Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG
Copyright © 2005 by ABCM

METHODOLOGY FOR THERMOGRAPHY APPLICATION IN EVALUATION OF DEFECTS AND NON-APPARENT INCLUSIONS IN MATERIALS

Sinthya Gonçalves Tavares
Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais - Av. Antônio Carlos 6627 – Pampulha – Belo Horizonte – MG – Brasil – 31270-901
gtavar@terra.com.br

Ângela Mara Cunha
Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais - Av. Antônio Carlos 6627 – Pampulha – Belo Horizonte – MG – Brasil – 31270-901
amscunha@yahoo.com.br

Roberto Márcio de Andrade
Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais - Av. Antônio Carlos 6627 – Pampulha – Belo Horizonte – MG – Brasil – 31270-901
rma@ufmg..br

Abstract. *Over the last few years not only have various publications reported the effectiveness of the cost-benefit relationship of using thermography in industry on preventive and predictive maintenance programs but they have also highlighted its effectiveness. The capability to identify potential problems like defects and non-apparent inclusions, humidity, overheating spots in equipment and or in phases of processes, from their very beginning, in a non-intrusive manner has been fostering the dissemination of this technique among several fields. This study will discuss the actual possibilities of employing thermography in thermal evaluations as well as its operational modes. The results of measurements in samples of known characteristics will be presented. The variables involved in the measurement process will be discussed and the influence upon the measurement results will be evaluated. Thus it will eventually be possible to suggest measurement which allow for optimization of the application of such technique. The experimental procedures have been carried out in the laboratories of Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais.*

Keywords*: thermography, experimental trials, non-apparent inclusions, internal defects*

1. Introduction

Factors such as wide range of application, easy operation, quick measurement and answer, relatively easy interpretation of results and possibility of being utilized on moving objects have been adding more value to non-destructive thermal evaluations – NDTE (Dowling et al., 1998, Titman, 2001, Chrzanowski, 2001) Further examples are the studies which used thermography, referred in this work and in most of the literature as NDTE synonym, in order to collect data. Works such as Adams *et al.* (1988) that looked for to measure the loss of heat in incubators, is had validates of the technique. Another example is the use of the thermography in the quality control and project of semiconductors. (Talwar, Jogai and Loehr, 1998), in the industry of inks to determine the setting time (Can, 1998), in the evaluation of fatigue in materials (Luong, 1995), in the identification of leaking in canals (Engelbert, Hotchkiss and Kelly, 1997), in the control of process and product quality (Andrade, 1999), amongst other applications.

In the sector of materials, the thermography has found a number each bigger time of uses, especially masonry structures diagnose. It is justifiable, therefore, when submitted the adverse conditions for which they had been projected, these structures present variations in the integrity standards and, consequently, in the field of temperature. These alterations as presence of humidity, infiltrations, losses of heat and non-apparent inclusions, easily are caught for technique application.

In this work is present a methodology for thermography application in fails and non apparent inclusions evaluations in materials. Through results gotten in samples of known characteristics the real possibilities of the thermography job in thermal inspections will be raised. The involved variables in the measurement process will be argued and its influence on the measurement results will be evaluated, being able itself to suggest a measurement methodology that allow to optimize its application. The experimental procedures have been carried out in the laboratories of Departamento de Engenharia Mecânica da Universidade Federal de Minas Gerais. However, initially will be raised the possible ways of the technique application.

2. Infrared Tehrmography

The identification of defects and non-apparent inclusions in materials is possible from the field superficial temperature analysis, when the structure is submitted to thermal excitement. The thermal diffusion process is affected by the presence of imperfections, inclusions, humidity, generating an alteration in the superficial temperature field in defectives structures in comparison with the temperature field in a normal structure. The same occur when exist the presence of overheating points generated, for example, for electric defects.

In point of view of the thermal stimulation, thermography can be classified in active and passive (Maldague, 2000).

In the passive thermography, natural contour conditions are used in the analysis, a time that no thermal stimulation is used. In this case, it must exist a natural temperature difference between the object under study and the environment where it's inserted (Maldague 2000, Tavares and Andrade, 2003).

The problem in this scheme can be associated with qualitative characteristics of the obtained results. This makes that passive method can be used, preferential, in the evaluation of humidity presence, in preventive and predictive maintenance, in the evaluation of processes and industrial components, and distribution electric nets, where the periodic accompaniment of the normal operation, supplies conditions to the appraiser to identify the presence of anomalies. On the other hand, in these situations a differential temperature already exists, greater than sensitivity of thermal camera, between the environment and the object under study. In accordance with Maldague (2000) a temperature differential of the order of 2ºC between the hot spot and its neighborhood can indicate problem, however, only above of 4ºC an evidence abnormality really exists.

In situations where is desired to get results with characteristics more quantitative than qualitative, the use of the active thermography is preferred, because this demonstrated to have a greater potential in the identification and qualification of the defects instead the passive.

In the active thermography, some thermal stimulation methodologies can be used, each one with characteristics and proper limitations (Maldague, 2000, Carlomagno and Meola., 2001). The choice about the kind of thermal stimulate depends not only of the testing surface characteristics, but the type of information required.

The more used stimulation techniques are the pulsed thermography, the modulated or "Lock-in" thermography and the pulse phase thermography.

The pulsed thermography, PT, is the most traditional of them consisting in the stimulation through energy pulses. The study normally is done during the sample cooling through temperature decline curve analyze (Maldague, 2000). The energy pulse is achieved by light flashes, laser rays or still hot air jet. In particulars situations can be used a cold stimulation, through cold air jet (Carlomagno and Meola, 2002). One advantage of the cold stimulation is the reflecting reduction caught for the thermal camera, unlike when a hot stimulation is used (Maldague and Marinetti, 1996).

For stimulation using light flashes or laser, the thermal energy is supply to material in form of squared pulse, that extend as heat waves, from the material surface for its interior, subordinate to the Fourier diffusion equation (Maldague and Marinetti, 1996). This propagation and the waste by radiation and convection generates fast change of the material temperature. It is caught and registered by thermal camera (Maldague and Marinetti, 1996). The phenomenon evolution can be remarked over the images sequence acquisition that processed supplying information about the structure including possible fails, its dimensions, depth and thermal resistance. (Carlomagno and Meola, 2002).

The modulated thermography, MT, (or lock-in thermography) is based in thermal waves generated in steady state in the interior of the sample under study. In this case, on the contrary of pulses, the sample surface is subjects to a periodic stimulation of heat waves, in a determined angular frequency (Maldague and Marinetti, 1996). The thermographic system is connected to a thermal wave generator, which works in way to generate temperature sine-modulation (Sakagami and Kubo, 2002). The modulation is generate for a non linear electric signal created in a lock-in module that permits the control of the exact dependence in the time, between the recorded temperature signal and the reference signal (i.e. the sine-modulation heating). The sample answer to this stimulation is also sinusoidal, which the amplitude and phase depend of the entrance frequency (Maldague and Marinetti, 1996). The practical result is the oscillation of the temperature field in steady state, to which the change of the superficial temperature occurs in the same frequency that of the applied source of heat (Sakagami and Kubo, 2002). The system used a series of images and compares the temperatures, extracting the noise of the sinusoidal waves in each point of the image, generating the thermogram (Carlomagno and Meola, 2002). To get the temperature modulation magnitude and phase is used Fourier analysis, whit temporal temperature dependency in each image pixel.

The Pulse Phase Infrared Thermography, PPT is a signal processing technique based in the domain duality between frequency and time and in the Fourier transformed that allows passing of one to another domain. In this way, the temperature evolution on time can be to lead for the frequency domain, allowing access several frequency that, in fact, is the phase and amplitude spectral distribution (Maldague and Marinetti, 2002). Although in PPT, the pulse is the same as in PT, the results are not only presented with respect the amplitude and frequency, but also with respect the phase, like in MT. (Carlomagno and Meola, 2002, Maldague and Marinetti, 2002).

More details can be founded in Tavares and Andrade (2003) e Tavares, Cunha and Andrade (2004).

3. Experimental Procedure

The experimental tests had been carried through during the month of June of 2004 in the laboratories of the Departmento de Engenharia Mecânica of the Universidade Federal de Minas Gerais. In order to prevent solar reflexes in the images it was opted to carrying through the assays in the afternoon, after the sunset.

For the accomplishment of the tests, a masonry wall was projected and constructed, where four kinds of bricks had been used: common brick (of dimensions 200x100x50mm), pierced brick (of dimensions 300x200x100mm), blocks of concrete (of dimensions 300x150x100mm) and calcium silicate bricks (of dimensions 400x200x150mm). In the bricks junction and for the wall covering was used mass mixed.

In section 1 concrete block had been used. This section had, internally, tubing destined to cover of electric wiring. Whit this, it was expected to evaluate the thermography capacity in identifying possible points of overheating provoked by electric currrent covering, generated from a source of 110V.

In section 2, constructed in common bricks, internal fails had been simulated through the inclusion of material with different thermophysics properties in relation to the base material. For in such a way, small pieces of polystyrene had been used. The section 2, was divided in 5 subs-section, accordance with the arranged of the polystyrene plates and ink applied on the surface. This work will present the results gotten in the section 2C, which was re-covered with a fine coat of yellow ink. Of the right side, RS, of the section 2C, the polystyrene plates, of edge d, had been introduced between a first one and second one layer of plaster, both of 2mm of thickness. Of the left side, LS, the fails had been also introduced on the first layer of plaster of 2mm of thickness, however, under a layer of plaster, with 4 mm of thickness. With this searched to evaluate the effect of the depth in the defects identification.

In the construction of section 3 calcium silicate bricks had been used.

In section 4, constructed with pierced bricks, was inserted, about 100mm under the surface, a copper tube connected to other of PVC, both with 127mm of diameter. Each one occupied half of the dimension in the section and both had half of its length isolated for a polyurethane covering. During the tests this tube contained water in the ambient temperature (25ºC) and at 92ºC.

Figure 1 presents, with quotas in millimeters, the wall used in the tests. The fails dimensions as well as the plaster layers of Section 2, are detailed in Fig. (2) e (3). All the imperfections are thickness equal 2mm.

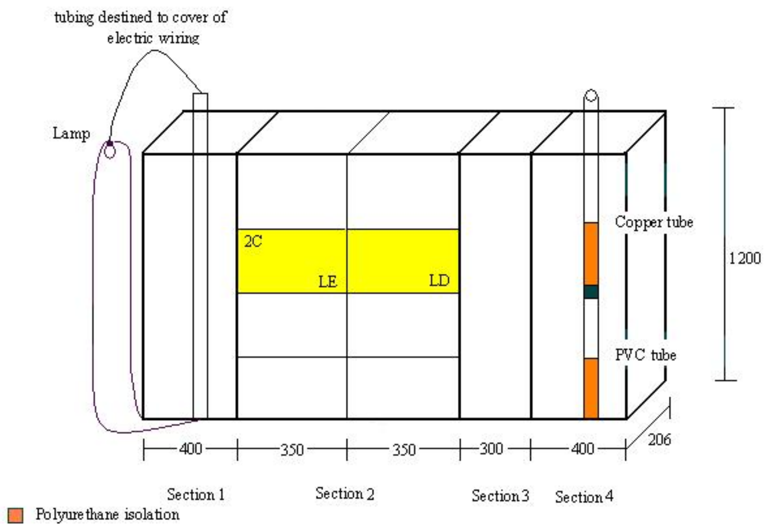

Figure 1. Assay wall

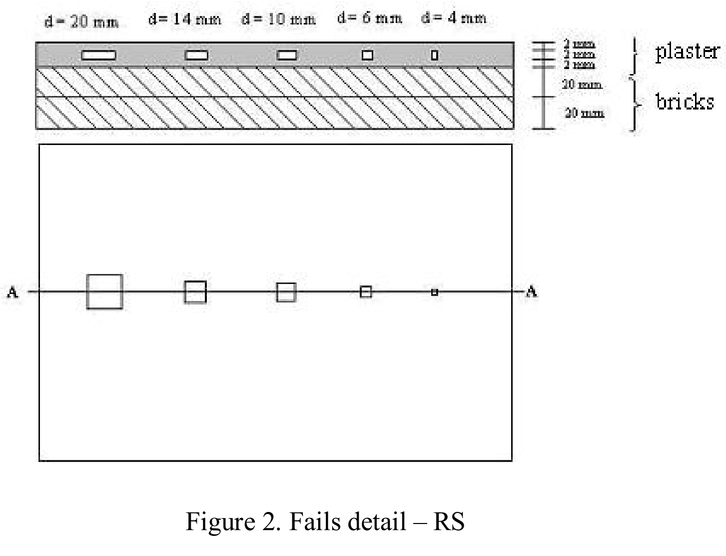

Figure 2. Fails detail – RS

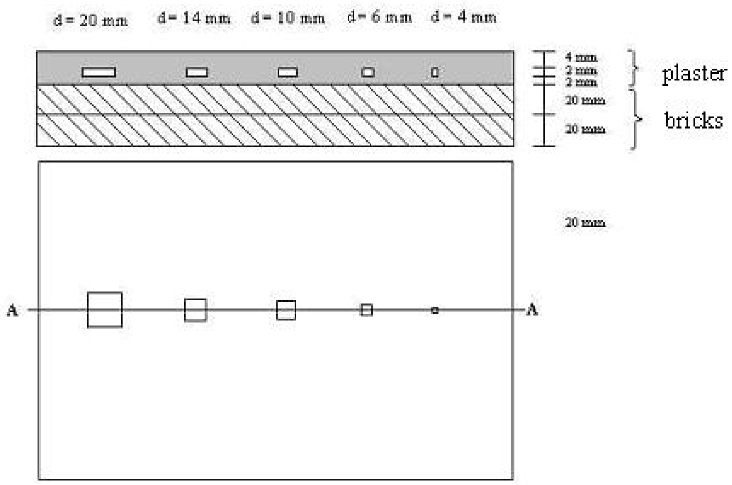

Figure 3. Fails details – LS

The wall temperature was also monitored through thermocouples type K installed along the surface of the same one. The values gotten for thermocouples, observed its uncertainty, had been used for the surface emissivity adjustment before the beginning of the tests. In this study, the emissivity on section 2C surface, gotten during the thermal camera adjustment, it was of 0,92. This value is situated inside the band presented for the ink manufacturer used to re-cover this section that is 0,83±0,10. For sections 1, 3, e 4 the emissivity gotten during the thermal camera adjustment was 0,90. According to Incropera and DeWitt (2003), for concrete surface, the emissivity can to vary of 0,88 to 0.93.

The ambient temperature during the assays, was of 19,1ºC±1,0ºC. It was measurement with a thermometer which has expanded uncertainty of 0,2ºC for this band of temperature. The transmissivity of the environment was considered equal 1,0. In the sections 1, 3 and 4 analysis was opted to use the passive thermography, taking qualitative analysis into consideration, what is enough to the intentions of this study. For the section 2C case, where a quantitative analysis would be more appropriated, the active thermography was used in its pulse method. For this, an electric heater with power of 0,85 kW was used, installed in regions next to surface under analysis. Adopted warm up time was of 1 minute, to allow a section uniform heating. The images had been taken in equal times intervals during the section cooling period.

Aiming to repeat the measurement procedure, the assays had been repeated, in identical conditions of test, for 12 times. For each series, 5 images had been made, representing, in the case of the section 2C, 5 instants to sample cooling.

The thermal camera used in this study was one type AGEMA Thermovision 570, whose specifications are presented in Tab. 1.

Table 1. Characteristics of thermal camera AGEMA Thermovision 570 used in the tests

ITEM	SPECIFICATION
Operation frequency	60Hz
Focal distance	0,5m until infinite
Band of watched temperature (based in black body temperature)	-20ºC a 1500ºC,
Measurement uncertainty (for 30ºC in a black body)	± 0,2ºC
Vision field	24º (horizontal) x 18º (vertical)
Detector cooling system	Thermoelectrial
Spectral answer	7,5 to 13 μm;
Thermal sensibility	<0,15ºC

During all the assay of the sections 1, 3, and 4, the thermal camera had been positioned in a distance of 2,10m from to surface of the wall, having remained an angle of 90º between the lens and the surface. In order to evaluate the effect of the distance on the gotten results, for the section 2C two distances had been used: 1,30m and 2,10m. The lesser necessary distance between the thermal camera and the object in analysis, described for the manufacturer of the equipment is 0,5m. The angle of 90º aims to minimize measurement noises.

A methodology for accomplishment of the diagnostic for NDTE that aims at the accompaniment the diverse variables involved in the measurement process can then be suggested. These variables will go to reflect in form of measurement uncertainty, on the gotten results. This methodology can be summarized in agreement follows:

1) Choice of the thermal excitement methodology, observed the characteristics of the object under analysis and restrictions about the surface heating. The desired answers also must be in accordance with the technique characteristics

and limitations. In equipment with heat generation proper, as in this study when the analysis of the tube of water and electric net, normally, no additional excitement is necessary.

2) Choice the period of the year for passive thermography with the natural conditions use. In the summer the high incidence of solar rays, a bigger differential of temperature between the sample and the environment is possible and consequently one better method answer is possible. To period of the year choice take more importance when the surface has heating restriction.

3) Choice the position between the sample and the sun way. The sample must be located, in the east-west direction to prevent solar reflection in the pictures.

4) Previous knowledge about material thermal physics characteristics and about the optics surface characteristics**.** It allows anticipate the answers, opening the possibility of the results validation through mathematical analysis. Special attention must be dedicated to surface emissivity, essential for thermal camera adjustment and measurement uncertainty determination**.** This variable unknown masque the results and is one of the responsible for false alarm of irregularities. One way to determinate the sample emissivity is trough the temperature measurement of the sample surface using a lesser uncertainty contact technique**.** It is adjusted the emissivity in thermal camera to indicate the same temperature. An alternative to this metodology is to cover the material surface with known emissivity material.

5) The thermal camera distance adjustment. The distance adjustment between the sample and the thermal camera must be in agreement with the manufacturer indications or, in other words, into thermal camera instant field of view (IFOV). This proceeding allows the better resolution of thermal image. Anothers characteristics supplied for the equipment manufacturer must be remarked as: minimum resolution thermal different (MRTD), minimum detected thermal different (MDTD), resolution or thermal sensibility (NETD). These characteristics not supply an estimate about the equipment intrinsic uncertainty, but only can be a reference for equipments comparison.

6) Environment temperature and transmissivity determination, which is essential to determinate the measurement uncertainty. Enclosed whit the emissivity, the environment temperature and transmissivity are the components needed to calculate the measurement uncertainty. The fourth component refers to the equipment intrinsic uncertainty, supplied for the manufacturer.

7) Assays repetition, always possible, as important proceeding for uncertainty analysis.

8) Image analysis with temperature gradients identification, obtained from contrast intensity value present in the digital image.

4. Results

In section 1 analysis, the temperature field present was uniform, not being possible to identify any point of higher temperature than it could indicate the presence of the electric current. This situation can have been caused for two factors: current low value (0,5A) and presence of the thermal isolation on the wire. In cases where short circuits occur, this isolation is spoiled and higher temperatures points are achieved. Works, as Rogers (2004), show the capacity of the thermography in identification of electric defects just because the presence of these overheating points.

Figure 4 represents the results gotten for sections 3 and 4.

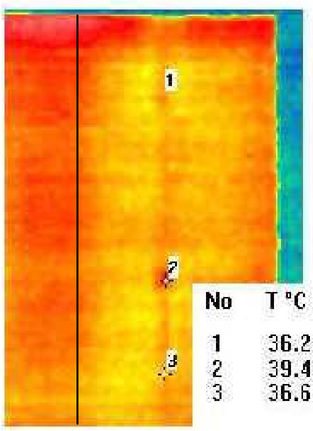

Figure 4(a). Hydraulical tubing with water in the ambient temperature

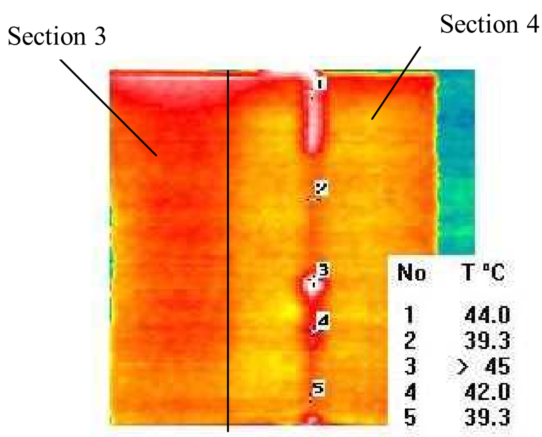

Figure 4(b). Hydraulical tubing with water to 92ºC

The thermogram presented in the Fig. 4(a) refers to gotten image 25 seconds after the inspection beginning, when the water used was in ambient temperature. Only passed this time, the balance condition between the sections in the wall with and without tube was modified, and as this, was possible to identify a lower temperature area (more reddish color) that neighboring region, indicating the not apparent tube presence. However this identification was only possible in the sectors where the presence of the thermal isolation did not exist.

The thermogram presented in the Fig. 4(b) indicate the image obtained 10 seconds after the inspection beginning, when used water to 92ºC. In this case, the easiness in the tube identification is related to the greater temperature differential existent between the wall section where it was introduced the tubes (and that, consequently, it contained hot water), the other sectors and the environment temperature. The difference enters the wall temperature wall and the environment, during the accomplishment of the assays, must it the fact of that assays had been carried through in the end of the afternoon, when the wall, after to have been displayed to the sun during all day, it had absorbed considerable amount of energy already. Confirming the information supplied for Maldague (2000), the results had demonstrated that temperature differentiate in order to 1ºC between the complete section and that one under analysis is already capable to indicate, as in the case of the Fig. 4(a), the abnormality presence, however, for its real characterization distinguishing of temperature above of 4ºC they become necessary, as seen in the Fig. 4(b).

Still with respect to the Fig. 4, in the not isolated regions, the copper tubing indicated an average temperature of 47ºC when covered for hot water. In reason of the copper conductivity to be greater than PVC, for the PVC tubing, the thermography identified an average temperature of 42ºC. In the Copper-PVC set, the isolated regions for polyurethane represented colder areas and, consequently, darker areas in the thermogram. The technique indicated an average temperature for these regions of 40ºC. Interesting situation occurred when it could be observed a point of overheating (47ºC) in the junction enters the PVC and cooper tubing. It was confirmed, later, that this measurement indicated the leak existence on that point.

Who can be see in Fig. 4(b), the technique also allows to view the limit enters the section constructed in calcium silicate (section 3) and the pierced brick section (section 4). This occurs due the expressive thermal conductivity difference between calcium silicate brick and pierced brick ($k_{pierced\ brick} >> k_{calcium\ silicate}$). The biggest brick thermal conductivity becomes easy the heat diffusion having registers about great surface temperatures for the calcium silicate.

For the section 2C is present the temperature decline in section whit and whitout presence of fails. This becomes possible to analysis the answer of quantitative than qualitative way as in termogram analysis.

The Figure 5 presents, for the sample right side, RS, the temperature decline for fails of edge equal 20,14 and 10mm and of its neighborhood, obtain by thermal camera placed 1,30m and 2,10m from the wall surface. The expanded measurement uncertainty to 95% for these distances, calculated according to methodology presented in Tavares e Andrade (2003) and Chrzanowski, Fischer and Matyszkiel (2000), was, respectively, 0,6 and 0,3ºC. The indicated times referring to period after thermal source retreat, in which the images had been made.

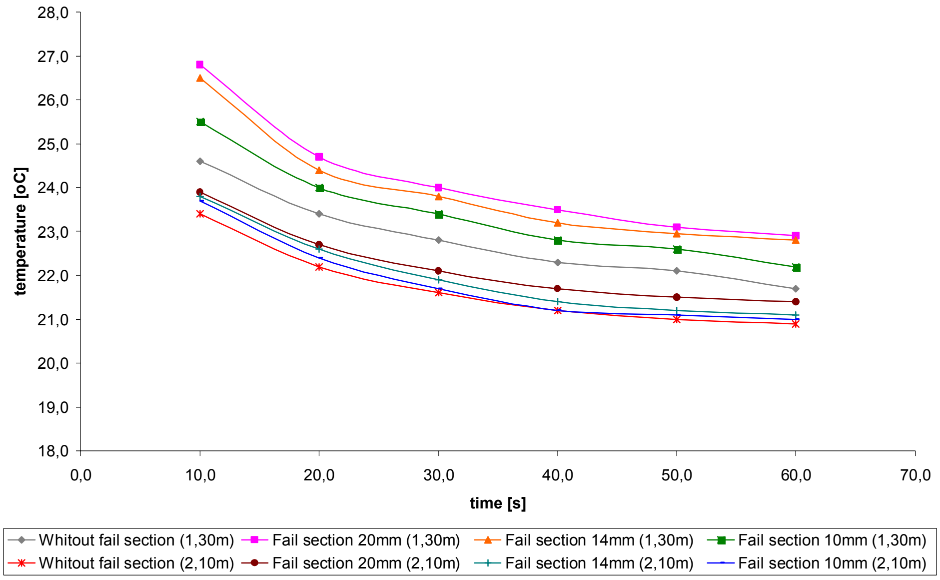

Figure 5. Decline of the temperature– Section 2C – RS

Figure 6 presents, for the left side of the sample, LS, the temperature decline for fails of edge equal 20, 14 and 10mm and of its neighborhood, obtain by thermal camera placed 1,30m and 2,10m from the wall surface. One more time, the expanded measurement uncertainty to 95%, for these distances, calculated according to methodology presented in Tavares e Andrade (2003) and Chrzanowski, Fischer and Matyszkiel (2000), was 0,5 e 0,4ºC, respectively.

The registered temperatures when the measurement system was located more distant form measure object had been well lesser of that registered lesser distances, as well as the decline were much less pronounced. This evidence the influence of the distance enters the system of measurement and the object under analysis on the results of the measurement. Such behavior was already waited a time that, the increase of the distance between thermal camera and mesurand is determinative to the image quality being that the thermographical image resolution decreases with the increase of the distance. This happens because each point in the thermographical image corresponds to specific area in mesurand surface. The distance increase implies that each one of these points represents a bigger mesurand area. As result, the radiation caught for the measurement system is the average of the emitted for this area, or either, the average of the emitted one for mesurand each point. Its makes with that some details of the image have been lost, being critical in surfaces with high variation of emissivity. On the other hand, for further distances between mesurand and measurement system the signal/ noise relation increase due to inversely proportional relation between the energy caught for the equipment and the square of the distance.

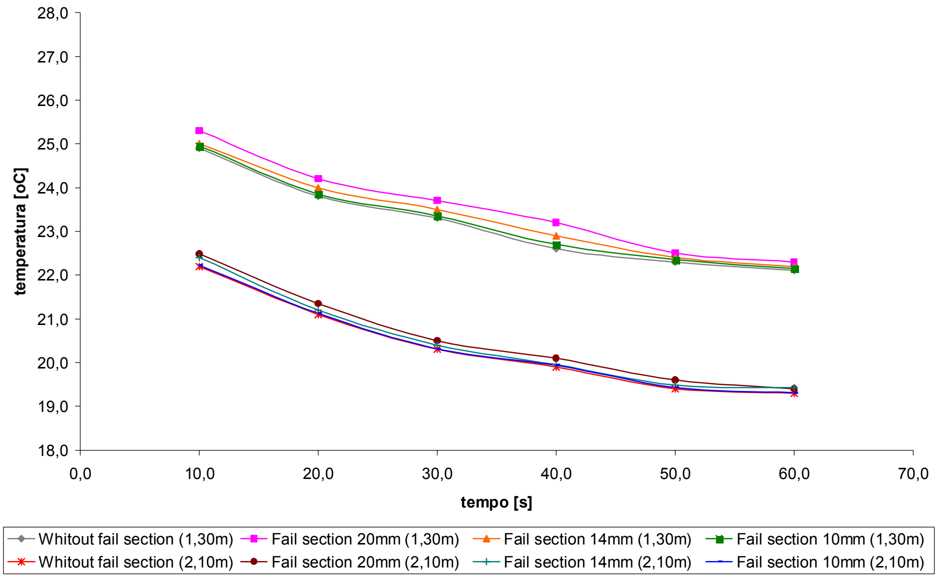

Figure 6. Decline of the temperature– Section 2C – LS

If by one side lesser distances between the object and the system of measurement allow the individual analysis of small areas of the mesurand, increasing the results quality, otherwise it increases the measurement time. So the importance in determination of the maximum distance between the mesurand and the measurement system that it does not intervene with the results of the measurements in diagnoses processes. Still in this direction, another factor to be observed is that, the increase of the distance between the mesurand and the system of measurement increases the effect of the transmissivity on the results. Of the way, the maximum distance to be implemented must be such that the environment transmissivity effect is minimal.

For the right side of the sample, RS, where the imperfections are located more superficially, the technique allowed identify all the fails (temperature differentials between the area whit and without fails greater than measurement uncertainty) when the distance between the sample and thermal camera was 1,30m. For 2,10m, fails whit edge equal 20 and 14mm were identifiable, however, for the imperfection of edge equal 10mm the system presented temperature differences very next to measurement uncertainty, what would create some doubts about the result.

For the left side (LS), a rigorous analysis on the results show that these are suspected cause the temperature difference between the area whit and without fails are next or lesser than the measurement uncertainty. This happened independently of the distance between the sample and the thermal camera. Than, could be said that the problems on results are associated with the distance between the mesurand and the measurement system, as well as the reduced thickness and deeper imperfection location.

Others methods as MT and PPT, could be to maximize the results quality.

5. Conclusions

Due to innumerable advantages the thermography has been used in the most different fields of science as tool in the attainment of the transient field of superficial temperature.

Of the point of view of the thermal stimulation, the thermography can be classified in passive and active. For the active thermography, diverse thermal excitement techniques can be used. The stimulation techniques more usually used are the pulsed thermography, modulated thermography, and pulse phase thermography.

In this work is presented methodology for the thermography application in the evaluation of defects and inclusions non apparent in materials.

From the implementation of this methodology and using the passive technique, it was possible to identify the presence of different materials in the same structure as well as non-apparent inclusions, in this case, tubing, with and without presence of thermal isolation, contend hot and cold water. The application of the same methodology, however, it was not capable to identify overheating points with electric current presence This situation can have been caused for the current low value (0,5A) and for the presence of the thermal isolation on the wire.

When of the active technique implementation, in its pulsed version, it was possible to identify diverse dimensions internal imperfections. When the fails met more superficial, and the distance between the measurement system and sample was lesser, imperfections until 10mm of edge and 2mm of thickness had been correctly identifiable, or either, the temperature difference between the area whit and without fails was greater that the measurement uncertainty. For bigger distances between the measurement system and mesurand the results had been considered suspected, a time that the temperature difference between the area whit and without fails met in the limit of the measurement uncertainty.

With this, was proved that yonder of the knowledge about the surface emissivity, temperature and environment transmissity, that in set with the intrinsic uncertainty of thermal camera, composes the measurement uncertainty, existing the necessity a ideal distance determination between the object under observation and measurement system that maximizes the results quality, without, however, to raise of representative form the assay time. The use of other thermal excitement methods, as MT and the PPT, could also maximize these results quality.

6. References

Adams, A. K., Gill, A. S., Ek, J. R., Nelson, R. A., 1998, "Contribution of conduction to total infant energy expenditure", Journal of Thermal Biology, vol. 23, pp. 267-272.

Andrade, R. M., "Tecniche di misura non invasiva per il controllo di processo e di qualità nella produzione ceramica", 1999, Tesi di Dottorato, Università degli Studi di Ancona.

Can, M., "Simultaneous convective heat and mass transfer in impingement ink drying", 1998, International Comm Heat Mass Transfer, vol. 25, nº 6, pp. 863-874.

Carlomagno, G. M., Meola, C., "Infrared thermography in the restoration of cultural properties", 2001, Conference 4360 Thermosense XXIII Proceedings of SPIE, vol. 4360.

Carlomagno, G. M., Meola, C., 2002, "Comparison between thermographic techniques for frescoes NDT", NDT&E Internacional, vol. 35, pp. 559-565.

Chrzanowski, K., "Evaluation of thermal cameras in quality systems according to ISO 9000 or EN45000 Standards", 2001, Proceedings of SPIE, vol. 4360, pp. 387-401.

Chrzanowski, K., Fischer, J., Matyszkiel, R.,"Testing and evaluation of thermal cameras for absolute temperature measurement", 2000, Journal of Optical Engineering vol. 39, no 9, pp. 2535-2544.

Dowling, M. J., Kinsella, T. E., Bartels, K. A., Light, G. M., 1998, "Radiographic image processing for industrial applications", Proceedings of SPIE, vol. 3396.

Incropera, F. P., DeWitt, D. P., 2003, "Fundamentals of heart and mass transfer", Fifth edidtion, John Wiley & Sons, Inc., New York.

Luong, M. P., "Infrared thermographic scanning of fatigue in metals", 1995, Nuclear Engineering and Design, vol. 158, pp. 363-376.

Maldague, X., "Applications of infrared thermography in non destructive evaluation", 2000, Trends in Optical Nondestructive Testing (invited chapter), Pramod Rastogi Ed., pp. 591- 609.

Maldague, X., Marinetti, S., "Advances in pulse phase infrared thermography", 2002, Infrared Physics & Technology, vol. 43, pp. 175-181.

Rogers, R., "Termografia em Subestações de Energia Elétrica", 2004, Private Communication, IV Encontro de Termografia em Furnas, Furnas, MG, Brazil.

Sakagami, T., Kubo, S., "Applications of pulse heating thermography and lock-in thermography to quantitative nondestructive evaluations", Infrared Physics & Technology, vol. 43, pp. 211-218, 2002.Talwar, D. N., Jogai, B., Loehr, J. P., "Novel type II strained layer superlatices for long wavelength infrared detectors", 1998, Mater Science Engineering, vol. B51, pp. 12-17.

Tavares. S. G., Andrade, R. M., "Metodologia de ensaio e análise de incerteza na aplicação da termografia", 2003, Anais do III Congresso Brasileiro de Metrologia, Recife, PB, Brasil.

Tavares, S. G., Cunha, A. M., Andrada, R. M., "Metodologia Experimental para Aplicação da Termografia em Ensaios Térmicaos não Destrutivos", 2004, Proceedings of the 10th Congress of Thermal Sciences and Engineering – ENCIT 2004, Brazilian Society of Mechanical Sciences and Engineering, ABCM, Rio de Janeiro, Brazil.

Titman, D. J., "Applications of thermography in non-destructive testing of structures", NDT&E Internacional, vol. 34, pp. 149-154, 2001.