Int. J. Engng Ed. Vol. 22, No. 2, pp. 373–380, 2006
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Infrared Thermography as a Useful Tool to Improve Learning in Heat Transfer Related Subjects*

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In this paper we present infrared thermography as a technique to aid the process of teaching–learning in subjects related with heat transfer. The main aim pursued is to make it easier for students to learn and understand the phenomena involved in heat transfer modes in a fast, intuitive way by using infrared images. To achieve this objective we have developed a series of exercises for use in practice sessions. Here, we describe some of the practical exercises concerning the different heat transfer mechanisms: conduction, convection and radiation, and share the results obtained from our experience gained over two academic years.

INTRODUCTION

THE SORBONNE DECLARATION [1], the subsequent declarations and communiqués in Bologna 1999, Prague 2001 and Berlin 2003, and the next meeting to be held in Bergen 2005 on the European higher education area, mark important transformations in teaching work that must be implemented by 2010 for the signatory countries.

The capital idea revealed at the Bologna Process regarding the teaching field is to move the main axis in the educational process away from the individual that teaches toward the individual that learns, i.e. the student. This change of perspective demands educators at universities to make a serious effort to adapt.

On the other hand, the difficulties that students have in assimilating and understanding the fundamental phenomena of heat transfer are well known by teachers of this discipline. Classical laboratory practicals are an invaluable aid to put this situation to rights. However, after several years of educational experience, we have noticed that these practice sessions offer a series of drawbacks. Therefore, in this paper we undertake the task of applying the Bologna guidelines and improving the classical experimental practicals referring to the subject Thermal Engineering taught in the fourth year of the Industrial Engineering degree course at Universitat Jaume I in Castellón, Spain.

The main objectives pursued in the subject Thermal Engineering are students' comprehension and learning of the heat transfer phenomena, i.e. conduction, convection and radiation. To achieve this aim, up till now we have been using mainly theoretical classes given on the blackboard, which have been complemented with practical sessions carried out with standard educational laboratory equipment. Now, in accordance with the guidelines that are being shaped in the Bologna Process, we have devised a set of practical exercises based on students' using and handling an infrared camera to discover and understand important principles or concepts involved in the heat transfer phenomena.

With these practicals the students are able to approach heat transfer in a very intuitive way. The students set up a device with the elements previously prepared by the educator and, when they run the experimental setup, they can observe the heat transfer phenomenon through the infrared camera in a quick, visual manner. Of course, the theoretical basis must be explained before starting the practice session and can be clarified with the thermal images taken while the practicals are being carried out.

This paper is structured as follows. The essential principles of IR thermography and the equipment used are outlined in the second section. The third section includes descriptions of some of the practical exercises that have been devised. The fourth section describes how these practice activities have been applied in the laboratory and how they have been received by students. Finally, the main

* Accepted 25 July 2005.

conclusions from the work are summarized in the last part of the paper.

IR EQUIPMENT USED: FUNDAMENTAL PRINCIPLES OF OPERATION

Temperature is the most common physical property measured. This data give us useful information about objects and people.

Any object with a temperature above 0°K emits electromagnetic radiation and the wavelength is the parameter that characterizes this radiation. The energy associated to a radiation of a particular wavelength λ is given by Planck's Law.

$$W_\lambda = \frac{2 \cdot \pi \cdot h \cdot c^2}{\lambda^5 \cdot (e^{h \cdot c/(\lambda k \cdot T)} - 1)} \cdot 10^{-6} \quad (1)$$

where:

W_λ = spectral radiation of the black body at wavelength λ (W/m)
c = speed of light (2.988×10^{-8} m/s)
h = Planck constant (6.626×10^{-34} J · s)
k = Boltzmann constant (1.381×10^{-23} J/K)
T = absolute temperature of the black body (K)
λ = wavelength (m)

If we integrate Planck's Law along the wavelength spectrum the Stefan-Boltzmann Law is obtained. This law gives us the total radiation energy emitted by a body at temperature T. For the ideal case of a black body, the integration results in the equation $W = \sigma \times T^4$, and for a real body the integration yields the equation $W = \epsilon \times \sigma \times T^4$, e being the emissivity, ranging between 0 and 1, and s is the Stefan-Boltzmann constant (5.7×10^{-8} Wm^{-2}K^{-4}).

These two laws provide the theoretical basis on which infrared technology is developed. The sensors in an infrared camera perceive the radiation emitted in the infrared spectrum by the surfaces it is focused on and transform it into a thermal pattern. In thermal images, surfaces at different temperatures, emitting different radiation energies, are differentiated with distinct colors. This is what we call an infrared image.

At this level, the analysis of an infrared picture can be only qualitative, i.e., the thermography shows us which surfaces are hotter or colder compared to others. To be able to measure the temperature and carry out quantitative analyses it is necessary to know the emissivities of the surfaces. With the emissivity data, the temperature is calculated by applying the Stefan-Boltzmann Law.

Apart from emissivity there are other factors that must be taken into account to obtain accurate thermal patterns: humidity, distance to the object, surface curvature, optical focusing, image composition, etc. All these factors and those related with the handling of the camera are explained to the students while the practice session is under way.

As can be inferred from the above explanation, infrared thermography is a non-destructive, non-contact testing technology. Initially, this technology was developed from 1946 onward for military purposes of localizing, detecting and similar applications, but due to its clear advantages with respect to other techniques for measuring temperature it has since been used in many civil applications from research to maintenance [2, 3]. To quote a few examples, we can read about medical applications [4–6], agriculture and livestock [7, 8], non-destructive testing [9–11], research in heat transfer coefficients [12, 13], construction [14, 15], monitoring and predictive maintenance, etc.

In fact, it is a tool that offers a graphic representation of the thermal state of an object's surface, which can then be used to draw different conclusions according to the case.

In this paper, the applications are extended to the field of education, and more specifically to the learning and comprehension of modes of heat transfer, using a ThermaCAM SC 2000 thermographic camera, manufactured by FLIR Systems AB.

APPLICATION

The set of practical exercises presented in this paper were conceived to allow students to discover and understand how the mathematical equations and theoretical concepts and laws on which heat transfer modes are founded are transferred to reality. By means of the infrared camera conduction, convection and radiation leave the numerical world and became part of the visual world, which in turn allows for intuitive learning to take place.

Thus, the introduction of infrared technology into the laboratory provides a powerful tool for the student to comprehend the principles of the subject and hence learning becomes easier and more enjoyable. At the same time, it introduces students to the possibilities offered by this technology.

Following this paragraph, we provide a description of the different practice sessions that were devised. They are presented according to the different modes of heat transfer.

To perform quantitative analyses with infrared images, one common problem arises in all the practical activities carried out—the value of surface emissivity. Following is described the solution to this problem. Emissivity appears as a property of the object in the camera parameters, and so, to calculate it, we adjust its value until the temperature measured by the IR camera matches the temperature value measured with a calibrated thermometer equipped with a surface temperature probe.

Heat transfer by conduction in composite geometries: a multilayer wall

This sort of structure is used as an example to

Fig. 1. Multilayer wall setup.

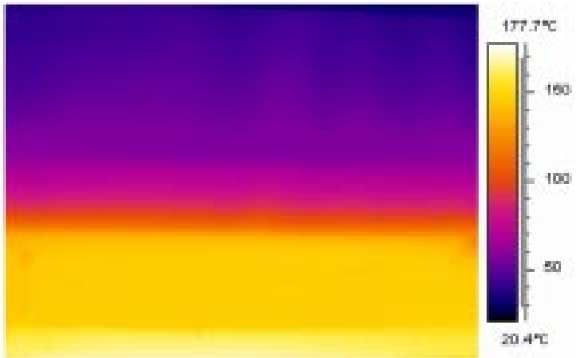

Fig. 2. IR image of the multilayer wall.

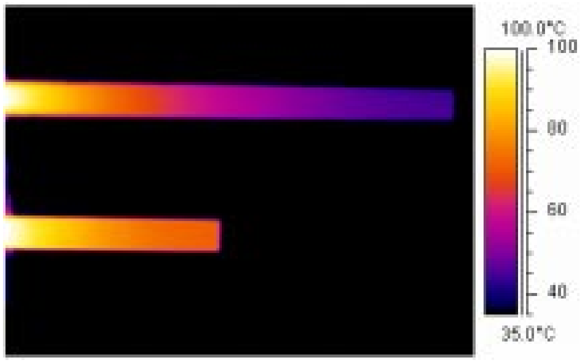

Fig. 4. IR image of fins.

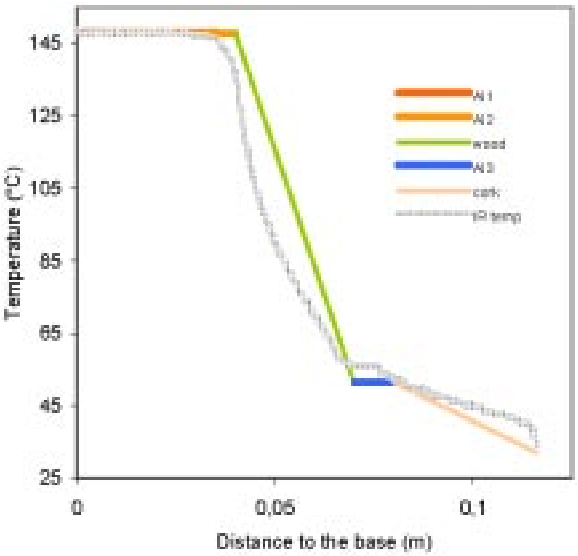

Fig. 3. Comparison between temperatures calculated theoretically and those measured with the IR camera.

explain and develop the theoretical concepts involved in the one-dimensional steady-state conduction heat transfer mode without internal generation of energy. The mathematical relations that result when Fourier's Law is applied and simplified are well known by students. These relations state that the rate of heat transfer per square meter is related to the temperature difference between the surfaces of the wall, the wall thickness and the conductivity of the material. The students use them to solve problems set out in the classroom but perhaps in a mechanical way, without being too aware of what they really mean or entail.

While the practical is being set up, the students can choose between sheets, arranged previously in the workshop, made of different materials but with the same surface area and thickness. In addition, they have at their disposal sheets made of the same material but with different thicknesses so they can compose several multilayer walls.

After the wall is assembled, it is placed over a source of heat and isolated all around to ensure a one-dimensional heat flow, as Fig. 1 shows.

When the steady state is reached, a window in the isolation is opened to allow the thermal images to be taken. Those thermal pictures can be visualized instantaneously with the camera or stored on a PC for later analysis. Fig. 2 shows the thermal pattern of the wall shown in Fig. 1.

In the thermal image (Fig. 2), the temperature distribution can be observed directly and the temperature changes due to the different thermal resistance of each material are highlighted with a color degradation.

Figure 3 shows the comparison between temperatures calculated according to the corresponding equation and those measured with the thermographic camera. They can be seen to be

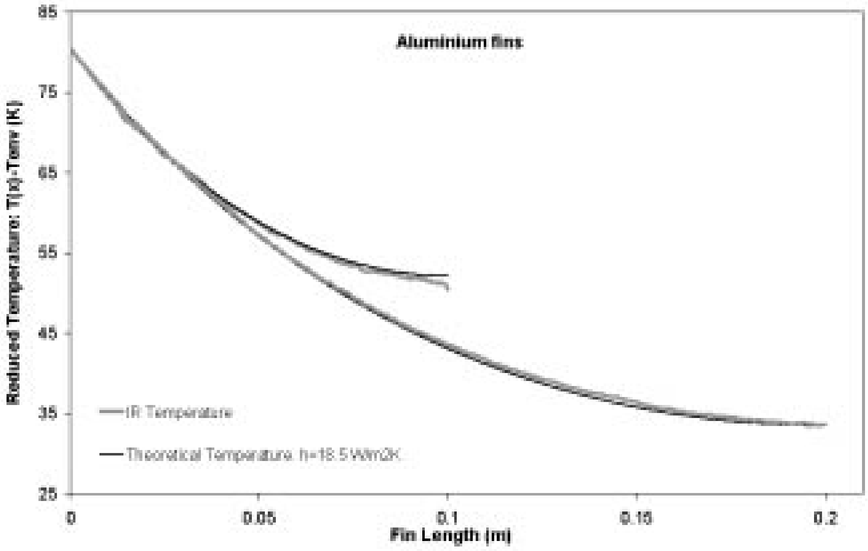

Fig. 5. IR temperature versus theoretical temperature.

Fig. 6. Unsteady-state setup.

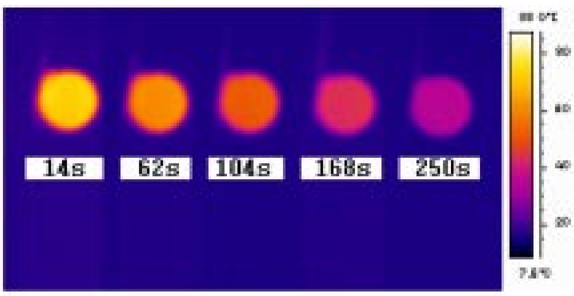

Fig. 7. Sequence of IR images.

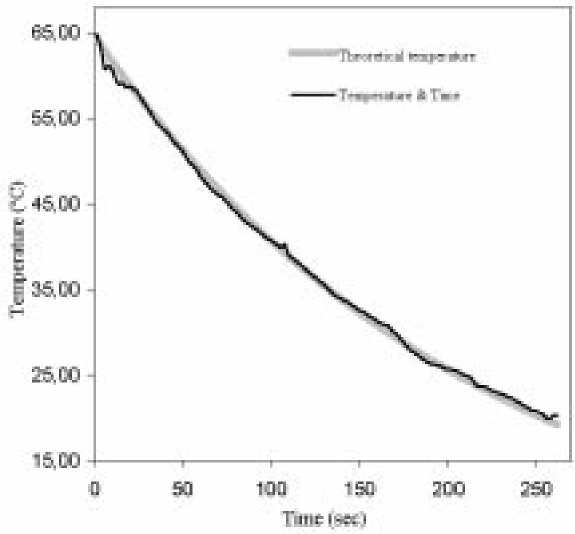

Fig. 8. Comparison between expression and IR.

very similar, and there is only a deviation at the interfaces between panels.

This simulation enables students to understand effects that are not taken into account in the theoretical equations. Thus, the temperature distribution is no longer linear at the interfaces, but instead it is deviated due to boundary effects between the surfaces (contact resistance). It also presents the concept of non-homogeneity of certain materials, such as wood (conglomerate), where a linear distribution is not followed because there are variations in the thermal conductivity inside them.

The different groups of students can compare and discuss results (thermal images and corresponding graphs) obtained and stored by other groups with other wall compositions.

If classical manufactured laboratory equipment were used to do the same practice activity, it would only be possible to draw a graph on which to observe the evolution of the measured temperature through the different layers. This represents a less enriching practical than the equivalent session carried out with thermography.

Heat transfer in extended surfaces: uniform cross-section straight rectangular fin

Finned surfaces are taken as a common example to explain combined conduction-convection heat transfer.

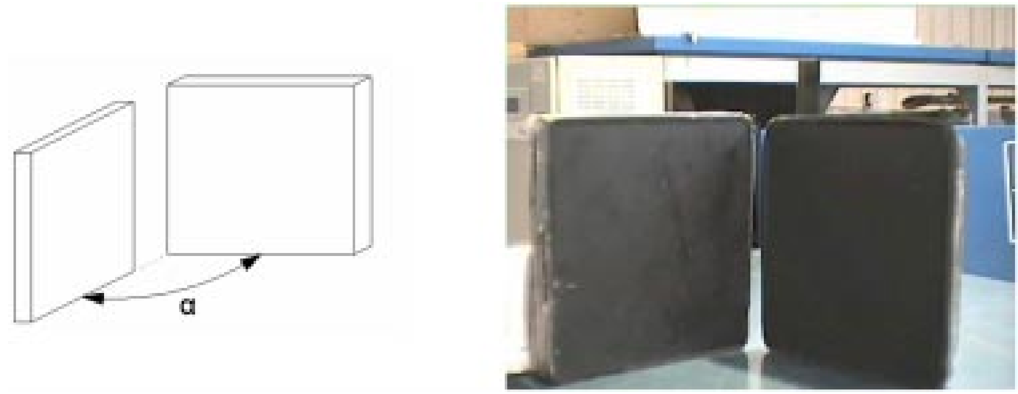

Fig. 9. Layout and setup.

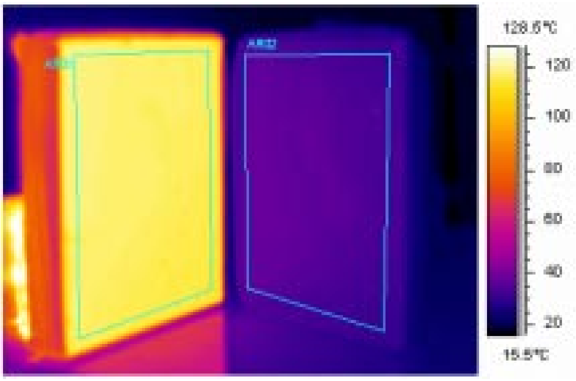

Fig. 10. IR image of the setup.

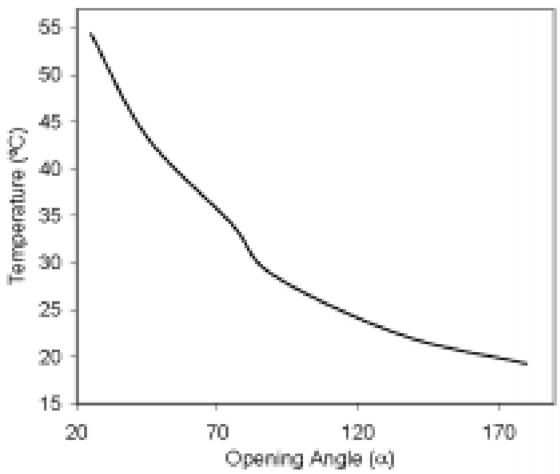

Fig. 11. Variation in the temperature of panel 2 according to the value of a.

In this practical exercise, the steady-state distribution of temperatures in two aluminum fins of rectangular profile welded to the same metallic surface is analyzed. The temperature on the metallic surface is kept constant with a heat source applied on the opposite side where the fins are welded.

The cross-section fin size and the other experiment conditions simulate one-dimensional steady-state conditions, with heat dissipation by natural convection over its surface (considering a uniform convection coefficient).

The infrared thermographies taken of the fins when the steady state is reached are shown in Fig. 4.

The images in Fig. 4 show the temperature distribution over the fin surface. With these thermal patterns, the students become aware of the utility of extended surfaces in order to dissipate heat. Moreover, as the fins have distinct lengths, they can understand two important concepts. First, the concept of efficiency in fins, i.e. why there is an optimal fin length and why it is not reasonable to use the longest possible fins. Second, the concept related to the assumption of an adiabatic fin tip, a case that becomes closer to the real situation when the length of the fin increases.

With the data acquired by means of the infrared camera, students become involved in the estimation of convection coefficients on surfaces. Another application of those data is the comparison between theoretical and actual temperature distribution to check for agreements between them, as Fig. 5 shows. In the graph in Fig. 5, students are given a numerical representation of the two statements about fin length exposed above.

As extended surfaces are commonly used in many devices, in the same practical the students are invited to use the infrared camera to investigate several machines in the laboratory that utilize fins and explain why they are applied on each particular machine. Thus, they can discover the extended surfaces, for instance, placed in coils, reciprocating open-type compressors or in electronic equipment, among many others.

Approximation to unsteady state heat transfer: small diameter sphere

From among all the unsteady cases that can be treated with infrared technology, this practical exercise was selected to appear in this paper because it was proposed by a student.

The non-contact property of infrared technology allows us to analyze the lumped capacitance model, a sort of transient conduction given in bodies with a small Biot number. More specifically, we studied the case of a small sphere that is suddenly immersed in a medium with a constant temperature (i.e. infinite heat capacity), comparing the experimental results with the theoretical resolution. For a transient to be considered as pure, the Biot number must be lower than 0.1, so the ball size is selected to accomplish this condition.

As Fig. 6 shows, the setup we devised is very simple. A small steel ball is heated with a hairdryer. The ball is hung from a thin thread with very low conductivity in order to avoid interference in the transfer of heat from the ball to the environment. When the ball is hot enough and has reached a steady temperature, the hairdryer is switched off and the cooling transient begins until a new equilibrium temperature is reached.

During the time the unsteady state lasts, the camera is programmed to take pictures sequentially. The thermal patterns obtained can be recorded onto a film and played in order to see the full unsteady cooling process. Fig. 7 shows a montage with thermal images of the cooling transient; this montage displays the distribution of the temperature of the ball in time.

The temperature distribution over time measured with the camera can be contrasted with the theoretical evolution of temperatures. The result is shown in Fig. 8.

Thus, with the camera the student performs the cooling transient in a visual manner and obtains the data to check the mathematical developments.

Radiation heat transfer mode: the influence of the view factor

In this case, the aim is to analyze the influence exerted by the view factor on the method of radiation heat transfer between two surfaces.

The setup consists of two metal sheets made of the same material and with an identical surface area and thickness. To avoid the problems produced by low emissivity, the surfaces are painted with a high emissivity paint (above 0.9).

The metal sheets are arranged as appears in Fig. 9. One of the sheets is heated to a high temperature (panel 1), which is kept constant throughout the experiment, while free evolution of the temperature is allowed in the other metal sheet temperature (panel 2). In this way, a net exchange of thermal power is established between the two surfaces, depending on their temperatures, emissivity rates and the view factor between them.

Since the IR camera measures temperatures on surfaces without contact, what is done in the practical is to register the mean surface temperature on the unheated sheet for several opening angles a (see Fig. 10). Thus, the final result is a graph of the mean temperature of panel 2 versus the opening angle between the two panels, as shown in Fig. 11.

Since, in this case, the opening angle is the only variable that the view factor depends on, the obvious conclusion is that the greater the opening angle (in other words, the lower the view factor), the smaller the radiation heat exchange will be, which results in a lower temperature on the metal sheet.

APPLICATION IN THE COURSE

The subject *Thermal Engineering* consists of fifteen hours' laboratory work distributed into four practical sessions. Practicals based on infrared thermography were introduced in the academic year 2003/2004. During that year practical sessions based on infrared technology were carried out together with classical practical exercises using manufactured laboratory equipment. Each laboratory session was made up of three classical and one infrared practical, each lasting about thirty minutes.

From reading this paper, it will already have become clear that the materials utilized in the infrared practicals we devised are very common and simple. Besides this material, the students used a FLIR ThermaCAM SC2000 infrared camera to take the thermal images and ThermaCAM^{TM} Researcher 2002 software to work on the images.

The experience was quite satisfactory. The students' evaluations and their behavior in the practicals made it clear that this new tool was of interest to them. The teachers were repeatedly asked in the different sessions about how to use the IR Camera, as well as its operating principles, applications, etc. Moreover, students took it on themselves to begin to explore and discover the infrared images from surrounding objects and tried to explain their meaning. Therefore, thermography was seen to arouse students' attention and interest, which makes them more receptive to learning.

The great shortcoming was, and still is, the shortage of IR Cameras and the number of students per camera. Unfortunately, we only have one IR camera, and not more than three or four students can use it simultaneously in a practical.

Within the framework of a project aimed at adapting infrared technology to the classroom, in the present academic year, we have kept last year's structure of laboratory sessions and we have also created a new laboratory group that is only working with the IR camera, thus taking full advantage of its possibilities in the laboratory. This group carries out all the practicals we devised, and proposes and develops new ones under the teacher's guidance.

What is clearly observed is the ease with which students assimilate concepts once they are able to interpret the thermal patterns. This is undoubtedly due to the visual component of infrared technology and the eagerness students display to go further when they are allowed to discover any heat transfer phenomenon by themselves.

Acknowledgements—This project was sponsored by the U.S.E. of the Jaume I University under the program 'Projectes de Millora Educativa N-131'.

CONCLUSIONS

In this paper, IR thermography has been presented as a technique to aid the learning of heat transfer phenomena. The aim is to make it easier for students to understand and follow the phenomena involved in the process of heat transfer, as well as to introduce new technology, in this case IR thermography, into the classroom.

With the applications that were implemented it was found that the subject became more enjoyable for students, and this makes them feel more motivated and involved in the teaching–learning process to the point that they proposed and developed new practical activities. At the same time, it was also observed that students needed less time to understand the concepts they were being taught in the classroom.

Nevertheless, the project is not still completely finished and currently it is at a stage in which it is being improved in accordance with the students' and lecturers' evaluations. This is actually reaching a point where we are considering the possibility of changing the subject's program to begin the course with the radiation mode, thereby making it easier for students to understand the concepts of infrared technology.

The great shortcoming detected in this project concerns the number of students per IR camera; if proper learning is to take place the number of students per IR camera must not be more than three or four. This obviously links up with the economic side of this project.

Regarding the budget that this learning method implies, people who adopt it must take into account two important aspects. Firstly, they can use basic IR cameras, which are cheaper than those with the whole range of features. Secondly, money can be saved by not acquiring some manufactured laboratory equipment, which is replaced by cheaper setups made of materials that can be found in the department workshop.

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