STUDIES ON THE APPLICABILITY OF INFRARED IMAGING OF THERMAL PROCESSES IN TROPICAL REGIONS

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Abstract. *The main aim of this work is to contribute on the assessment of the applicability of infrared imaging on the analysis of thermal processe. Particular care is taken about the peculiarities of the process and equipment working at tropical regions. As introduction several recent papers on the assessment of the applicability are cited. It is presented a brief and basic theory behind the infrared detection. The applications covered are of two kinds: visualization of processes and engineering applications. It is shown four types of phenomena that can be visualized using infrared imaging: drying of paper, mixture of cold and hot water, water thermal stratification and drying of gypsum plaster board. Then it is presented several applications of infrared thermography: air infiltration detection, moisture infiltration detection, unbinding of façade material, human skin temperature, the influence of the position of the equipment on the temperature field, human recognition, localization of hot spots and the influence of the ambient temperature on the temperature of electronic components.*

Keywords: *infrared thermography, thermal processes visualization.*

1. Introduction

Infrared imaging is commonly used in Brazil. But this utilization is almost restricted in the predictive analysis of electrical components and the equipments are usually owned by major electrical power generation and distribution industries. In those analyses usually the component under test is changed if its temperature is above a somewhat arbitrary empirically determined temperature. Around the world, infrared imaging is also used largely in non destructive tests in general as seen in various scientific papers published in the specialized literature. In respect to analysis of thermal processes, there is a lot of investigation about the kind of phenomena where infrared imaging could be important in increasing their understanding.

In the present work we have three major aims: (a) to present preliminary research in infrared imaging done in Federal University of Pernambuco, (b) to contribute with the effort in determining the most suitable applications of infrared imaging in respect to thermal analysis and (c) to alert some peculiarities of equipments working or phenomena occurring in tropical regions. In all the experiments presented in the present work it was used a FLIR S45 infrared camera with 240x320 measurement points, 60 Hz image acquisition, precision of ± 2 ºC and sensitivity of 0.08 ºC.

In respect of research being done in Federal University of Pernambuco there are also three major tracks: (a) study on the basic phenomena of emission, transmission, reflection, scattering and detection of infrared applied to the infrared imaging itself, (b) development of software to qualitative and quantitative analyses of thermal process and (c) assessment of the real focus of applicability of infrared imaging.

The papers cited bellow constitute a good picture of the recent research being done in respect of the assessment of the applicability of infrared imaging. Kim, Kim and Han (2005) in South Korea presented a low-cost module for the detection of concealed grooves in an aluminum plate. Montelpare and Ricci (2004) in Italy used infrared thermography allied to ink tracers to evaluate heat transfer coefficient in fins. Gonzales et al. (2005) in Spain presented the use of infrared thermography allied to morphing algorithms to detect and evaluate defects on radiant heaters. Ibarra-Castanedo et al. (2004) in Canada present various methods of data analysis required in the processing of thermograms (infrared images) in the process of analysis or defect detection. Fenot, Vullierme and Dorignac (2005) in France studied the effect of the jet configuration on the local heat transfer. Ludwig, Redaelli, Rosina and Augelli (2004) in Italy presented a study of moisture detection using infrared measurement. Smith, Baughn and Byerley (2005) in USA present the visualization of thermal tufts using an encapsulated phase change material. Meola, Carlomagno and Giorleo (2004) in Italy showed a method of using thermography for material characterization. Guerrero, Ocaña and Requena (2005) in Spain present a study the influence of some factors (as material, color, shape and solar incidence) on the accuracy of the thermogram. Al-Kassir et al (2005) in Spain presented a study of the use of thermography in HVAC applications including the influence of humidity in thermal building materials. Herrick and Hutchinson (2004) in UK showed a good example of the use of thermography in clinical diagnostic where they compare various kinds of exams in vascular imaging.

In Section 2 we present the basic theory behind infrared detection, in Section 3 we use some examples to illustrate the visualization of thermal phenomena using infrared imaging, and in Section 4 we discuss a few engineering application of infrared imaging. In all the text we try to stress peculiarities of phenomena and applications occurring at tropical regions.

2. Theory and equipment.

The spectrum of electromagnetic radiation is divided in bands: cosmic rays, γ-Rays, X-Rays, ultraviolet, visible light, infrared, microwave and radiowaves. Although the physical laws of the electromagnetic radiation in all bands are the same, the type of interaction and effects between wave and matter are different. The infrared radiation acts mainly on the vibration of molecules. A somewhat arbitrary division inside de infrared band is: the near infrared (0.75-3 μm), the middle infrared (3-6 μm), the far infrared (6-15 μm) and the extreme infrared (15-100 μm).

Considering a blackbody object (an object that absorbs all the radiation at any wavelength), Max Planck developed a formula (Eq. (1)) describing the spectral emittance:

$$W_{b\lambda} = \frac{2\pi hc^3}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)} \times 10^{-6} \qquad (1)$$

where:

- $W_{\lambda b}$ – Blackbody spectral radiant emittance at wavelength λ [Watt/m^2.μm]
- h - Planck's constant [6.626x10^{-34} J.s]
- c - Velocity of light [2.998x10^8 m/s]
- λ - Wavelength [m]
- k - Boltzmann's constant [1.381x10^{-23} J/K]
- T - Absolute temperature of a blackbody [K]

Integrating Eq. (1) from λ=0 to λ=∞ one obtains Stefan-Boltzmann's equation:

$$W_b = \sigma.T^4 \qquad (2)$$

where:

- W_b - Blackbody total radiant emittance [W/m^2]
- σ - Stefan-Boltzmann's constant [W/m^2.K^4]

Real objects are not perfect blackbody emitters. The total radiant emittance of a real object is always somewhat lesser than the blackbody emission. To make the correction a factor called emissivity is put in Eq. (2) yielding Eq. (3):

$$W_b = \varepsilon.\sigma.T^4 \qquad (3)$$

where:

- ε - emissivity

In general the emissivity of each material is function of the wavelength. An usual simplification is to consider that the emissivity of a given material is constant to all wavelengths. In this case, the material is called a graybody.

In a real situation the measured surface will not be a perfect blackbody emitter, there will be reflection of radiation and part of the emitted and reflected infrared radiation will be attenuated by the atmosphere between the surface and the camera. So, the total radiation reaching the camera detector is:

$$W_{tot} = \varepsilon.\tau.W_b + (1-\varepsilon).\tau.W_{refl} + (1-\tau).W_{atm} \qquad (4)$$

where:

W_{tot} - Total radiation power reaching the detector (measured)
W_b - Total radiation power emitted by a blackbody in the same temperature as the object (calculated)
W_{refl} - Total radiation power emitted by all the surfaces in the hemisphere seen from a point on the object
W_{atm} - Total radiation power emitted by the atmosphere between the camera and the object
ε - Emissivity of the surface been measured
τ - Transmissibility of the atmosphere between the camera and the object

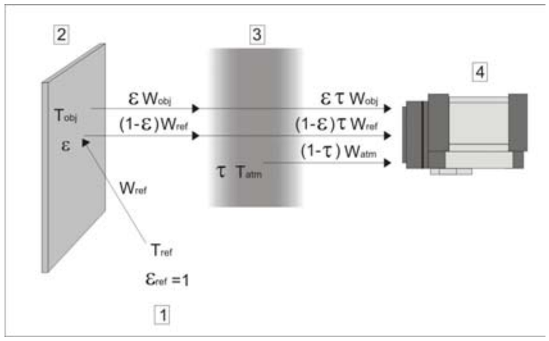


Figure 1 – Major phenomena occurring during the measurement

Figure (1) shows the main processes occurring during the measurement. Solving Eq. (4) for W_b and using Eq. (2), it is possible to determine the temperature of the surface. It is important to stress: (a) the emissivity of real materials is not constant to all wavelengths, (b) the transmissibility of the atmosphere is function of the distance, temperature, gases and humidity.

2.1. Equipment

In the experiments showed in this work it was used a S45 infrared camera (FLIR). Its thermal sensivity is 0.08 ºC, accuracy of ± 2 ºC, has a 320x240 uncooled microbolometer detector, it is capable of video acquisition in 60 Hz, it works on the spectral range 7.5 to 13 µm where there is minor atmosphere attenuation by water vapor and CO_2 and operates in the following ranges: -40 ºC to +120 ºC, 0 ºC to 500 ºC, up to + 1500 ºC.

3. Visualization of Thermal Process

In order to analyse the imaging of the infrared emission of surfaces two main fronts are considered: quantitative and qualitative. The quantitative analysis can be used as first measurement in process where it will be a posterior high accuracy measurement (e.g. the choice of the best place to locate thermistors), in the measurement of process where it is needed a high number of temperature points (e.g. the molding and mechanical blowing of glass bottles where the temperature in every point is relevant) and in highly complex geometries (e.g. electronic boards). On the other hand, thermography is important in qualitative analysis: testing of the hypothesis used in the mathematical modeling or experimental plant (e.g. uniformity of the thermal field), discovery of phenomena not yet considered in the process in study (e.g. moisture infiltration) and better understanding of the process. Although the better understanding of the process by a human should not interfere in the measurement it certainly interferes in the quality of the mathematical model, in the location of the probes and in the kind of variable measured. The quantitative analysis should not be underestimated since it permits the visualization of the whole process otherwise invisible to human analysts.

In this section we present the visualization of four processes: surface drying, mixture of hot in cold water, stratification of hot and cold water, and gypsum plaster board drying.

3.1. Drying of a sheet of paper

In this section we present a process of drying of a sheet of paper. It is an example of the potential of infrared imaging in detecting the effect of dew saturation in building materials, evaporative cooling, water aspersion and drying in open space. In this experiment the paper sheet was completely saturated with water at 21.7 ºC. A stream of air (temperature of 27.6 ºC, relative humidity of 51%, cross sectional area of 8mm x 70mm, velocity of 14,4 m/s and located at 1 cm of the paper sheet) was directed parallel to the paper (1 cm above the sheet). Figure 2.a shows the paper sheet before the air stream. Figure 2.b (13 seconds after the air stream, 2.c (112 seconds after the air stream) and 2.d (245 seconds after the air stream) present the effect of evaporative cooling (bluish coloration). Figures 2.c and 2.d show in the upper middle part of the paper sheet a hotter region caused by the total drying of the region and consequent equilibrium with the air stream. As written above this example stresses the importance of infrared imaging in detecting the beginning and end of drying processes.

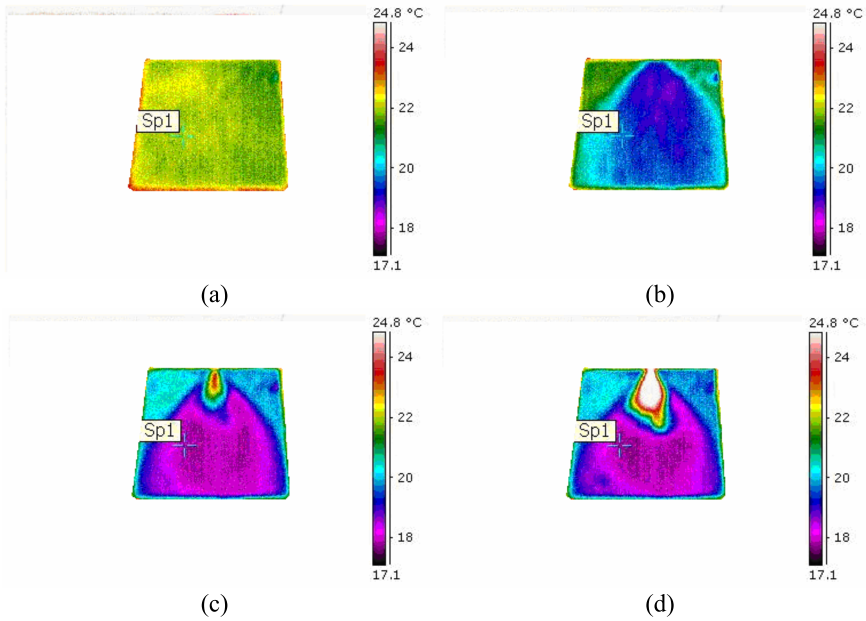


Figure 2 – Drying of a sheet of paper

3.2. Mixture of hot and cold water

Figure 3 shows a process of mixture of hot water (73 ºC) thrown in a polystyrene cylinder with cold water (18 ºC). Polystyrene was chosen because it is semi-transparent to infrared rays. Figure 3.a shows the cylinder with cold water. Figure 3.b presents the hot stream (in the upper right part of the cup) and the warm water in the lower part. It is important to stress that it is possible to visualize only the temperature of the water in the front part of the cylinder. That is the cause of the discontinuity of the hot path between the hot jet and the warm part bellow. Figures 3.c-g show the movement and dissipation of the warm water. Finally Fig 3.h present the water completely homogenized. In this example it is shown how fast hot and cold water mixture occurs in the cylinder. This effect was produced by the movement of the hot water flow through the stagnant cold water, and by the natural convective effect caused by the relative position the hot and cold water mass in the cylinder. In the next section an experiment, about how to do in order to avoid or delay the process of mixture using basic stratification techniques, is presented.

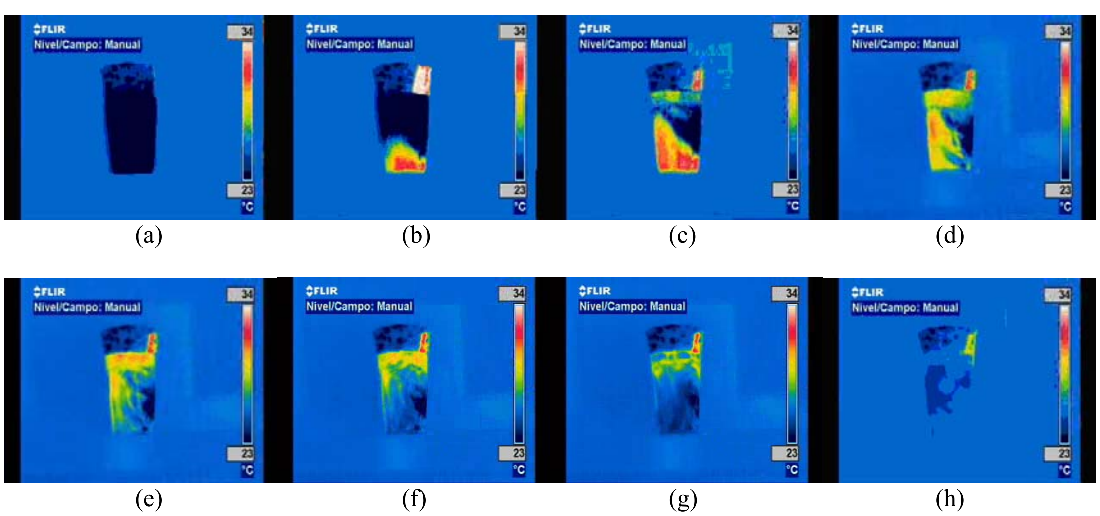
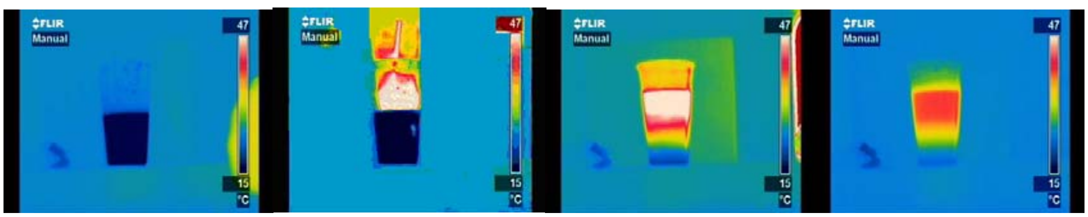


Figure 3. Mixture of hot water in a cup with cold water.

3.3. Stratification of hot and cold water

To minimize the mixture of hot and cold water depicted in Fig 3 it was devised an experiment where the hot water was thrown in an upper cylinder with tiny 1mm holes in the bottom. The upper cylinder was located 5 mm above the water of cold water in the lower cylinder. That way, both the flux of water and the velocity of the jet are minimized. Figure 4.a shows the lower cylinder with cold water. Figure 4.b presents the hot water being thrown in the upper cylinder. Figure 4.c shows only the lower cylinder after all the hot water has passed through the tiny 1 mm holes and reached the lower cylinder. Figure 4.c shows the stratification after 1min:30sec and Fig. 4.d shows the stratification after 10 minutes. The thermal stratification is very important in thermal storage process and the knowledge of the phenomena allows to optimize and to develop: new techniques of stratification; the better tank shape for storage; new diffuser design to provide a good stratification performance, etc.

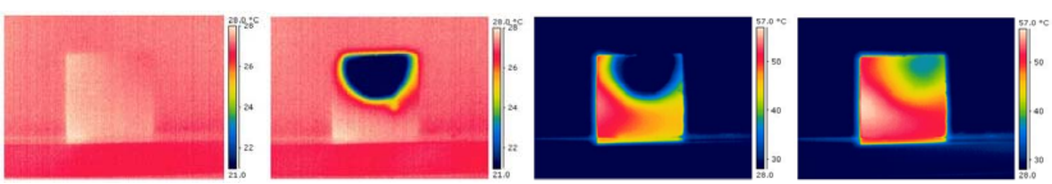


(a) (b) (c) (d)

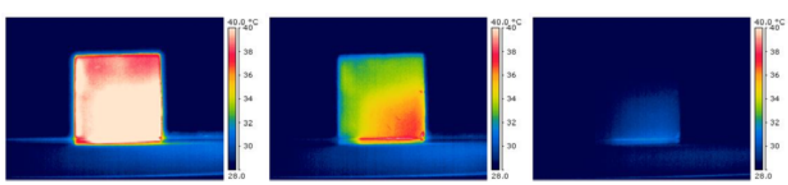
Figure 4. Stratification of hot and cold water using a device with two cylinders. The lower cylinder contains cold water. The upper cylinder containing hot water has tiny 1mm holes in its bottom.

3.4. Drying of a gypsum plaster board

The next experiment was devised to demonstrate the power of infrared imaging in detecting water infiltration in building materials and the process of natural or industrial drying of gypsum plaster board. The gypsum-sample had dimensions of 10x10x2 cm. It was made a hole in the upper surface with 0.8 cm of diameter and 2.6 cm of depth. The sample was put parallel to an air stream (in Fig 5 the air stream goes from the left to the right). Figure 5.a presents the thermal state of the sample after 5 minutes in contact with a cold air stream (17 cm at the left of the sample, 8mm x 70mm, 27.6 ºC, 57% of relative humidity and 9.4 m/s). After the thermal equilibrium was reached it was introduced water in the hole (20 ml, 20 ºC). Figure 5.b shows the sample 8 minutes after the introduction of water in the upper hole. After 42 minutes, the cold air stream was changed by a hot air stream (17 cm at the left of the sample, 8mm x 70mm, 61.8 ºC, 12% of relative humidity and 10.6 m/s). Figure 5.c shows the sample 6 minutes after the hot air stream and Fig. 5.d shows the sample 26 min after the beginning of the hot air stream. The hot air stream was sustained for 42 minutes. After that, the cold air stream was impinged on the board again. Figure 5.e shows the sample 20 seconds after the cold air, Fig. 5.f shows the sample 100 seconds after the cold air and Fig. 5.g shows the sample 7 minutes after the cold air stream. From Fig. 5.f it is possible to observe that in the end of the process the sample was completely dried on its surface at least. It is important to notice the scale of Fig 5.a-b (21-28 ºC) are different from Fig 5.c-d (28-57 ºC) and Fig. 5.e-g (20-40 ºC).



(a) (b) (c) (d)



7(e) (f) (g)

Figure 5 – Drying of a gypsum plaster board.

4. Engineering Applications

In this section we present infrared visualization applied not only to the understanding or quantification of thermal phenomena but manly in respect of its potential in solving engineering problems. Figure 6.a presents an almost invisible breach between the door and the wall of a refrigeration chamber. It is possible to see the effects of the hot air coming inside through the breach. Here it is important to notice that this kind of visualization (air infiltration) is not easy to detect in conditioned buildings in tropical areas. This occur because the difference of temperature between inside (24 ºC) and outside (30 ºC in coastal regions) is small. In temperate climates the infiltration (of cold air in that case) in conditioned buildings is easier to detect because of the higher temperature difference (24 ºC inside, <5 ºC outside). In the case shown in Fig. 6.a it was the case of a refrigeration chamber (11 ºC) inscribed in an ambient air at 32 ºC, not a conditioned building, so the easy visualization .

Figure 6.b shows in the middle left a lighter region representing façade material becoming loosened. This phenomenon was not easy to detect optically. Figure 6.c presents in the middle a purplish (colder) region demonstrating moisture infiltration. In this case also the phenomenon was completely invisible. This kind of material unbinding or moisture infiltration is very usual in tropical climates where impermeable coating of walls and façades is not often used. The early detection of these processes is very important to minimize the thermal load or to prevent serious building degradation.

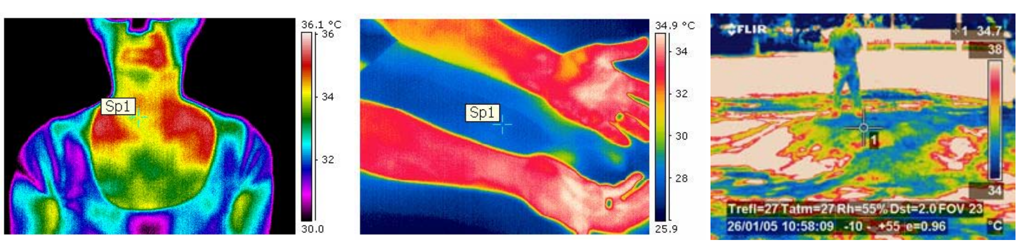
(a) (b) (c)

Figura 6. Visualization of phenomena optically invisible: (a) hot air infiltration through the space of a closed door, (b) light stains are façade material becoming loosen, (c) bluish region indicating moisture infiltration through the wall.

There are several and important uses of infrared imaging in clinical diagnostic. For example there is the detection of breast cancer, inflammations, viruses etc. In tropical and poor countries where there is an easy spread of contagious illness it is very important to use infrared imaging in preliminary diagnoses. This early examinations can be done both in huge clinical emergencies as well in the houses of the people. Figure 7.a shows the temperature field of a health young woman. Another kind of study is the determination of skin temperature in respect of the level of activity of the person.

Figure 7.b shows the vascular imaging of the middle aged woman hands. On the left hand we can see the result of a thrombophebitis that occurred 15 years ago. Colder regions can be observed if a comparison is done with the right hand. They demonstrate a worst local blood perfusion. A temperature difference of approximately 1°C was measured between the dorsum of the hands.

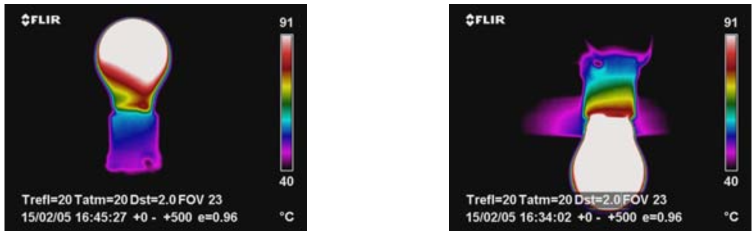
Figure 7.c shows a person standing under the shade of a tree in a sunny day. Notice it is possible to detect the human form only against the portion of the ground lightened by the sun (in white). During the night, in tropical regions, the temperature of humans and of the ground and walls are very close. So an important application of thermography in colder climates (human detection) is very difficult in tropical areas.



(a) (b) (c)

Figure 7. Some applications: (a) surface temperature of human beings (b) vascular imaging, (c) human beings recognition in tropical climate.

Another engineering application is the choice of the better way to operate a device. For example, Fig. 8 shows a incandescent lamp installed in two distinct ways. It is possible to notice, in Fig. 8.b, the higher temperature of the lamp socket when the lamp is operating upside down. The socket temperature is decreased in several degrees when the lamp works upside.



(a) (b)

Figure 8. Influence of the position of the lamp on the temperature of the lamp socket.

Figures 9.a-d show the interior of a personal computer cabinet working at two distinct ambient temperatures. In both cases the computer was left 20 minutes to reach thermal equilibrium and the same process was running in the computer (memory and processing consuption). Fig. 9.a and Fig. 9.c show the exact same experiment with distinct temperature scales. The same occurs between Fig. 9.b and Fig. 9.d. The contrast between Fig. 9.a and Fig. 9.b shows the great influence of the ambient temperature on the working temperature of the components inside the computer. In Fig. 9.c and Fig. 9.d the scale begins at the ambient temperature and goes 20 ºC higher. The contrast between Fig. 9.c and Fig. 9.d shows the components working always at the same temperature above the ambient temperature. One exception is the Winchester surface temperature on the lower middle part. In that case, when the ambient temperature is increased on 15.5 ºC, the temperature of the Winchester is increased in only 5 ºC. Another evident hot spot in the images is the electrical motor of the microprocessor cooler on the middle right.

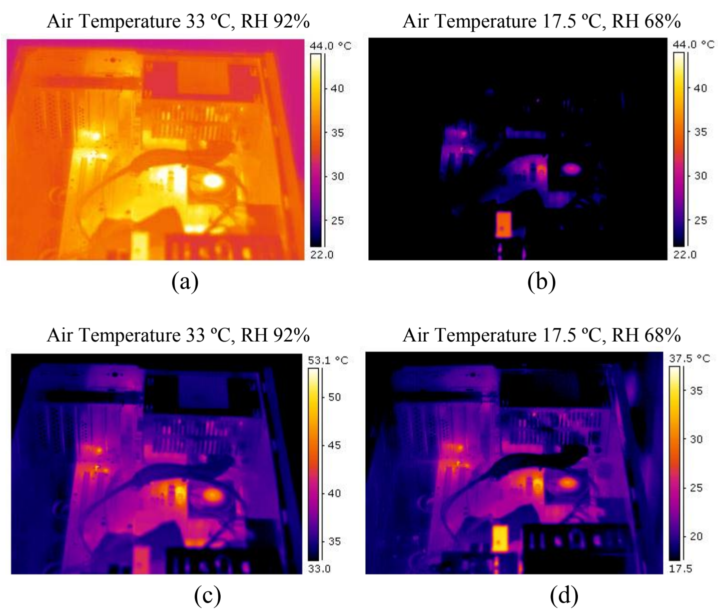


Figure 9. Temperature distribution inside a personal computer cabinet working at two different ambient temperatures: 33 ºC and 17.5 ºC

5. Conclusions

Infrared imaging should be more used in thermal analyses. It is very clear its importance in quantitative (applications with a high number of temperature points or complex geometry) and qualitative (hypothesis confirmation, phenomena understanding, discovery of hidden effects). One should not underestimate the qualitative analysis.

The actual applicability of infrared imaging (in the visualization of thermal process or equipment thermal analysis) has been in study around the world. The aim of this workis contribute in this assessment. Additionally we believe some peculiarities of tropical regions have been disclosed and must be well exploited.

6. References

Al-Kassir, A.R., Fernandez, J., Tinaut, F.V. and Castro, F., 2005, "Thermographic study of energetic installations", Applied Thermal Engineering, Vol. 25, pp. 183–190.

Fenot, M., Vullierme, J.-J. and Dorignac, E., 2005, "Local heat transfer due to several configurations of circular air jets impinging on a flat plate with and without semi-confinement", International Journal of Thermal Sciences, IN PRESS, pp. 1-11.

González, D.A. , Madruga, F.J., Quintela, M.A., López-Higuera, J.M. (2005), "Defect assessment on radiant heaters using infrared thermography", NDT&E International, IN PRESS, pp. 1–5.

Guerrero, I.C., Ocaña, S.M. and Requena, I.G., 2005, "Thermal–physical aspects of materials used for the construction of rural buildings in Soria (Spain)", Construction and Building Materials, Vol. 19, pp. 197–211.

Herrick, A.H. and Hutchinson, C., 2004, "Vascular imaging", Best Practice & Research Clinical Rheumatology, Vol. 18, No. 6, pp. 957–979.

Ibarra-Castanedo, C., González, D., Klein, M., Pilla, M., Vallerand, S. and Maldague, X., 2005, "Infrared image processing and data analysis", Infrared Physics & Technology , Vol. 46, pp. 75–83.

Kim, B. C., Kim, Y.H and Han, J.S., 2005, "A low-cost thermographic device for the detection of concealed groove in metal plate", Sensors and Actuators, A 118, pp. 248–253.

Ludwig, N., Redaelli, V., Rosina, E. and Augelli, F., 2004, "Moisture detection in wood and plaster by IR thermography", Infrared Physics & Technology, Vol. 46, pp. 161–166.

Meola, C., Carlomagno, G.M. and Giorleo, L., 2004, "The use of infrared thermography for materials characterization", Journal of Materials Processing Technology, Vol. 155–156, pp. 1132–1137.

Montelpare, S. and Ricci, R., 2004, "An experimental method for evaluating the heat transfer coefficient of liquid-cooled short pin fins using infrared thermography",Experimental Thermal and Fluid Science, Vol. 28, pp. 815–824.

Smith, J.S., Baughn, J.W. and Byerley, A.R., 2005, "Surface flow visualization using thermal tufts produced by an encapsulated phase change material", International Journal of Heat and Fluid Flow, IN PRESS, pp. 1-5.

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