ESTIMATION OF THE TWO-DIMENSIONAL TEMPERATURE DISTRIBUITION OF COMBUSTION IN A CROSS-SECTION OF A FUEL-OIL TUNNEL FURNACE FROM FLAME RADIATION IMAGES

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Abstract. Estimation of temperature distribution of combustion of fossil fuel in a furnace can be made by using a method based on radiative image processing. In this method, the radiant energy received by the image-formation elements (pixels) of a CCD camera is dominated by the radiant energy emitted from the gas medium and the wall surface inside the system. In this paper, a numerical-experimental study for estimation the two-dimensional distribution of temperature in a cross section of a tunnel furnace using radiative images in the visible range is presented. To capture the radiant energy images, two CCD cameras are used. The cameras were mounted in the center of two appositive vertical walls of a furnace. The values of the ratio of the directional radiant energy received by the elements of the CCD camera sensor to that emitted from every gas and wall element have been calculated using the DRESOR method which is based on READ Monte Carlo method. A radiation model was established to relate the flame images with the 2-D temperature distribution. For temperature distribution estimation, an inverse radiative method was used. A revised Tikhonov regularization method was used to reconstruct the 2-D temperature distribution from the flame radiation images. The experiment was done in a 13 kg/hr fuel oil/ GLP tunnel furnace with 0.7 m x 0.7 m cross section. The instrumentation system consists of two image detectors, a frame- marker, and a microcomputer with a frame-grabber. The 2-D temperature distribution in 100 discrete meshes in the cross section at the burner zone was deducted continuously using this instrumentation. Radiative properties of the gas media and the walls of the furnace were taken from bibliography and are assumed constants. The results show that the 2-D temperature distribution appears typically to have a single-peak shape with temperatures higher in the center and lower near of the wall.

Keywords: 2-D temperature distribution, Flame radiation image, Inverse radiation, Monte Carlo, Radiative Energy Transfer.

1. INTRODUCTION

Radiative heat transfer in high-temperature devises such as boiler furnaces and combustion chambers is very important. Combustion in industrial furnaces and utility boilers is one of the most complex physical and chemical processes occurring in large-scale tree-dimensional spaces. In those equipments, there are the need for a high-quality monitoring, diagnosis and control systems for the safe and economics combustion process. The measurement of temperature is essential for the development of combustion theory and technology, and it can be used for control purposes. However, because of the larger-scale, high temperature, strong pulse of flame in furnaces, the most widely applied methods such as thermocouples, high temperature pyrometers, acoustic method, and measurement techniques based on laser are hardly used in measurement of temperature distribution in industrial furnaces.

In a pioneer work, Hottel and Broughton (1932) shown the feasibility of temperature and total emissivity determination of a luminous flame in a furnace from a pair of apparent temperatures obtained with an optical pyrometer, using color screens of two different effective wave lengths successively. The luminosity of a flame, caused by thermal decomposition of the hydrocarbons constituents of the fuel is dependent in a complex manner on excess air, type of mixing of air and fuel, air preheat temperature and fuel composition. After, Flower (1983, 1989) uses this technique in open flames, either premixed or diffusion flames. Similar to the two-color optical principle, a multicolor method has also been developed and applied by Cashdollar (1979), Levindes et al. (1992) and Panagiotou et al. (1996). However, all this applications detect only a single-point temperature within a flame.

The early researches for temperature distribution measurements of combustion gases were based in the acoustic principle (Muzio et al., 1989). However, due the limitation of the velocity propagation of the acoustic waves, this method is difficult for application in large-scale furnaces when is necessary to obtain temperatures distribution with time and spatial high resolution. Tomography techniques based in emission (Correia et al., 2001) to obtain 3-D temperature distribution within a flame were used, and non-uniform distribution of the absorption coefficient within a flame was considered. Kawamura et al. (1989) utilized two CCD cameras to acquire the images of a flame at two different wavelengths, and the temperature distribution was calculated from the ratios of gray levels of various points in the two images. However, the difficulty with this method is to synchronize two cameras at a high shutter speed, in addition to requiring a consistent spectral response from the two cameras. Zhou et al. (1995) proposed a simple way to monitoring a 2-D temperature distribution in a pilot furnace utilizing a two-color pyrometer and gray images; however, the method needs an installed thermocouple as part of the system. Images processing techniques of flames in the visible region have been used for flame visualization of pulverized coal combustion in large-scale furnaces (Huang et al., 2000). In this method, the flame images captured in the visible region by the CCD cameras are proportional to the intensity distribution in the detector viewing angle. The two-color method only measures the temperatures of the soot particles within the flame, because Planck's radiation law only fits the continuous spectra from solid particles rather than the band spectra of gas molecules such as CO_2 and H_2O. In fact, the non-uniform distribution of the parameters of emission, absorption and scattering take more complicated the radiative image processing.

In energy balance application in industrial furnaces, the estimation of heat flux and the temperature distribution are dependents one to other according the energy conservation law, and the estimation can be realized by the solution of an inverse radiation problem (Kudo et al., 1996). Temperature distributions in two-dimensional systems were estimated by Li (1997) from simulated measurements of radiative intensities leaving in some points of the boundary surface. After, the two-dimensional temperature distribution in a rectangular cavity was calculated from the simulated information of radiative energy detected by CCD cameras in the corners of the boundaries of the system, and the inverse problem was converted in a programming linear problem and their solution was based in an internal point method (Zhou et al. 2000).

Tikhonov (1963) proposed a first regularization method to solve heat conduction inverse problems, and after then, researches have been intense in this area. Reginska (1996), proposed a method for regularization parameter determination in the Tikhonov method, and Holloway et al. (2001) modified that method to obtain a regularization parameter using finite differences.

In this work, a numerical-experimental technique for reconstruction of temperature distributions is presented. This technique based on radiative images processing is applied to two-dimensional temperature field reconstruction of oil flames in a pilot tunnel furnace. A set of monochromatic radiative images in the visible wavenumber range together with the two-color method is used. The images are acquired in a test cross section of the furnace which has gray and diffusely reflecting surface walls. The gas combustion is considered a gray, emitting, absorbing and scattering medium. A brief introduction of the READ and DRESOR method (based on Monte Carlo method) are presented. These methods are used to solve the radiative problem. A modified regularization Tikhonov method to solve the inverse problem of estimation of temperature distribution is utilized. Firstly, color flame images are captured, and then, the temperature images are calculated from color flame images through image processing. Furthermore, the temperature distribution in a cross section of the furnace is estimated.

2. EXPERIMENTAL SET UP

The experimental tests were realized in a pilot tunnel furnace with rectangular cross-section. The objective of the experimental tests is reconstruct 2-D flame temperature distribution in a cross section from flame radiative images. The test furnace is dual-fuel (natural gas/GLP and light diesel). The burner is installed at center of the back wall of the furnace. The furnace is 4.2 m long and the dimension of the cross section is 0.7m x 0.7m. A thermographic system that uses two color CCD cameras in visible range is utilized to capture and process radiative images. Figure 1 shows a scheme of the thermographic system.

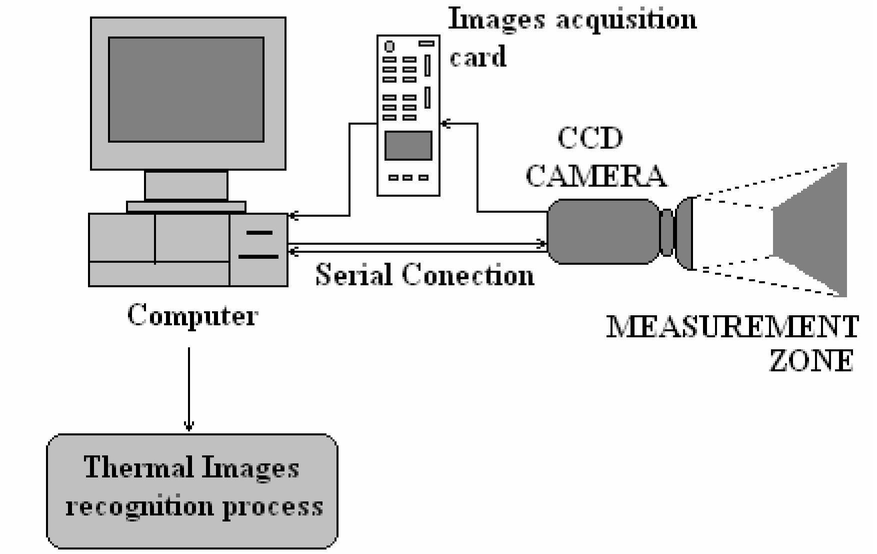

Figure 1. Scheme of the thermographic system

The acquisition system consists of two color image detectors, two cooling and propulsion device, a frame-grabber, an IPC and associate software. The image detectors are installed in two appositive vertical walls of the furnace and they are located in a cross-section 0.8 m away to the burner. A color image detector is formed by a color CCD camera and an image guide. The visible radiation image conveyed by the image guide entered the color CCD camera. The cooling and propulsion devices use air to cool the image detectors to avoid over-heating, and control the advance and retreat of the image detectors. A lens with viewing angle of 90° is fixed at end of the image guide. The camera sensor has 752 (H) x 582 (V) resolution elements (pixels). The shutter speed was adjusted as needed to obtain a readable image. The video signal from a color image detector is sent to the IPC by a frame-grabber. A two-dimensional digital color image with 24-bit true color is acquired in the IPC. The system can be display 25 frames by second. A specific software manager the hardware and do the digital conversion of the images and the storage process. The reconstruction of the temperature field from the radiative images information is made by considers the gas combustion as a gray medium. The algorithm of reconstruction uses a modified Tikhonov method (Lou and Zhou, 2005) and it needs the previous estimation of the radiative properties and radiative transport information which have to be obtained from the solution of the specific radiative problem. For this kind of problem, which is necessary to solve the intensity field with directional resolution, the solution of the radiative problem can be made using the DRESOR method (Cheng and Zhou 2007) which is based on the READ Monte Carlo Method. A brief introduction of the DRESOR method is presented in the next section.

3. THE MONTE CARLO METHOD

There are different computational methods to analyze radiative heat transfer problems. One of the more popular is the Monte Carlo method, a statistical method in which the history of large numbers of photons bundles is traced. The first radiative heat transfers papers using this method are due to Howell e Perlmutter (1964, 1964). In the Monte Carlo method a large statistical sample of photon energy bundles are traced from their point of emission to their point of absorption or their leaving the geometry under investigation. To obtain statistically meaningful results relations need to be development between random numbers and point of emission (from a surface, or from within the medium), direction of emission, wavenumber of emission, distance traveled before absorption (within the medium), distance traveled before scattering, scattering direction, probability of reflection from a surface, and reflection direction (Modest, 2003). The Monte Carlo method has the advantage that almost any problem of arbitrary complexity can be addressed with relative ease, but has the disadvantages of statistical scatter in the results and its large computational time. Yang et al. (1995) proposed a Monte Carlo READ (***r****adiant* ***e****nergy* ***a****bsorption* ***d****istribution*) method to improve classical Monte Carlo solution techniques. Zhou and Cheng (2004) proposed the DRESOR method (***D****istributions of* ***R****atios of* ***E****nergy* ***S****cattered by the medium* ***O****r* ***R****eflected by the boundary surface*) based on READ method to solve intensity field with directional resolution.

3.1 The DRESOR method

The DRESOR method is based on Monte Carlo method. First, this technique was developed to solve the RTE in a gray plane parallel medium (Zhou and Cheng, 2004). Recently, the method was extended for rectangular two-dimensional gray medium in (Cheng and Zhou, 2007). The DRESOR method was design to obtain the intensity field with directional resolution in every point of the media and radiative equilibrium is not required. The integral equation of radiative transfer for a arbitrary medium that emits, absorbs and isotropic scatter is (Modest, 2003)

$$I(\boldsymbol{r},\hat{\boldsymbol{s}}) = I_w(\boldsymbol{r},\hat{\boldsymbol{s}})\exp\left[-\int_0^s \beta ds''\right] + \int_0^s S(\boldsymbol{r}',\hat{\boldsymbol{s}})\exp\left[-\int_0^s \beta ds''\right]\beta ds' \tag{1}$$

The source term $S(\boldsymbol{r}',\hat{\boldsymbol{s}})$ and the boundary conditions are given (Modest, 2003) as

$$S(\boldsymbol{r}',\hat{\boldsymbol{s}}) = (1-\omega)I_b(\boldsymbol{r}') + \frac{\omega}{4\pi}\int_{4\pi} I(\boldsymbol{r}',\hat{\boldsymbol{s}}_i)\Phi(\hat{\boldsymbol{s}}_i,\hat{\boldsymbol{s}})d\Omega_i \tag{2}$$

$$I_w(\boldsymbol{r}_w,\hat{\boldsymbol{s}}) = \varepsilon(\boldsymbol{r}_w)I_b(\boldsymbol{r}_w) + \int_{\hat{\boldsymbol{n}}.\hat{\boldsymbol{s}}<0} \rho(\boldsymbol{r}_w',\boldsymbol{r}_w,\hat{\boldsymbol{s}})I(\boldsymbol{r}_w,\hat{\boldsymbol{s}}')\left|\hat{\boldsymbol{n}}.\hat{\boldsymbol{s}}'\right|d\Omega' \tag{3}$$

The formulae for $I(\boldsymbol{r},\hat{\boldsymbol{s}})$ on the DRESOR method is presented by Cheng and Zhou, (2007) as

$$\begin{aligned} I(\boldsymbol{r},\hat{\boldsymbol{s}}) = \frac{1}{\pi}\Big\{ & \pi\varepsilon(\boldsymbol{r}_w)I_b(\boldsymbol{r}_w) + \int_{\mathbf{W}} R_d^s(\boldsymbol{r}_w',\boldsymbol{r}_w,\hat{\boldsymbol{s}})\left[\pi\varepsilon(\boldsymbol{r}_w')I_b(\boldsymbol{r}_w')\right]dA' \\ & + \int_{\mathbf{V}} R_d^s(\boldsymbol{r}'',\boldsymbol{r}_w,\hat{\boldsymbol{s}})\left[4\pi\beta(1-\omega)I_b(\boldsymbol{r}'')\right]dV'' \Big\}\exp\left[-\int_0^{\boldsymbol{s}}\beta ds''\right] \\ & + \int_0^{\boldsymbol{s}}\frac{1}{4\pi\beta}\Big\{4\pi\beta(1-\omega)I_b(\boldsymbol{r}') + \int_{\mathbf{W}} R_d^s(\boldsymbol{r}_w',\boldsymbol{r}',\hat{\boldsymbol{s}})\left[\pi\varepsilon(\boldsymbol{r}_w')I_b(\boldsymbol{r}_w')\right]dA' \\ & + \int_{\mathbf{V}} R_d^s(\boldsymbol{r}'',\boldsymbol{r}',\hat{\boldsymbol{s}})\left[4\pi\beta(1-\omega)I_b(\boldsymbol{r}'')\right]dV'' \Big\}\exp\left[-\int_0^{\boldsymbol{s}}\beta ds''\right]ds' \end{aligned} \tag{4}$$

where, $R_d^s(\boldsymbol{r}_w',\boldsymbol{r}_w,\hat{\boldsymbol{s}})$ denotes the ratios of the energy scattered by a unit area around the point $\boldsymbol{r}_w$ into a unit solid angle around the direction $\hat{\boldsymbol{s}}$ to that emitted from a unit area around the point $\boldsymbol{r}_{\boldsymbol{w}}'$; $R_d^s(\boldsymbol{r}'',\boldsymbol{r}_w,\hat{\boldsymbol{s}})$ denotes the ratio of the energy reflected by a unit area around the point $\boldsymbol{r}_w$ into a solid angle around the direction $\hat{\boldsymbol{s}}$ to that emitted from a unit volume around the point $\boldsymbol{r}''$; $R_d^s(\boldsymbol{r}_w',\boldsymbol{r}',\hat{\boldsymbol{s}})$ denotes the ratio of the energy scattered by unit of volume around the point $\boldsymbol{r}'$ into a unit solid angle around the direction $\hat{\boldsymbol{s}}$, to that emitted from a unit area around the point $\boldsymbol{r}_{\boldsymbol{w}}'$; $R_d^s(\boldsymbol{r}'',\boldsymbol{r}',\hat{\boldsymbol{s}})$ denotes the ratio of energy scattered by unit volume around the point $\boldsymbol{r}'$ into a unit solid angle around the direction $\hat{\boldsymbol{s}}$ to that emitted from a unit volume around the point $\boldsymbol{r}''$. This R_d values are called as DRESOR values.

Because the DRESOR values are determined among different points of the medium in different directions, the space of the medium and the solid angle 4π should be divided into different discrete elements at first. The outline of the DRESOR method can be found in Zhou et al. (2004), Zhou and Cheng (2004) and Cheng and Zhou (2007). The method follows the general procedure of the READ method Yang et al. (1995). In the READ method the total energy is divided N_0 energy bundles with initial normalized energy E_0 =1.0 for each bundle. The treatments for the rays traveling in the medium, such as stochastic determination of the emitting direction and the change of the traveling direction are all described in Yang et al. (1995).

4. MEASUREMENT PRINCIPLE

In this work, the furnace system is assumed to be filled by a gray emitting, absorbing, and scattering gas-particle mixture, surrounded by gray emitting, absorbing, and reflecting wall surfaces. For processing a flame image in the visible region, the radiation emitted, absorbed and scattered by the suspended particles (such as soot) is considered, while the radiation emitted and absorbed by the gaseous components such as CO_2 and H_2O in the flame is neglected, since it is significant only in the infrared region.

4.1 Image processing

The color image of a flame is composed of three monochromatic images of red, green, and blue. So, three monochromatic images under the visible wavelengths of red, green, and blue can be acquired by a color image detector. According to the spectroscopic responses of the CCD camera of the color image detector, the central wavelengths of red, green, and blue sensors are $\lambda_r = 700$ nm, $\lambda_g = 546.1$ nm, and $\lambda_b = 435.8$ nm, respectively. The sensitive bands of the red, green, and blue images to the visible radiation around their central wavelengths are not narrow, but the assumption of gray, continuous radiation from the particles of combustion medium led us to assume that *R*, *G*, and *B* data in a color image are directly proportional to the approximate monochromatic radiations in their central wavelengths, respectively. So,

$$I(\lambda_r) = f(R) \approx k_r R,\ \ I(\lambda_g) = f(G) \approx k_g G,\ \ I(\lambda_b) = f(B) \approx k_b B \tag{5}$$

where k_r, k_g, k_b are the calibration coefficients. According to Wien's radiation law, we can obtain

$$\boldsymbol{k_r} = \boldsymbol{C}_1\varepsilon_{\boldsymbol{r}}\boldsymbol{e}^{-C_2/\lambda_{\boldsymbol{r}}\boldsymbol{T}} /(\pi\mathbf{R}\lambda_{\boldsymbol{r}}^5); \quad \boldsymbol{k_g} = \boldsymbol{C}_1\varepsilon_{\boldsymbol{g}}\boldsymbol{e}^{-C_2/\lambda_{\boldsymbol{g}}\boldsymbol{T}} /\left(\pi\mathbf{G}\lambda_{\boldsymbol{b}}^5\right); \qquad \boldsymbol{k_b} = \boldsymbol{C}_1\varepsilon_{\boldsymbol{b}}\boldsymbol{e}^{-C_2/\lambda_{\boldsymbol{b}}\boldsymbol{T}} /(\pi\mathbf{R}\lambda_{\boldsymbol{b}}^5). \tag{6}$$

A blackbody furnace with temperature range from 1073 K to 3273 K (with temperature errors within ± 5 K) was used to calculate the calibration coefficients. The flame temperature image can be calculated from the ratio between two monochromatic images of red, green and blue. Based on the two color principle, that is

$$T_m = -C_2\left(\frac{1}{\lambda_r}-\frac{1}{\lambda_g}\right)/\ln\left(\frac{I(\lambda_r)\lambda_r^5}{I(\lambda_g)\lambda_g^5}\right) = -C_2\left(\frac{1}{\lambda_r}-\frac{1}{\lambda_g}\right)/\ln\left(\frac{k_r R\lambda_r^5}{k_g G\lambda_g^5}\right). \quad (7)$$

It is noted that the temperature image and radiative intensity image calculated by Eqs. (5) and (7) are the cumulative result of the 3-D distribution of flame radiation inside the furnace. If one wants to acquire temperature along the direction of a ray such as 2-D temperature distributions, the inverse calculation of radiative transfer must be used. The detailed method is as below.

4.2 Reconstruction of temperature distribution inside the furnace

In order to reconstruct the 2-D temperature distribution of combustion medium in furnaces, we need an equation to relate the 2-D temperature distribution in the furnace with the boundary radiative information received by the image detectors. In application, the furnace system studied is divided into ***M*** spatial meshes for its medium zone and ***M'*** surface meshes for its surface area, and the total number of image pixels in the image detectors is set as ***N***. According to a new solution method (Zhou et al., 2004) proposed for the radiative transfer equation (RTE) in an absorbing, emitting, and scattering gray enclosure, the radiative intensity image ***I*** received by image detectors can be calculated as

$$\mathbf{I} = \mathbf{A}_I\mathbf{T}, \quad (8)$$

where $\mathbf{I} = (I(1)\cdots I(j)\cdots I(N))^T$ can also be measured using image processing techniques described in previous section, $\mathbf{T} = (T^4(1)\cdots T^4(i)\cdots T^4(M+M'))$ represents the 2-D temperature distribution in the furnace, $\mathbf{A}_I \in R^{N\times(M+M')}$ can be obtained from DRESOR method (Zhou and Cheng, 2004, 2007), and related with the installation and imaging parameters of the image detectors, and the radiative properties of particulate medium.

A temperature image $\boldsymbol{T_m}$ can be calculated from two monochromatic radiation images from a color image by Eq. (7), and it was further related to the temperature distribution ***T*** by

$$\boldsymbol{T_m} = \boldsymbol{A'T} \quad (9)$$

where $\mathbf{T}_m = \left(T_m^4(1)\ \cdots\ T_m^4(j)\ \cdots\ T_m^4(N)\right)^T$, and the matrix ***A'*** is calculated from $\boldsymbol{A_I}$. As shown in Eq. (9), the radiative intensity captured by image detector, scaled as $\boldsymbol{T_m}^4$ (*j*), comes from the radiation inside the furnace, which is also scaled as $\boldsymbol{T}^4$ (*i*). So, $\boldsymbol{T_m}$ holds linear relationship with ***T***. A modified Tikhonov regularization method has been used to reconstruct the temperature distribution determined by Eq. (9) from the radiative temperature image $\boldsymbol{T_m}$ (Lou and Zhou, 2005). That is

$$\mathbf{T} = (\mathbf{A}'^T\,\mathbf{A}' + \alpha\mathbf{D}^T\mathbf{D})^{-1}\mathbf{A}'^T\,\mathbf{T}_m = \mathbf{B}\mathbf{T}_m, \quad (10)$$

where ***D*** is a regularization operator, *α* is a regularization parameter, $\mathbf{B} = (\mathbf{A}'^T\,\mathbf{A}' + \alpha\mathbf{D}^T\mathbf{D})^{-1}\mathbf{A}'^T$. From Eq. (10), we can see that the reconstruction of the temperature distribution in the system is a one-step calculation procedure. It has been proved in application that the updating time for ***T*** was less than 5 s and it is suitable for on-line monitoring. It is noted that in Eq. (10) the temperature of ***T*** consist of the temperature of wall and combustion medium in the furnace. However, because of the ill-conditioned of Eq. (9), it makes the reconstruction more difficult that the wall temperature is reconstructed with combustion medium. So, when this method is put into application, the radiation from wall is taken out from the temperature image $\boldsymbol{T_m}$ if the reflectivity and temperature of wall is known. So, the temperature distribution of combustion medium is reconstructed with more accuracy.

5. RESULTS

The system under analyses is shown in Fig. 2. The cross-section is 0.7m x 0.7m and it is located 0.8 m from the burner. The results that are shown to follow are for 13.4 kg/hr diesel fuel oil combustion rate. For numerical calculation of the temperature field reconstruction, the gas region is divided into 10x10 = 100 elements, and the wall boundary is divided into 10x4 = 40 elements. The wall emissivity is assumed as 0.7. The wall temperature is experimentally measured by a thermocouple in a center point of a wall furnace in the test cross-section and the overall wall temperature is approximate by this temperature. The absorption coefficient of the gas combustion is assumed as 0.7 m^{-1} (Mazunder and Modest, 2002). Many images are acquired in every experimental test. Figure 3 shows a set of characteristics flame images.

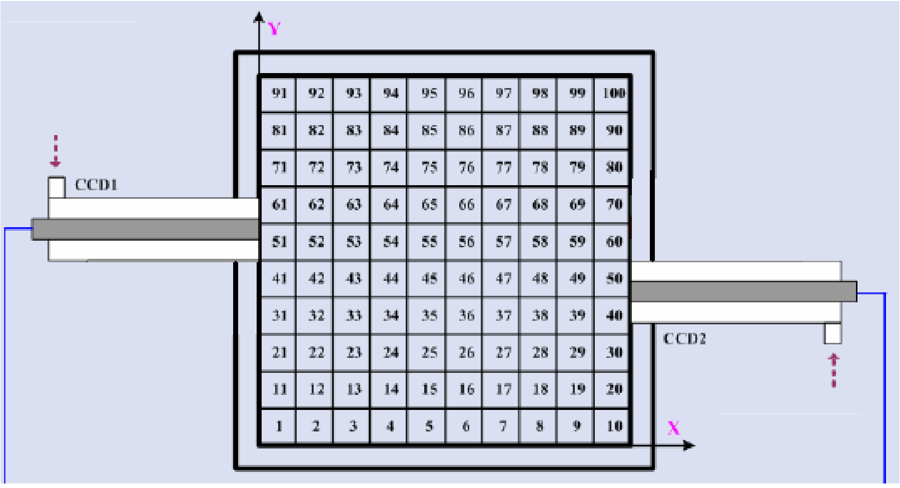

Figure 2. Scheme of the cross section and spatial grid

(a) Cameras CCD1 and CCD2

(b) Cameras CCD1 and CCD2

Figure 3. Flame images

In Figs. 4 and 5 are shown the graphics of a representative reconstruction of the two-dimensional temperature distribution for a same flame but for different time instant for the flame images in Figs. 3 (a) e 3 (b). The temperature values are in K. It is observed that the temperature distribution has a hotter point near the center and colder near the vertical walls. Also, the results show the upper tendency of the flame in the images of Fig. 3. Still, more work has to be made for validation and combustion characterization in different furnace operating conditions.

6. CONCLUSION

A new instrumentation system to estimate the temperature distribution in 2-D cross section in an oil furnace is utilized. The system consists of two color visible cameras, two detectors of flame images, a frame grab card, and an industrial computer. The flame image detectors were utilized to capture monochromatic radiation images on red, green and blue wavelength in the visible range. The medium is assumed gray. A modified regularization Tikhonov method is used for 2D temperature reconstruction from flame radiation images. The experimental tests were conduced in a pilot tunnel furnace. Results of temperature reconstruction of oil flame in a test cross section are qualitatively and quantitatively consistent. The faster process of visualization of the 2-D temperature distribution of fuel oil combustion shows that the method is suitable for the on-line monitoring of combustion temperature in industrial furnaces. There is still more work to do to improve the results by using radiative properties from experimental measurements in the system or methods of simultaneous estimation. This technique can be extended to apply in sugar cane furnaces and boilers.

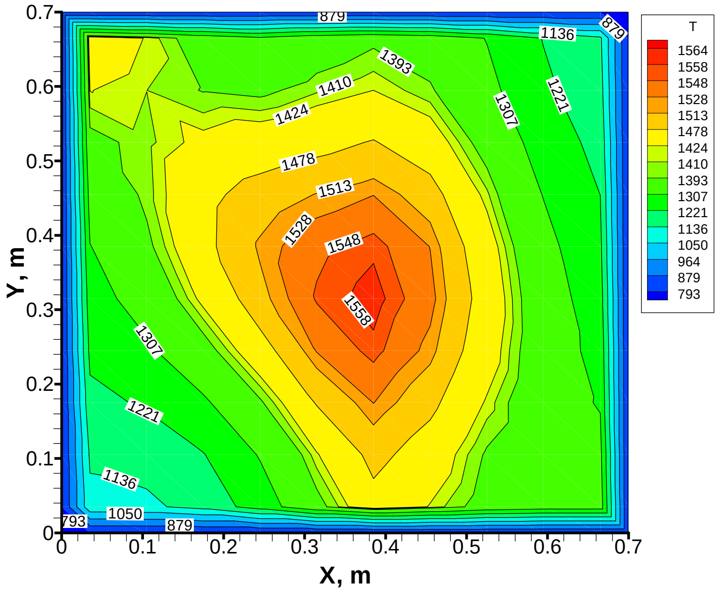

Figure 4. 2-D temperature distribution in a test cross section of the furnace for the image 3(a)

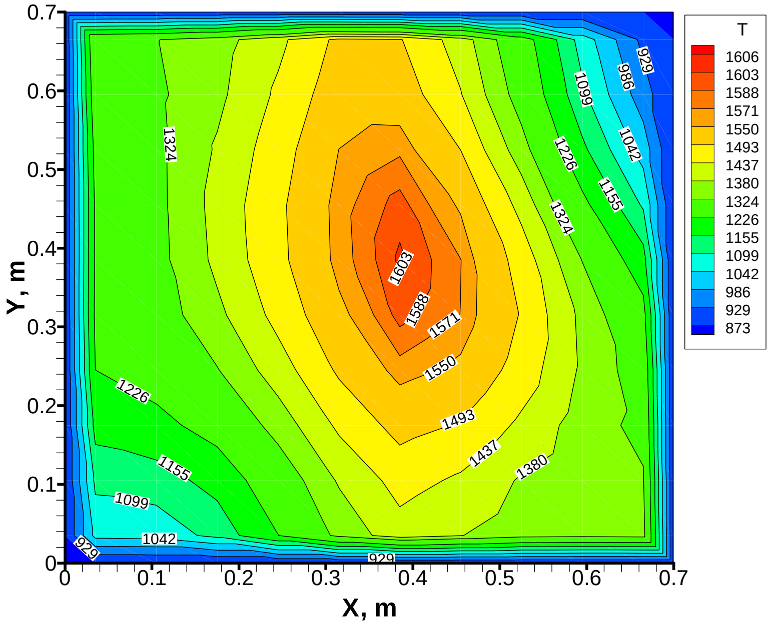

Figure 5. 2-D temperature distribution in a test cross section of the furnace for the image 3(b)

7. ACKNOWLEDGEMENTS

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