this approach also the error rate is very low.

The geometrical model allow the calculation of several geometrical and morphological parameters. The preliminary analysis of these parameters yields promising results for the characterization of different combustion conditions.

The major threads of future development extend towards the refinement of the characterizing parameters and the individuation of relationships between the geometrical parameters and the combustion setting.

The dynamical analysis of the time history of the parameters performed with traditional (Fourier Transform) and chaotic thechniques is also very promising and should allow a greater insight in the combustion phenomena.