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Three Dimensional Temperature Distribution Analysis of Ultrasound Therapy Equipments Using Thermochromic Liquid Crystal Films

Gerardo A. López Muñoz and Gerardo. A. Valentino Orozco
Department of Bionics,
Interdisciplinary Professional Unit of Engineering and Advance Technology,
National Polytechnic Institute
Mexico

1. Introduction

As a coherent ultrasonic wave propagates through biological tissue, it is attenuated due to absorption and scattering. Absorption results from the irreversible conversion of acoustic energy to local heat, and it is the primary mode of attenuation in tissue. Ultrasound ability to interact with tissue to produce local heating has been known for a long time and nowadays ultrasound physiotherapy is widely used in health care to treat tissue injuries (Haar, 1999).

However, a large number of therapeutic equipment does not meet international standards. Rigorous quality control to verify whether physiotherapy ultrasound equipment performance is within acceptable range of acoustic intensity output plays a very important role in this context (Artho et al., 2002). Thermographic method of color analysis with thermochromic liquid crystal films is a fast and simple way to evaluate the bidimensional thermal distribution in an acoustic field produced by the ultrasound physiotherapy equipment (Jones & Carnochan, 1986).

Thermochromic liquid crystal films temperature visualization is based on the properties of some cholesteric liquid crystal materials that reflect definite colors at specific temperatures and viewing angles. These properties depend on their molecular organization; they are composed of molecular layers, where each one has a light rotation respect to the closest adjacent plane around an axis. This propriety generates a helicoidal structure that reflexes the incident white light (Ireland & Jones,2000). Correspondence between color and temperature is possible since liquid crystals emit narrow centered bands around one wave length and these bands change regularly for others colors with temperature rise (Cristoforetti et al., 1993).

Color changes in thermochromic liquid crystal films are repeatable and reversible as long as the films are not physically or chemically damaged. The time response of thermochromic liquid crystal films is approximately 10 ms. Due to the reversibility and the repeatability of color changes, thermochromic liquid crystal films can be calibrated accurately and used in this way as a temperature indicators (Stasiek & Kowalewski, 2002).

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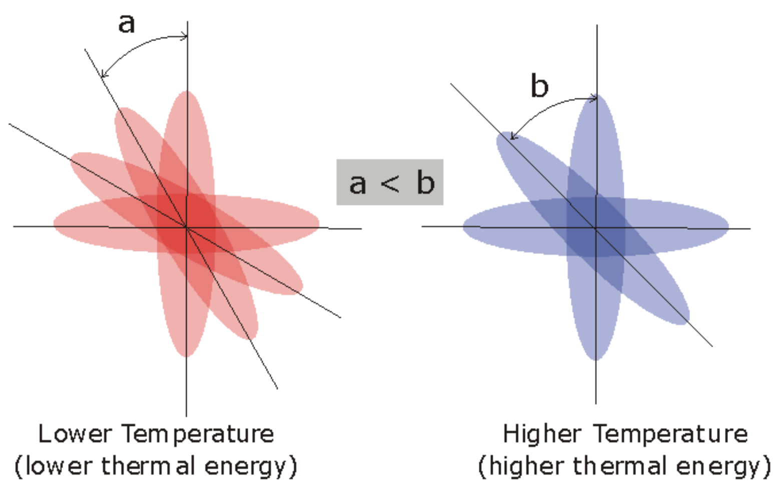

Fig. 1. Relative angles between the molecules with the change of temperature

The use of thermochromatic materials for thermal distribution mapping is based on the fact that the acoustic energy absorption by one medium and the temperature rise, according to the temporal average intensity of the ultrasound, is given by (Martin & Fernandez, 1997):

$$A = 2\alpha_a I, \tag{1}$$

where A is the energy absorption rate in the material, a_a is the absorption coefficient and I is the temporal average intensity of ultrasound.
As the intensity distribution is non-uniform in a cross-section of the ultrasonic beam (Fish, 1994), it is possible to observe changes in the intensity distribution or temperature in a plane where the beam is intercepted by the thermochromatic film (Macedo et al., 2003).
Digital image processing allows visualizing and extracting information from an image and it has many advantages over analog image processing. It allows a much wider range of algorithms to be applied to the input data, and can avoid problems such as the noise and signal distortion during processing (Castelman, 1996). Three-dimensional reconstruction is the process in which a sequence of two-dimensional images taken from a common scene is processed to create the planar projections of a volume (Gómez et al., 2006). Changes produced by the acoustic wave passing through a medium might be interpreted for obtaining the geometrical and mechanical characteristics of the medium.
Temperature qualitative measurements using thermochromic liquid crystal films have been described. They use digital image processing algorithms based on the conversion of color images to gray-scale images (Gómez et al., 2006). By using color models, an abstract mathematical model describing the way colors can be represented as tuples of numbers; it is possible to obtain a relation between the temperature rise and the color change in thermochromic liquid crystal films for a temperature qualitative measurement (Lopez et al., 2008).
This chapter describes the acquisition of a sequence of thermal images of physiotherapy ultrasound equipment with a thermographical system; a chromatic modeling of TLC films in the temperature range from 35ºC to 40ºC; DIP for extracting a quantity that represents color and obtaining a mathematical relation between color-temperature for a quantitative evaluation of temperature rise in ultrasonic thermal images and finally, a tree-dimensional reconstruction for a future medical parameters evaluation.

2. Methodology

A. Thermocromic Liquid Crystal Films

These materials reflect incident white light selectively due to their layered-molecular structure to show bright iridescent color. Their color change, due to temperature increases, usually from colorless to red at low temperature, through the colors of the visible spectrum to blue and colorless again (Hallcrest,2008). They are viewed normally against a black background, and the materials have good long-term stability.

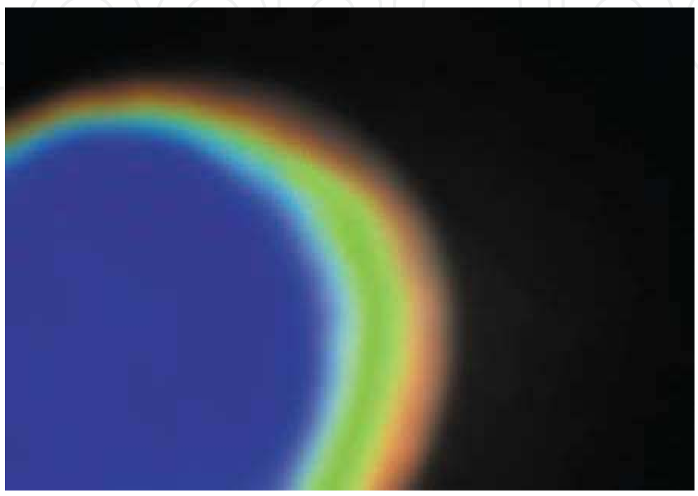

Fig. 2. Color changes in TLC films

The TLC film used in this work (R35C5W, Hallcrest®) has a start temperature of 35°C and a bandwidth of 5°C (Hallcrest, 2008).

Red Start (black to red)	**Green Start**	**Blue Start**	**Clear Point (blue to black)**
ºC	ºC	ºC	ºC
35±0.5	36±0.5	40±0.5	49±0.5

Table 1. Color-temperature relation for the TLC film

2.1 Practical implementation

A. Chromatic Modelling

The experimental setup for obtaining the sequence of thermal images is depicted in Figure 3. A TLC film was immersed in a black painted water tank (dimensions: 70 cm x 20 cm x 20 cm). In order to avoid image distortion due to bubble formation, degasified distilled water was used. The water temperature was increased up to 45ºC by using an aluminum water heater. A water pump was used to avoid the temperature gradients formation.
To get thermal images, the heater was removed and the temperature was monitored with an Hg thermometer (Brannan®, 0.1ºC resolution). The sequence of images started at 40ºC, with a temperature increase between acquisitions of 0.5ºC, and finished at 35ºC. The thermal images were viewed by using a metallic reflecting film at 45º from the TLC film and recorded by a commercial camera (Sony®, DSC-W55). A white light illumination system (color temperature of 6500º K) was used as floodlighting to control the white light intensity.

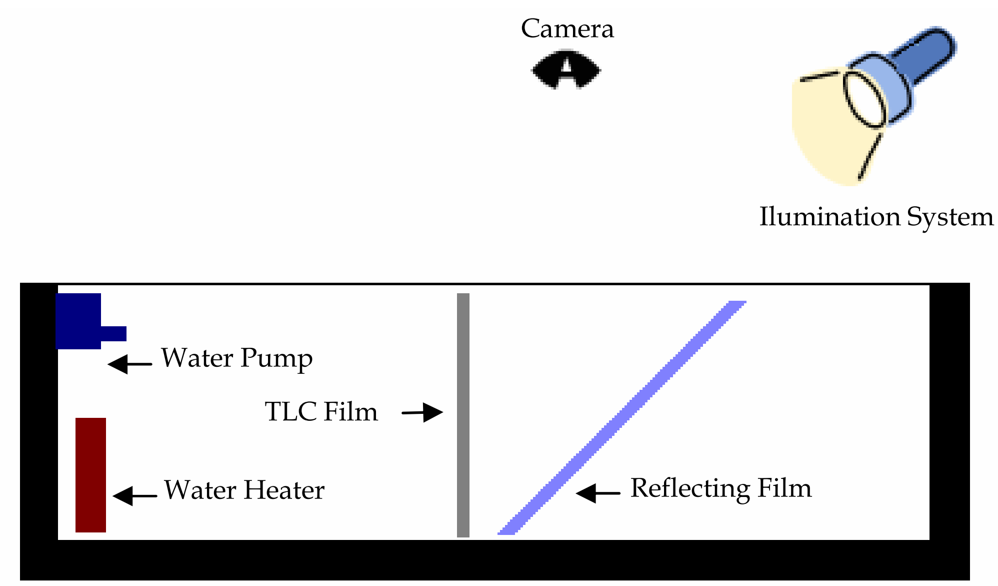

Fig. 3. Experimental setup

Numerical methods were applied to each thermal image to obtain the chromatic components in the RGB color model. The values of the components were between 0 and 255. The color was digitally represented with 1 byte. The algorithm is illustrated in Figure 4.

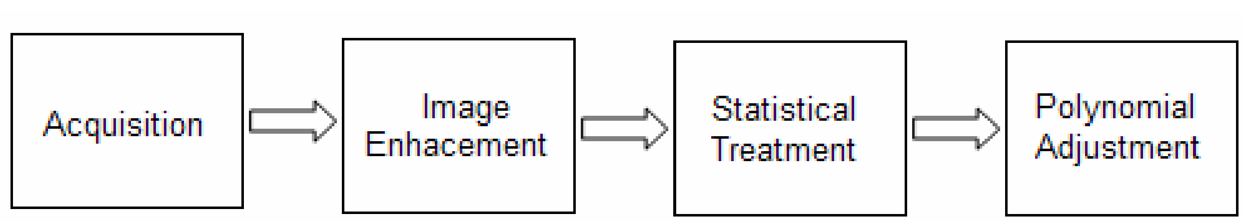

Fig. 4. Flow diagram of the algorithm for image processing

The image enhancement consists of spatial filtering to reduce noise of the images originated by electronic noise in the input device (digital camera) sensor and circuitry, or particles in the medium. For doing that a median filter was implemented.
The median filter, instead of the replacement of the pixel value with the mean values of neighboring pixels, replaces the pixel with the median of the neighboring values. The median is calculated by first sorting all the pixel values from the surrounding neighborhood into numerical order and then replacing the pixel being considered with the average pixel value. This filter is applied to each matrix (3) that represents the image in the RGB color model. The arithmetic average of the pixel values in filtered images is obtained for each chromatic component.

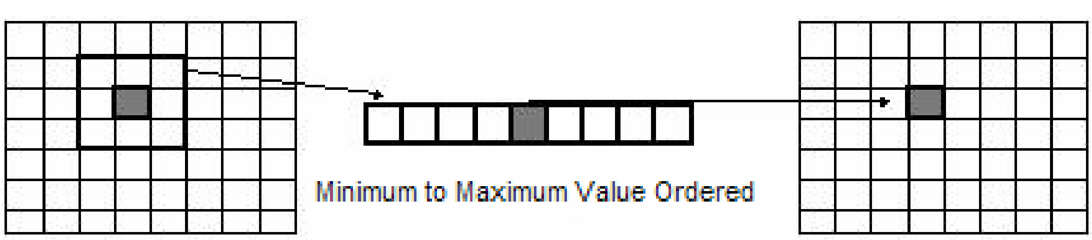

Fig. 5. Median Filter Implementation

Statistical treatment consists of obtaining the median value of the chromatic components on different thermal image sequences to describe the tendency in the color components with the change of temperature.
To obtain the polynomials that relate the change of the chromatic components and the temperature, the minimum quadratics adjustment is applied to the median of the pixel values in the color components.

B. Thermal Mapping

The experimental setup for exposing and viewing the thermal imaging system is illustrated in Figure 6.

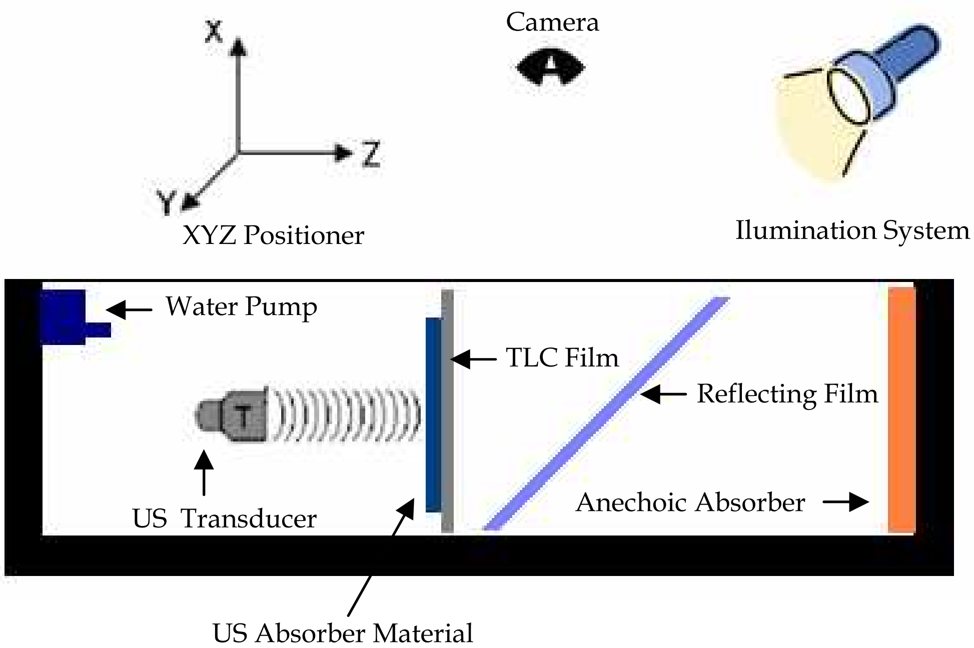

Fig. 6. Schematic of the experimental setup

Thermography system sensibility is related with the temperature rise induced by the ultrasound intensity and is determined by the absorbed ultrasonic energy (Martin & Fernandez, 1997).
The use of low reflection and high absorption attenuation coefficient materials enhances the heating of the TLC film. Polyvinyl chloride and polyurethane copolymer film with a water sonic wave reflection coefficient of 0,06 ±0,01 and a sonic attenuation coefficient of 23,5 ±1,02 dB•cm^{-1}•MHz was used (Macedo et al., 2003). These values agree with the IEC 61161 regulations for absorber materials (IEC, 1992).
A physiotherapy transducer (1MHz) and TLC film coupled to copolymer film with acoustic gel; were immersed in the black painted water tank filled with degasified distilled water. To minimize standing wave effects, ultrasound transmitted through the imaging system was absorbed and scattered by an anechoic rubber absorber positioned at the end of the system (Ham A, National Physical Laboratory) (Zequiri & Bickley, 2000). For mapping the temperature distribution on the copolymer film, the temperature of water was fixed at 34.5°C, below the start point of the TLC film. Circulation from water pump was added to system for a homogeneous water temperature.

Transducer was excited with a physiotherapy equipment (Ibramed®, Sonopulse) in continuous mode at 1 MHz and nominal ultrasonic intensity was set up to 2W•cm^{-2}.
An algorithm for processing the bi-dimensional thermal images sequence and for enhancing the visualization of the registered thermal phenomenon was developed. Figure 7 illustrates the processes of the digital image treatment.

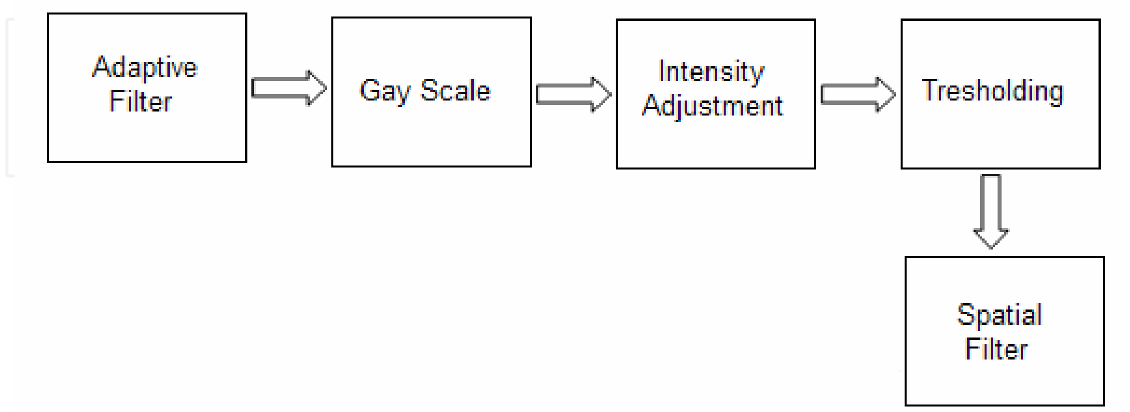

Fig. 7. Algorithm for image processing

Wiener adaptive filter implementation allows preserving edges and reducing noise in images facilitating three-dimensional reconstruction and temperature detection. Pixelwise adaptive Wiener method based on statistics estimated from a local neighborhood of each pixel was applied to the three layers that represent the image considering that the software uses RGB model for representing an image.
Adaptive filter estimates the local mean and variance around each pixel by using the following equations (Math Works, 2006):

$$\mu = \frac{1}{NM} \sum_{n_1, n_2 \in \eta} a(n_1, n_2), \tag{2}$$

$$\sigma^2 = \frac{1}{NM} \sum_{n_1, n_2 \in \eta} a^2(n_1, n_2) - \mu^2, \tag{3}$$

where μ is the local mean and σ^2 the variance in a *N*-by-*M* local neighborhood matrix for each pixel in the evaluated image. Then a pixelwise is created using the following expression:

$$b(n_1, n_2) = \mu + \frac{\sigma^2 - v^2}{\sigma^2}(a(n_1, n_2) - \mu), \tag{4}$$

where v^2 is the noise variance; the algorithm uses the average of all the local estimated noise variances.
Once the images are filtered, the image sequence is converted from color to gray-scale; three-dimensional reconstruction cannot be used with images represented with more than one matrix. The expression for the conversion is given by (Math Works, 2006):

$$I = 0.2989R + 0.5870G + 0.1140B, \tag{5}$$

where *I* is the gray intensity, *R,G,B* represent red, green and blue intensities for the transformed pixel.

Afterward, intensity adjustment for improving image contrast based on gamma correction was carried out. Gamma correction modifies middle values. Contrast in clear or dark areas is enhanced without affect neither white (255) nor black (0). Figure 8 illustrates image contrast improvement by applying gamma correction.

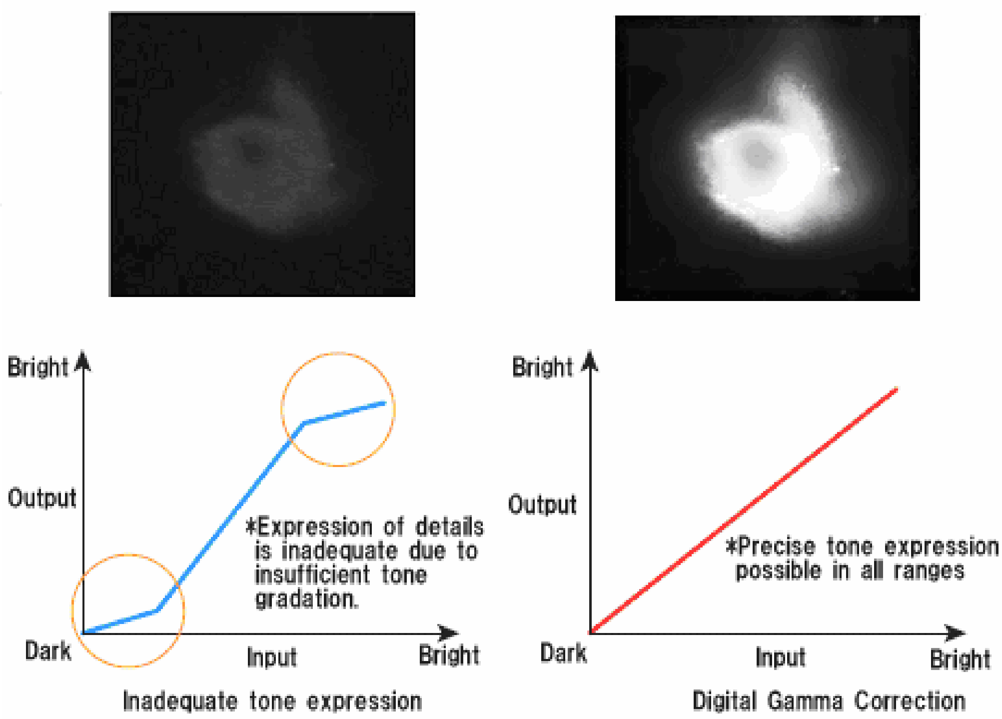

Fig. 8. Image intensity adjustment

Finally, the spatial filter consists of image thresholding and the resulting binary mask multiplied with the intensity adjusted image. Spatial filter eliminates environmental noise that distorts temperature distribution in thermal images enhancing visualization and three dimensional reconstruction.

C. Temperature Detection

Euclidean distance definition for two-point separation was used for the temperature detection taking into account color spatial point representation in the RGB color model. A numerical method for calculating Euclidean distance between evaluated pixel chromatic components in filtered thermal image and chromatic components for each one of the obtained temperatures in TLC characterization was developed. Distance is given by the following expression:

$$D(t) = \sqrt{(Rp - Rt)^2 + (Gp - Gt)^2 + (Bp - Bt)^2}, \quad (6)$$

where D is the Euclidean distance, t the evaluated temperature, Rp, Gp, Bp represent chromatic component values for the evaluated pixel and Rt, Gt, Bt chromatic component values for the evaluated temperature.

Subsequently, the minimum distance was calculated and was related with the temperature for the evaluated pixel.

D. Three-Dimensional Thermal Pattern Reconstruction

Gray scale filtered thermal images for volumetric thermal distribution reconstruction are used. The goal is to create a three dimensional matrix with all the processed images and to interpolate similar gray intensity values.

Three dimensional reconstruction is divided in the following four steps:

- Volumetric data organization and processing.
- Isosurfaces creation (interpolation).
- Reconstruction configuration: color, illumination and graphic texture.
- Vision angle and perspective.

First, images in a three dimensional matrix *V(x,y,z)* were organized, where *x,y* represent the coordinate and gray intensity level for the image and *z* represents the image number of the sequence. Manipulating the matrix for just taking a part of it was possible; that implies that it is possible to obtain cuttings of the temperature pattern in any transversal section for viewing the thermal distribution inside the volume.

Thermal image edge filtering was applied for a smooth volume isosurface. Then, image outline pixel values are interpolated with their respective gray intensity level. This procedure allows creating the volume geometry and giving a specific color to each of the interpolated gray levels. Finally, perspective, texture and illumination are configured. Figure 9 illustrates edge interpolation carried out by the algorithm for reconstructing the thermal distribution.

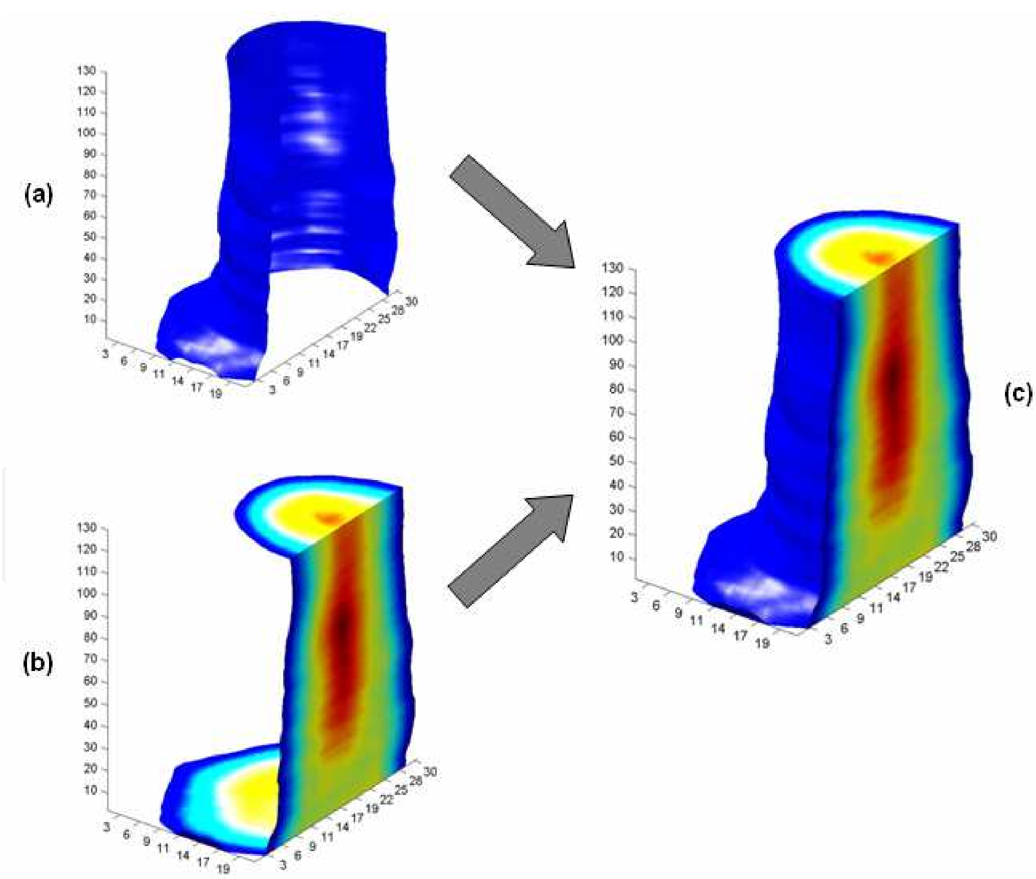

Fig. 9. (a) External edges interpolated. (b) Internal edges interpolated. (c) Reconstructed volume (Gómez et al.,2006).

3. Results

A. Chromatic Modelling

The images were taken at different times. Nine sequences of thermal images were taken. A median filter with a 15 x 15 kernel was implemented to improve the images. The arithmetic mean was applied to get the tuples of values for the chromatic components in the images. The tuples for the nine measurements were treated statistically with the median and the standard deviation.

For the polynomial adjustment, the minimum quadratics adjustment and the median were used. The polynomial degree was adjusted to the best fitting and the lowest degree considering the behavior tendency of the color component values.

Red components are higher in the range from 35ºC to 36ºC. Red components have a non-lineal behavior tendency (Figure 10).

The mathematical model for the chromatic red components is defined by the equation:

$$R=-4.30t^5+11.05t^4-4.75t^3-5.03t^2+2.66t+0.69, \quad (7)$$

where R is the intensity of the red components and t is the temperature defined between 35ºC and 40ºC.

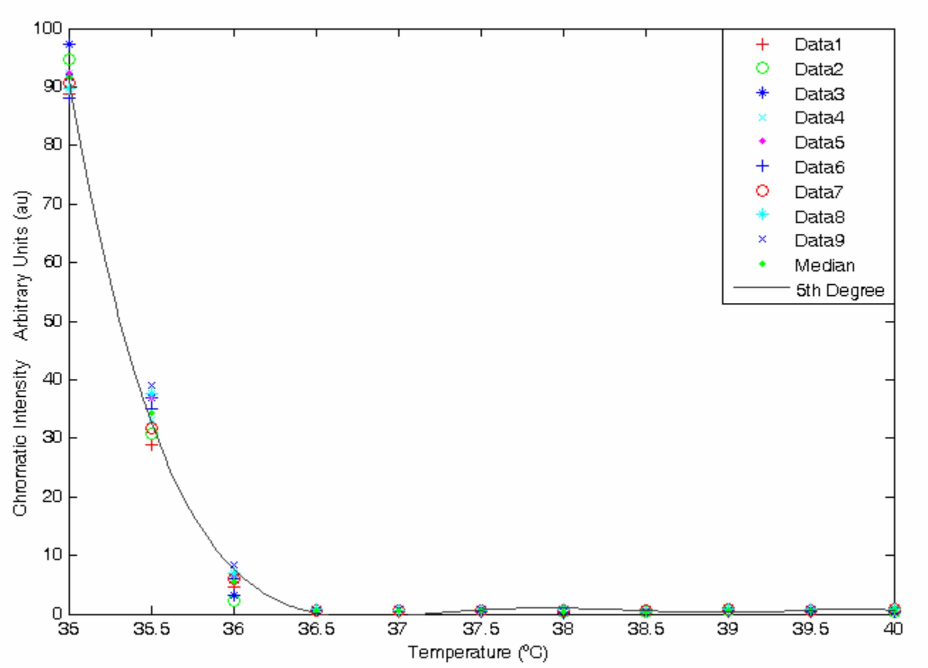

Fig. 10. Polynomial adjustment of the chromatic red component

Green components are present in the range from 35.5ºC to 37ºC. Green components have also a marked non-lineal behavior tendency (Figure 11).

The mathematical model for the chromatic green components is defined by the algebraic expression:

$$G=-3.12t^6+5.55t^5+1.43t^4-5.44t^3+7.37t^2-21.50t+77.3, \quad (8)$$

where G is the intensity of the green components and t is the temperature defined between 35ºC and 40ºC.

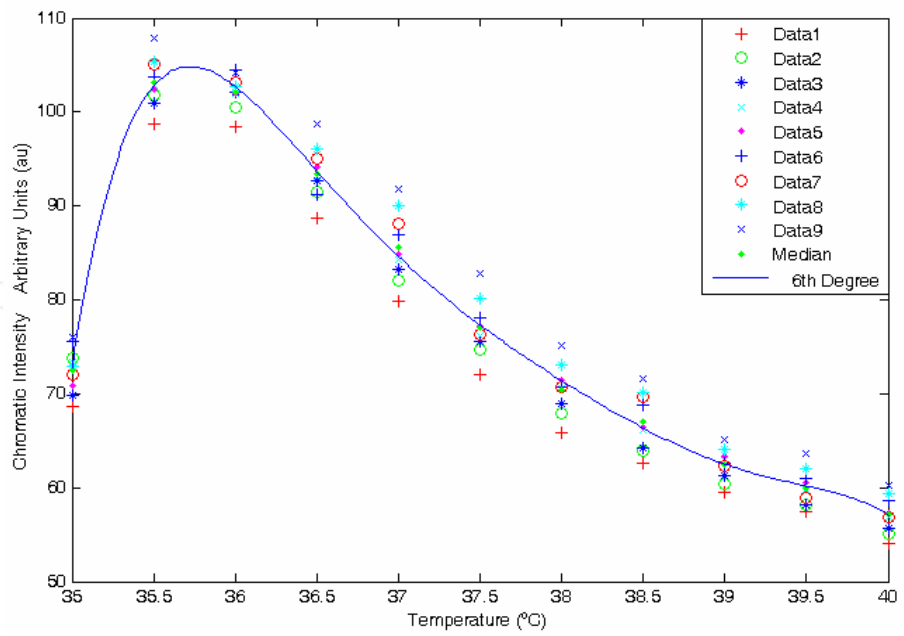

Fig. 11. Polynomial adjustment of the chromatic green component

Blue components are present in the range from 37.5ºC to 40ºC. Blue component has an almost-lineal behavior tendency (Figure 12).

The mathematical model for the chromatic blue component is defined by the expression:

$$B=-1.63t^4+0.41t^3-0.82t^2+31.81t+127.72, \tag{9}$$

where B is the intensity of the blue component and t is the temperature defined between 35ºC and 40ºC.

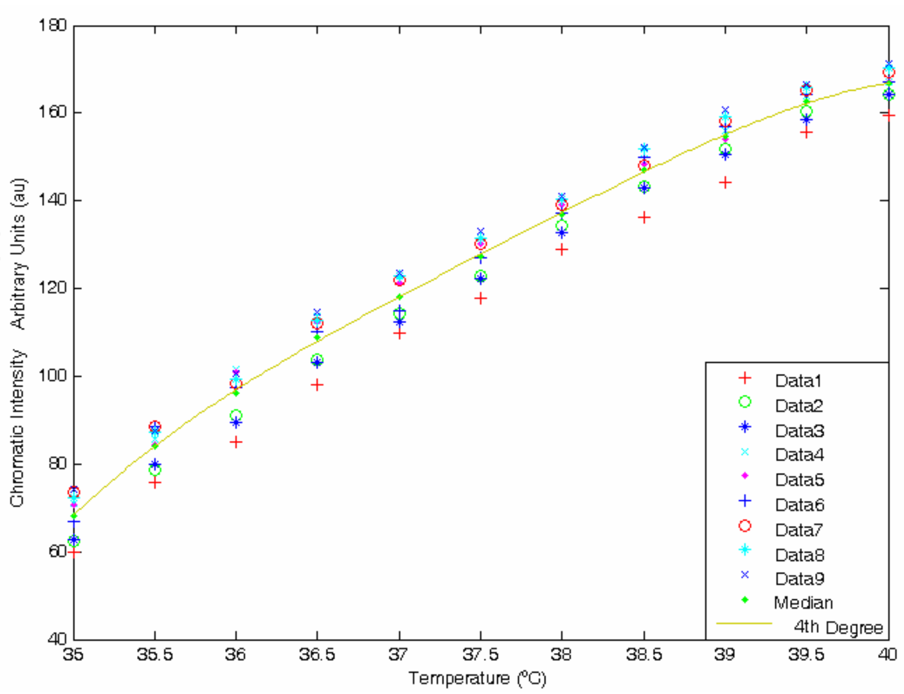

Fig. 12. Polynomial adjustment of the chromatic blue component

Temp.	Median			Standard Deviation		
ºC	Red	Blue	Green	Red	Blue	Green
40	0.56	167.20	56.92	0.19	3.60	2.03
39.5	0.63	163.92	59.85	0.19	3.60	2.04
39	0.54	155.87	62.68	0.16	5.19	1.78
38.5	0.47	148.34	66.37	0.10	5.13	3.15
38	0.44	139.03	70.67	0.14	4.03	2.75
37.5	0.52	130.34	76.33	0.13	5.20	3.15
37	0.51	121.16	84.83	0.14	5.14	3.87
36.5	0.64	11.20	93.11	0.13	5.82	2.93
36	6.06	98.25	102.11	1.90	5.88	1.86
35.5	35.10	85.76	102.85	3.46	4.78	2.69
35	91.75	70.76	72.90	2.87	5.39	2.50

Table 2. Statistical treatment for the chromatic components measurements

B. Thermal Mapping

Once the ultrasound beam was switched on, the formation of a stable thermal image on the TLC film took approximately 30 s. Measurements were made at 2 mm intervals up to 80 mm. Thermal images were taken every 30 s so that the image was steady. At the end a sequence of 40 images was obtained (Figure 13).

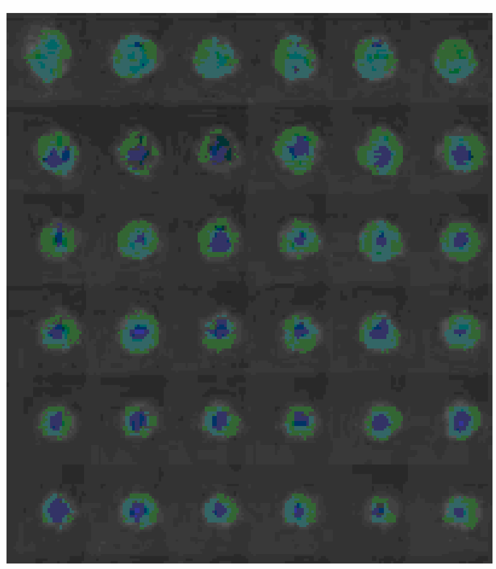

Fig. 13. Thermal image sequence

An adaptive Wiener filter with a 25 x 25 kernel was implemented to improve the images; binarization was applied with a 0.5 luminance level (Figure 14).

C. Temperature Detection

A graphic interface was developed. This graphic interface facilitates user interaction and avoids the necessity of working with the programming code. The algorithm is semiautomatic. Users have to take part in some image treatment process and parameters configuration (Figure 15).

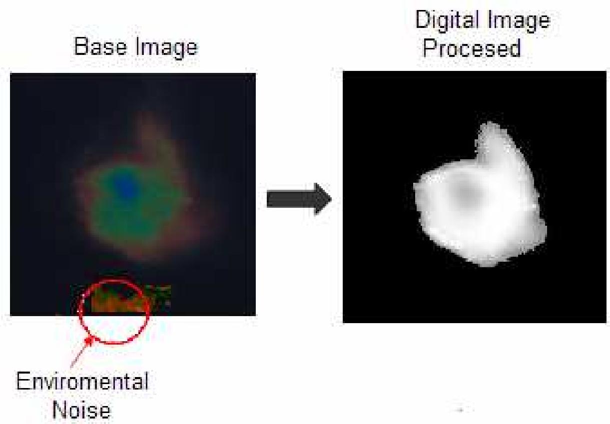

Fig. 14. Thermal image sequence

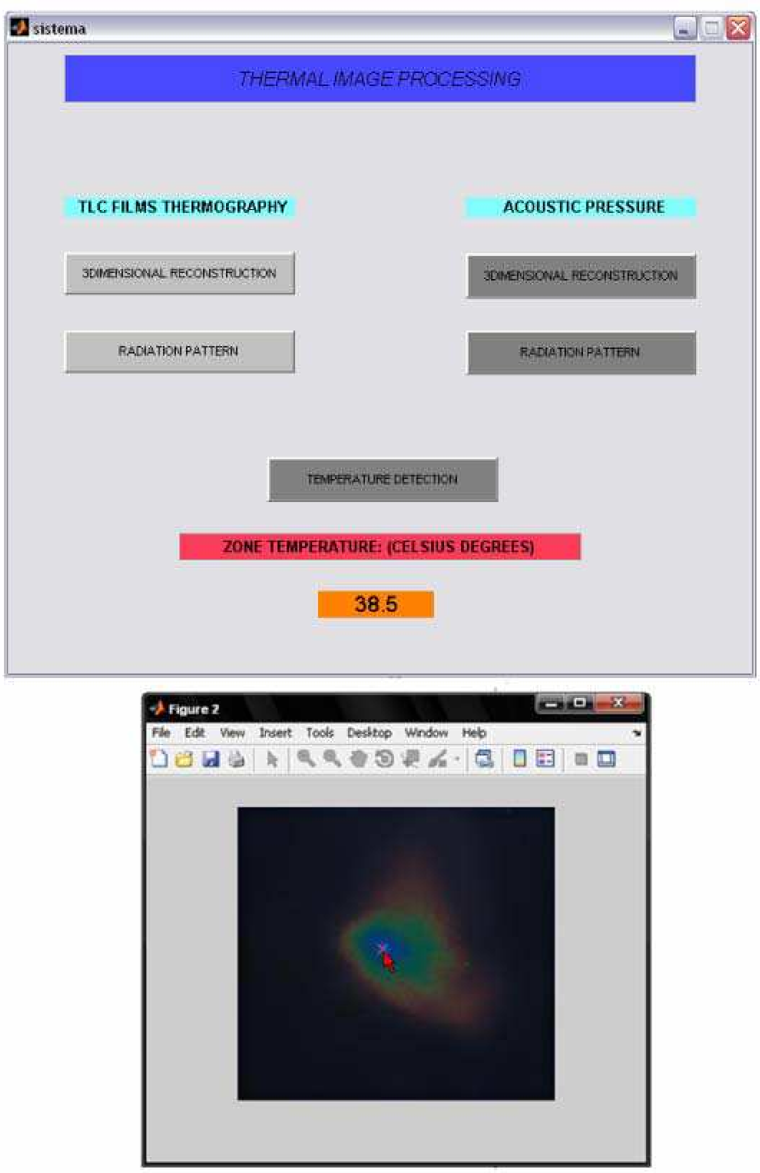

Fig. 15. Temperature detection with graphic interface

D. Three-Dimensional Thermal Pattern Reconstruction

For making three-dimensional reconstruction, each image of the sequence was superposed one behind the other in a three-dimensional array to interpolate pixel values corresponding to the edge of each image with the same level of intensity to create an isosurface. Color map, color bar, illumination and material were configured for the scene.

Radiation pattern gives information about the non-homogeneities of acoustic intensity when they are related to the gradients of temperature in thermal images (Figure 16).

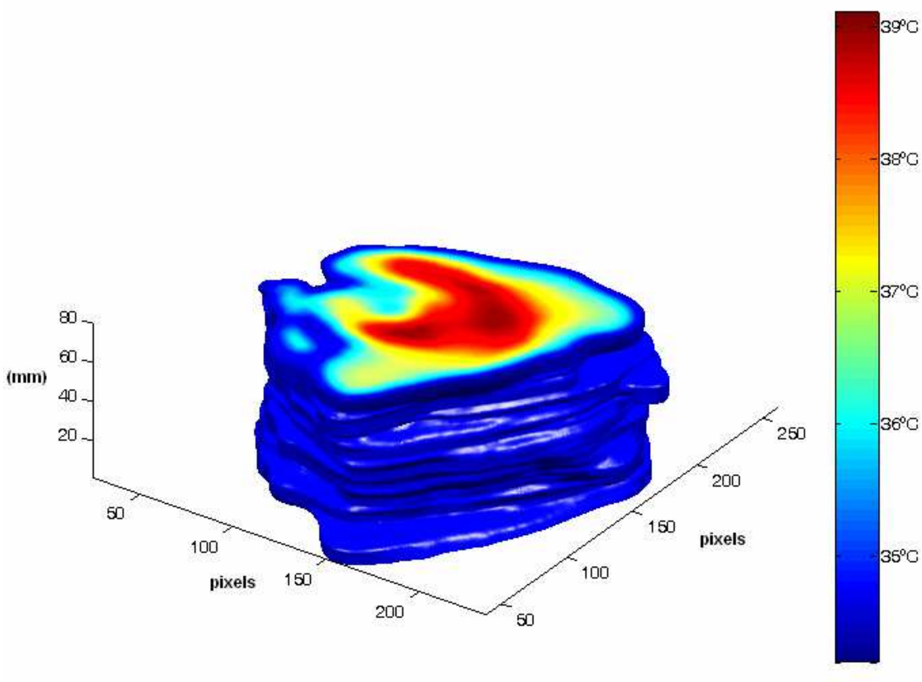

Fig. 16. Three-Dimensional temperature pattern reconstruction

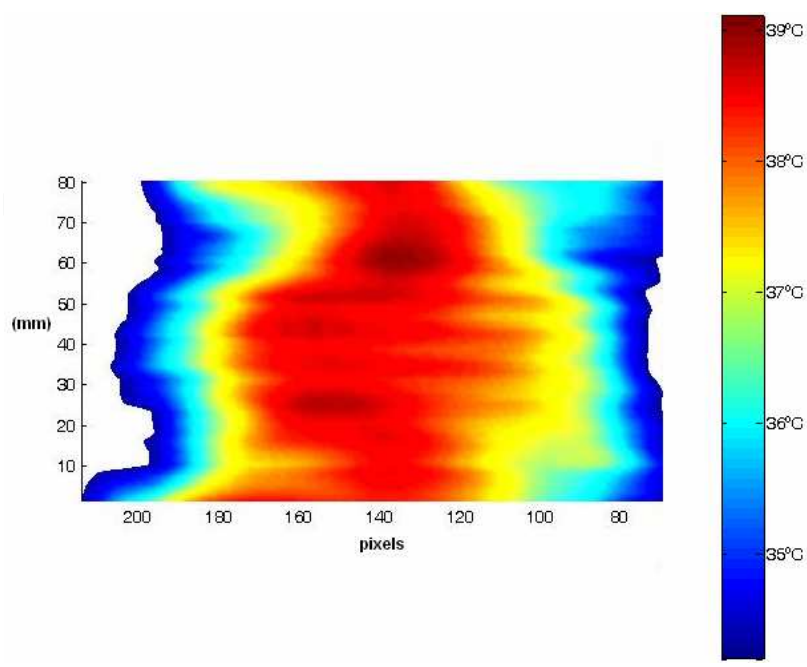

Fig. 17. Temperature pattern reconstruction.

Data of the three-dimensional (3-D) array was used for taking a transversal section for viewing thermal distribution inside the volume.
The thermal distribution pattern in the radiated copolymer shows a high temperature region distributed throughout *z* axis with two regions where the temperature reaches its maximum point, between 25 – 60 mm of depth (Figure 17).

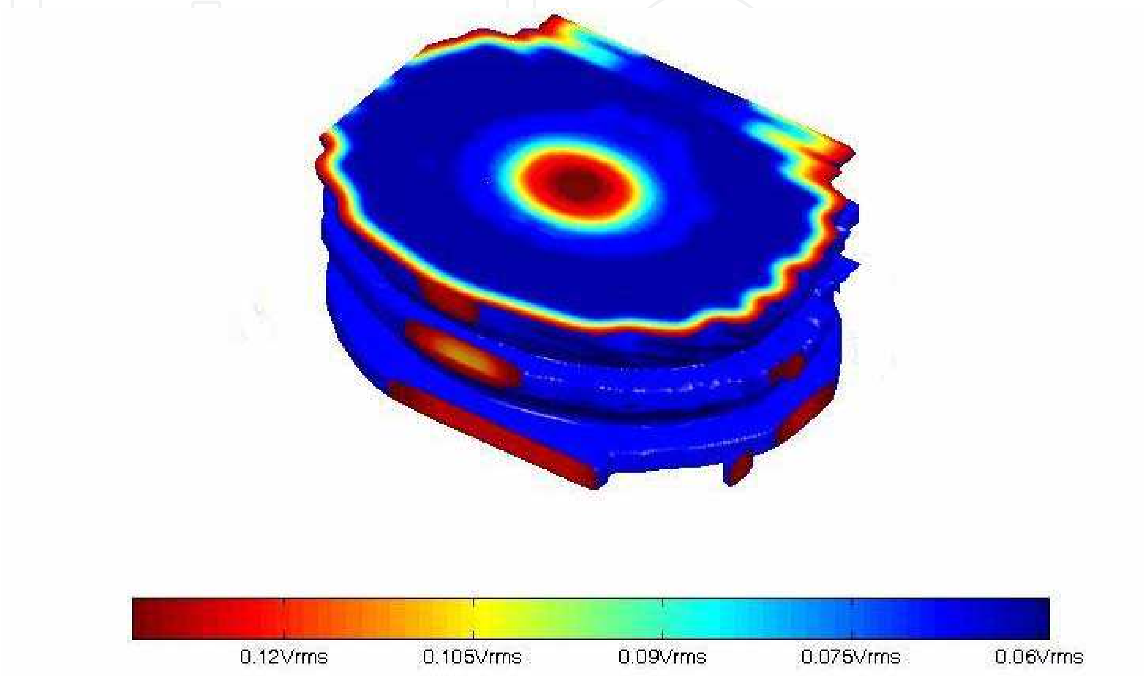

Fig. 18. Three-Dimensional acoustic pattern reconstruction

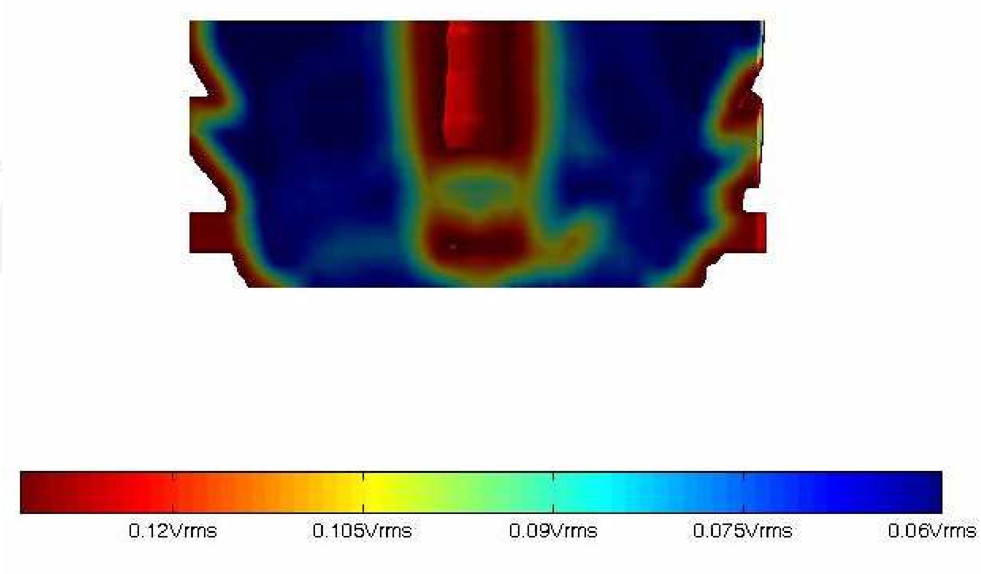

Fig. 19. Acoustic pattern reconstruction

System Validation wad done by comparing the radiation pattern obtained with the thermocromic liquid crystal films and the pressure acoustic mapping technique.This comparison was done using the acoustic field data obtained by Bazán (Bazán, 2005) for the theraphy transducer (Ibramed®, Sonopulse) @ 1MHz, along Z axis with 2mm separation between each measurement starting at Z = 0 mm and finishing at Z = 80mm.

4. Discussion

One of the main advantages of the technique based on TLC sheets is that the reflected light is within the visible spectrum allowing viewing and photography by using a rather conventional camera.

Chromatic modeling. DIP was used for a qualitative measurement of thermal distribution in gray-scale images (Gómez et al., 2006). In this work a sequence of thermal images between 30-35 Celsius degrees were obtained and a DIP algorithm was implemented for the mathematically modeling in the TLC film using the RGB color model. The use of a color model allows obtaining a mathematic relation between temperature and an abstract representation, as color is considered, to get a temperature quantitative measurement.

Thermal mapping. This method applied to ultrasound fields was proposed by Cook and Werchan (Cook & Werchan, 1971) improved by Macedo (Macedo et al., 2003) and Gómez (Gómez et al., 2006). Coupling polyvinyl chloride and polyurethane copolymer material to TLC film improves ultrasound absorption, delays thermal equilibrium and enhances system sensibility.

These techniques are dependent of the following factors:

Surrounding illumination – Uncontrolled light sources and possible reflections from surfaces in the TLC may cause errors in the measured temperatures; an illumination analysis is required in other applications of the method.

Viewing angle – The TLC colors depend on the angles between the camera and the TLC surface.

Controlled temperature conditions – It is important to control the temperature to achieve desired accuracy and to avoid the temperature gradients formation. Hysteresis is one of the problems when the crystals are heated above their clearing point temperature (Baknaria & Anderson, 2002).

Digital resolution – The minimal number of pixels needed per unit length of the TLC surface depends on the magnitude of the temperature gradient: locations with large gradients needing more pixels to achieve a desired accuracy. There is a possible algorithm failure when the thermal image resolution is increased. Time of processing also increases when resolution increases.

Temperature detection. A classifier algorithm for temperature detection was developed by using the RGB color model and the chromatic modeling by relating TLC film temperatures with colors and calculating distance separation between each temperature and the evaluated pixel in thermal image. Minimum separation distance was taken for estimating temperature in the evaluated pixel.

Three-dimensional thermal pattern reconstruction. The three-dimensional reconstruction of ultrasound thermal beamshape gives the possibility to know the radiation pattern (temperature distribution) and penetration depth which are important medical parameters for ultrasound physiotherapy treatment.

5. Conclusion

A thermographic technique based on TLC films to obtain two dimensional thermal images was developed; the practical implementation of the method is simple and low cost, it is a suitable way for chromatic and ultrasound therapy transducers characterization with TLC films.

DIP allows image improvement by reducing noise in thermal images and the possibility to manipulate images as a mathematical representation for an efficient obtainment of the required information in an image. Adaptive filter Wiener implementation allows reducing noise selectively enhancing definition in thermal images and tree-dimensional reconstruction.

The color change in TLC films is related with the chromic contribution of the components in the RGB color model and related with the changes in temperature. The statistical analysis shows the non-linear but regular change in the tendency for the RGB components. Tests with different TLC films in controlled environmental conditions are necessary trying to find a general mathematic model that describes thermochromic behavior allowing a higher resolution and extending measurement range.

An algorithm for chromatic modeling in TLC films based on RGB color model was developed obtaining a mathematical relation between color and temperature allowing a quantitative temperature measurement by using a classifier algorithm based on Euclidean distance. Neural networks are proposed for temperature detection algorithm alternative technique.

The future work is to develop tissue equivalent materials that mimic thermal and acoustic proprieties for obtaining the thermal distribution and to detect changes in beam uniformity for ultrasonic therapy equipment.

6. Acknowledgment

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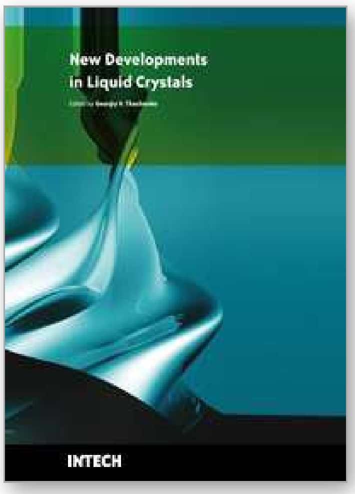

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Liquid crystal technology is a subject of many advanced areas of science and engineering. It is commonly associated with liquid crystal displays applied in calculators, watches, mobile phones, digital cameras, monitors etc. But nowadays liquid crystals find more and more use in photonics, telecommunications, medicine and other fields. The goal of this book is to show the increasing importance of liquid crystals in industrial and scientific applications and inspire future research and engineering ideas in students, young researchers and practitioners.