Embedding Physics into technology: Infrared thermography and building inspection as a teaching tool - a new participated strategy approach to the physics of heat transfer and energy saving for professional schools

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We describe an inquiry based path about heat conduction as part of a multidisciplinary project on energy saving in a professional school in a province close to Milan (Italy). The teaching-learning process dealt with heat losses in buildings detected with a thermal camera. Three consecutive activities were implemented: direct detection by the students of heat leakages due to thermal bridges in the school structure; simple standard technology laboratory activities on heat transfer, planned and performed by the students themselves, and finally a series of guided laboratory experiences with a thermal camera, to develop and clarify the previous lab activities on thermal conductivity. Key motivations of the project were: creating a link between the study of thermodynamics and its application to the "real" world; increasing students' motivation by using an Inquiry Based Science Education (IBSE) approach; studying if/how the "infusion" of a cutting-edge, and therefore science attracting, technology (thermography) might foster the teaching learning process, thus becoming a concrete cognitive tool promoting the students' approach to the scientific methodology.

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I. INTRODUCTION

Most students attending professional technical schools plan to directly enter the job market upon completion of their courses. They therefore show weak, often occasional, interest in abstract and theoretical subjects. A correlation between the theoretical subjects taught and their application and saleability in the "social contest" (the environment and the territory) should therefore be a priority for a teaching and learning process in such schools.

Considering the specific case of physics, we see that the presentation of the subject matter is usually essentially the same for all curricula. In Italy, for example, the number of credits (hours) of the course determines almost solely the depth of treatment of each and all subjects presented, irrespective of the specific address of the school, from the preparatory to the professional. Especially in professional schools, this produces an evident gap between the taught theory and the technical capabilities the students are developing. On the other hand, students are in general attracted by the glamour and novelty of vanguard technologies, and by the idea of their potential practical applications. As these aspects positively influence their motivation, school often tries to foster them by, for example, organizing meetings with experts, visits to factories and exhibitions, work stages and so on. Unfortunately, from the point of view of cognitive learning, their effectiveness is limited, as their contents and methods have nothing or little to do with the aims of scientific and technical education. For what concerns our principal aims, that is the introduction of some aspects of thermodynamics, in particular the concepts of temperature, heat, and the processes of heat transfer, a number of conceptual difficulties encountered by students are well known from the literature. They vary from ingrained common misconceptions, mostly related to the concepts of heat and temperature [1, 2], to difficulties in differentiating states and processes [3, 4] or to heat transfer problems [5]. Recently, reported experiences appear to recommend inquiry as an effective approach to develop students' conceptual understanding also in thermal physics [6, 7]. Koschmann [8] points out that the role of technology in a teaching learning process is related to the choice of a learning theory and to the choice of a teaching method. Following the constructivist idea that learners should be given responsibility and control over their learning [9–13], we adopted a "guided inquiry" approach [14]: the question is proposed by the teacher, while the method and the answers are given by the students. In fact, students should work in a sort of dynamic interaction among themselves, collaborating and discussing, while the teacher gives them only proper hints at the right moment. From the above considerations stems our proposal of a concrete interdisciplinary path involving technical as well as physics lessons, aimed at countering students' disaffection towards physics, and oriented according to the type of school. The idea is that physics gives the ways to interpret activities taken from the landscape of practical and technological activities. In this paper we briefly report our "problem–driven" [15] project and its pilot experimentation in an Italian upper secondary technical school which prepares future surveyors through a five year course.

Key points of our project were:

1) Start first with professional activities and only afterward pass to physics for "necessity";

2) Choose a subject of current interest relevant both to professional knowledge and to a branch of physics;

3) Use a suitable cutting edge technology for professional and physics activities in order to create interest in students, a clear bridge linking technical and physics lessons and as a cognitive tool that can facilitate a first approach to physics modeling;

4) Design an inquiry path leading students from practical applications to the physics of heat transfer through suitable laboratory experiments.

For what concerns point 2), the energy saving issue, and in particular the energy re-qualification of buildings (heating and cooling of buildings represent a large fraction of the energy consumption in developed countries), building inspection through thermography appeared a suitable subject for future surveyors: it is relevant to their future profession and has an obvious theoretical correspondence in the physics of heat transfer processes.

Concerning point 3), a natural choice for a high technology device was a thermal camera (imager).

Infrared long-wavelength radiation measured by a thermal camera are translated into temperature to obtain what is called a thermal image, after a proper calibration, and assuming that objects in the scene recorded by the camera can be considered black–body–like emitters with constant spectral emissivity [16]. The thermographic survey thus obtained has the advantage of covering, in just one shot, extended areas. This makes thermography particularly suitable for a number of practical applications [17, 18], ranging from medical non invasive diagnostic [19] to cultural heritage inspections [20]. In our experiment we measured temperature of water assumed to have emissivity of $0,98$.

We used a AVIO TVS 700 $8 \div 14$ μm camera 320 x 240 pixels with a 35 mm lens ($26°$ H $19,6°$ V Field Of View). As far as we know, educational applications of infrared thermography were first discussed in 2001 in [21], when thermal cameras where still too expensive for widespread use in schools. With time, their price has significantly decreased and reports of their use in didactics have become more frequent [22–27].

Regarding point 4), after a one hour introduction on the basic concepts of thermovision and the use of a thermal imager during technical lessons, which we do not linger on here, our path started hands-on with a thermographic survey of the school building, conducted by the students, who detected and mapped thermal bridges (parts of the building where heat transfer with the surrounding environment is abnormally high). Being exposed to a practical and engaging problem, students themselves showed interest in finding and interpreting the collected images. A similar approach and its effectiveness is well described in a recent paper [28]. At this point, physics lessons came to help with two guided 5E cycles in which students first devised some simple experiments on heat transfer phenomena which were performed using thermometers as measuring tools. A 5E cycle, typical of an IBSE approach, is composed of five entangled steps - Engage, Explore, Explain, Extend, Evaluate - that will be detailed for our case in the Paragraph II [29, 30].

Afterwords, an in class discussion led to the design of an improved experiment that was prepared and then performed using an infrared camera. A further in class discussion led to a final interpretation of the results obtained.

Physics lessons were interspersed with interdisciplinary technical seminars on thermal conductivity, energy and environment, the contents of the European energy certification and construction materials, complemented by a new inspection, this time of local building sites.

In sections II and III we discuss in some detail our path, its results and its pilot experimentation; discussions and conclusions are presented in section IV.

II. THE DIDACTICAL PATH IN DETAIL

The activity was divided into three phases.

Phase 1: basics of thermography.

Engage (1 hour): introductory meeting on thermal vision. 206 students, coming from 10 different classes (9th-12th grade), aged 14 to 17, 98% being males, with 15 teachers participated to an introductory one-hour lesson on thermal vision held by external experts. Thermal vision's basic principles at the base of building detection were introduced and illustrated via a number of examples of thermal mapping of buildings. The aim of this phase was to engage the students' interest in thermal vision by presenting its applications in the field of their future profession.

Explore (2 hours): mapping of the school building. After two weeks, 20 students (two from each class) carried out the mapping of the school building, assisted by a teacher and an expert from the local association of Construction Professionals and Territory. The activity took place in a winter morning, to maximize the thermal gradient between the inside of the building and the surroundings: during the two hours of the activity the outdoors temperature varied from $-5°C$ to $6°C$ and the indoors one from $17°C$ to $21°C$. Two different pictures of each part of the building were taken: one in visible light with a normal camera and one in infrared, with a thermal camera. An example is shown in Figure 1 (colours online).

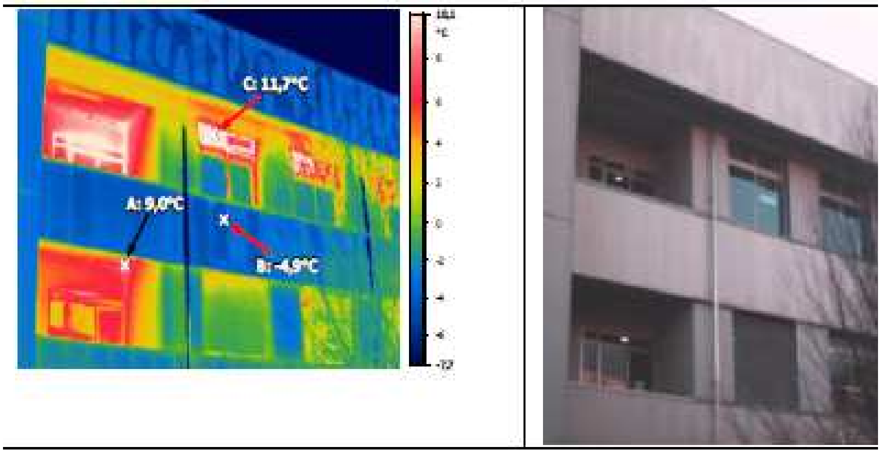

FIG. 1: The thermal image (colours online) reveals a hot spot at the top of the window. This is a poorly insulating structure, named thermal bridge.

Explain (1 hour + 1/2 hour test): what do the collected thermal images describe/indicate? The students discussed in class with the aid of an expert and of their physics teacher the images collected by their classmates.

They had the chance to appreciate that what seems a uniform surface when visually observed, can reveal important inhomogeneities in a thermographic image. The expert explained that some thermal anomalies, called thermal bridges, are areas where heat transfer occurs between indoor and oudoor parts of the same building more easily then in the surrounding regions. They can be related to defects, or to the presence of different materials, due for example to a remaking or to modifications of the building [17]. Taking a thermal shot of a building, it is thus possible to collect information regarding component elements, their shape, their physical characteristics, and their state of decay, as for example, the presence of moisture or plaster detachments [31].

Students were divided into 4 groups each of which had some normal plus some thermal images to analyze. They had to answer a few questions: a) which are the zones of higher and of lower temperature?; b) what is the link between temperature differences and heat transfer?; c) which are the best/worst insulated zones?; d) What does each image describe?; e) What is the principal process that an image is putting in evidence? This discussion gave the opportunity to the expert to monitor the students difficulties and common viewpoint conceptions. Finally, students answered a multiple choice test, useful to monitor their understanding of the basic principles of thermography and of the operation of thermal imaging techniques. The results are shown in Figure 2. It can be noticed that students had some uncertainties about the concepts of non destructive testing and of thermal bridges, that therefore the teachers had to further discuss with them.

Phase 2: lab activities on heat transfer.

Only one single second year class attended this and the next phase of the experimentation. The aim was to introduce the physics of heat transfer as an interpretative tool to better understand previous technical activities.

Engage (1/2 hour + home work). The students were given a task: design and perform a low cost, home made, laboratory activity to study heat transfer in different materials. In a brainstorming discussion, they decided to use cans filled with boiling water, measuring the cooling down of the water. Students were equipped with thermometers, but provided themselves (from home) the rest of the materials employed during the experimental activity.

Explore (home work 1 hour). Students worked in groups. Every group insulated two cans with different materials and, in order to study the efficiency of their thermal insulations, they compared the cooling of water inside them. Plain aluminum and brass cans were chosen. While aluminum cans are the ones used for beverages, and therefore had a small triangular aperture, the brass ones had flat bottom and were completely open at the top. In Table I the cans and the insulating materials chosen by the students are listed, and a picture of them is shown in Figure 3. Water temperature was measured every minute for about one hour, using thermometers inserted in the water through the

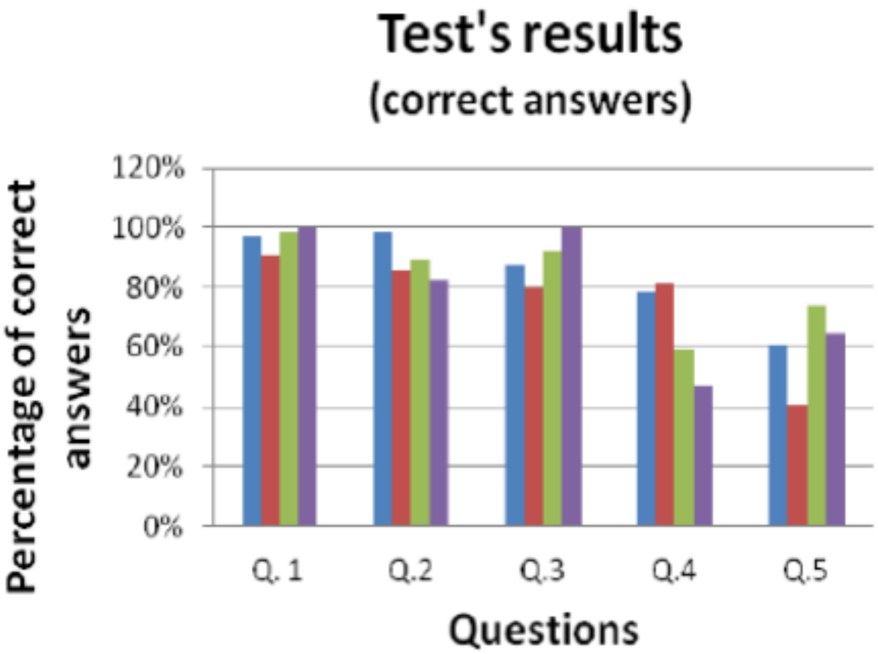

FIG. 2: Results of a multiple choice test on thermography. The questions concerned:
Q.1: "A thermal camera can photograph objects using: a) visible radiation, b) infrared radiation, c) ultraviolet radiation. (Correct answer: b)";
Q.2: "Can a thermal camera be used to measure the temperature of objects? a) yes, b) no, c) it only measures the difference of the indoor temperature with that outside. (Correct answer: a)";
Q.3: "A thermal camera can be used in building industry to identify: a) the exact value of the inside temperature of a building, b) the underground foundation of building, c) insulating properties of walls. (Correct answer: c)";
Q.4: "Which one of these following techniques is a "non destructive testing"? a) core sampling, b) infrared photography, c) mineralogical analyses of materials. (Correct answer: b)";
Q.5: "Thermal bridges in buildings correspond to: a) reduction of the thickness of the walls, b) increase in the loss of heat, c) higher thermal insulation. (Correct answer: b)".
The columns represent the students' ages: from left to right $14-17$ (colours online).

opening in the top of the cans. The resulting graphs are shown in Figure 4 where the rough temperatures are plotted as a function of time for each can.

Explain (1 hour). The data were then discussed among students and with the teacher. Students had to understand if the graphs allow to compare the insulation characteristics of the different cans. It resulted quite evident that a different representation of the data was required in order to compare the results. In fact, the measured temperatures started and ended with different values for each can and, even if from the qualitative trend of the graphs one could in some cases argue their "insulation power", nonetheless a measurable quantity characterizing this power had still to be determined or, to say better: discovered. Another brainstorming discussion led to the conclusion that a better understanding could come from plotting temperature variation, from the initial one, as a function of the time elapsed. But, since 10th grade students are used to deal with and interpret just straight lines graphs, even this new representation of the data, normalized to the initial temperature, failed to suggest them a clear indication of the insulation performance of the different materials used. Reminding a previous standard lab work on the determination of the period of a pendulum versus its length, at a certain point a group (and then all the others) decided to plot the temperature variations $T_i - T_f$ versus the square root of the time. Let us observe that although the teacher would have, instead, plotted $(T_i - T_f)^2$ versus t, she let students decide their way. Moreover, since students studied $T_i - T_f$, and not, as it could be usual, $T_f - T_i$, the temperature variations were increasing, instead of decreasing with time. The results are shown in Figure 5. It is evident that the curves, that are almost straight lines, can now be easily compared (for example, we can easily appreciate that in the sample E, the temperature changes much slower than in the sample J). The slope value of each curve is then a way of representing the insulation power of each can (the

group	can 1	material + insulation	can 2	material + insulation
1	A^*	brass + thick felt	B^*	brass + thin felt
2	C	aluminum + no insulation	E	aluminum + ceramic fiber
3	D	aluminum + no insulation	F	aluminum + packing polystyrene
4	G^*	aluminum + no insulation	H^*	aluminum + cotton wool
5	I	aluminum + cube of polystyrene	J	aluminum + rockwool

TABLE I: Couples of cans used by each students' group. The cans marked by (*) were completely open on the top.

greater the slope, the less the insulation). It must be noted however that, as also students observed, the curves are not extremely regular and they are linear only for quite a small time range. Let us observe, moreover, that no error bars were spontaneously calculated by the students nor considerations of the goodness of the measuring time and temperature techniques were made; therefore a discussion on the trend of the curves could not be thoroughly afforded. In fact, the goal was an inquiry activity leading principally to the discovery (not to the measurement) of a quantity characterizing conduction properties.

We point out that it is quite remarkable that students found spontaneously the dependendence of ΔT on $t^{1/2}$ since this is the result of an analytical solution of the heat transfer equation in the case of a semi-infinite solid, in which a sudden change of surface temperature is imposed [16, 18]:

$$\Delta T = \frac{2Q}{\sqrt{\pi \rho c k}}\sqrt{t}, \tag{1}$$

where (in IS units) ΔT is the surface temperature variation, ρ the density of the medium, c its specific heat, k its thermal conductivity, Q the heat flux and t the time. Although equation 1 is obtained in the particular case of heat diffusing in an extremely thick solid, this formula is a good approximation in many practical situations when the variation of the surface temperature depends on diffusion in an insulating material, the heat flux Q may be assumed one-dimensional, that means without significant heat losses in other directions. In the case of our experiment this description is a good one in the reasonable hypothesis that the water is at the same temperature of the can surfaces and that thermal diffusion occurs basically through the can side, the losses from the can's top and bottom being negligible.

We shall discuss the time behavior of temperature in detail when we shall compare these measurements with those performed using a thermal camera. We anticipate that the deviation observed at high time delays can be explained keeping into account that, as already said, Equation (1) is a good approximation only when the sample temperature is much different from the surrounding one, therefore it is not suitable towards the end of the process, when the sample temperature asymptotically approaches the external one. No observation of this kind was given by the teacher, because no question was asked by the students. The range in which each curve is sufficiently linear was determined by hand by the groups of students, but a linear least square fit was automatically performed for each curve using Excel ©. The resulting slopes and the number of points used for the fits (in parentheses) are shown in Table II.

Phase 3: lab work with a thermal camera.

Extend (approximately 3 hours). After a few weeks, to improve data analysis and to better connect the physics with the previously explained technology, the same experiment (with the same cans) was performed using a thermal camera under the supervision of two of the authors (N. L. and M. G.). The cans were filled again with boiling water, and the change in time of the temperature was now measured using a thermal camera (Figure 6). The five couples of cans employed by students were monitored during the cooling phase and measurements were taken every minute. The thermal camera measured the water temperature in the cans from the top. The cans were positioned on a piece of 1 cm thick cardboard placed on the floor. After about 1 h and 1/2, the cans were removed and their thermal prints on the cardboard were also detected by thermography (Figure 7) to visually check that thermal conduction took place also through the bottom of the cans. The different colors of the thermal prints, moreover, gave an indication that the relative importance of this effect was not the same for all the cans, even if – as can be seen from Table II – the differences in temperature of the prints are not large.

To compare the efficiency of the thermal insulating materials chosen by the student groups, temperature data were at first plotted versus the time elapsed since the boiling water was poured in the cans. Then, the cooling was plotted versus the square root of the time passed since the temperature in the cans started decreasing after pouring hot water in them (see Figure 8). This was done, in analogy with the thermometer measurements, in order to compensate for the different initial temperatures and, at the same time, to compare the data analysis with the one previously done by the students. A linear least square fitting was performed for each curve. The resulting slopes are shown in Table II, together with the corresponding slopes calculated from the data collected in Phase 2 (that is with thermometers) and

FIG. 3: The cans and their insulation used in phases 3 and 4 of the experimentation. From left to right, in the top row are cans A, C, and E as described in Table I; in the middle row, cans B, D, F, and I; and in the bottom row, cans C, H, and J (colours online).

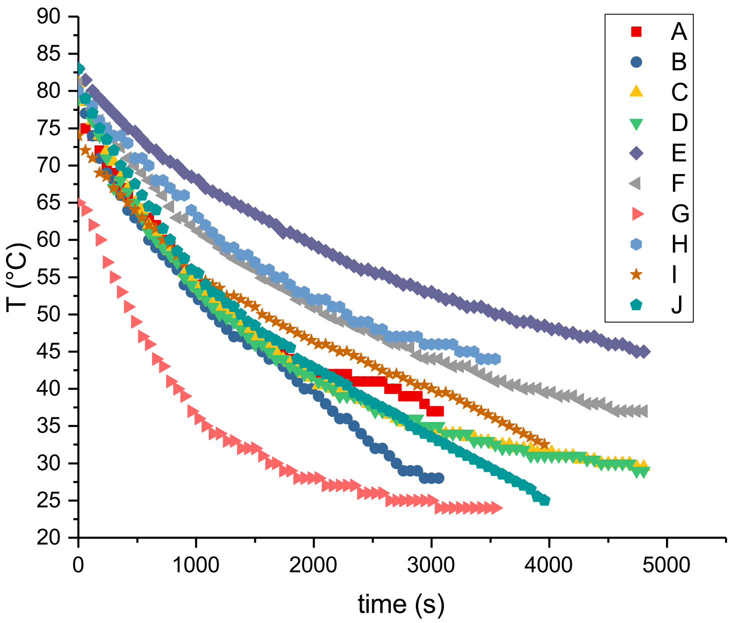

FIG. 4: Thermometer data: plot of the temperature of the ten cans vs. time. In the inset, the correspondence between the cans and the symbols is given (colours online).

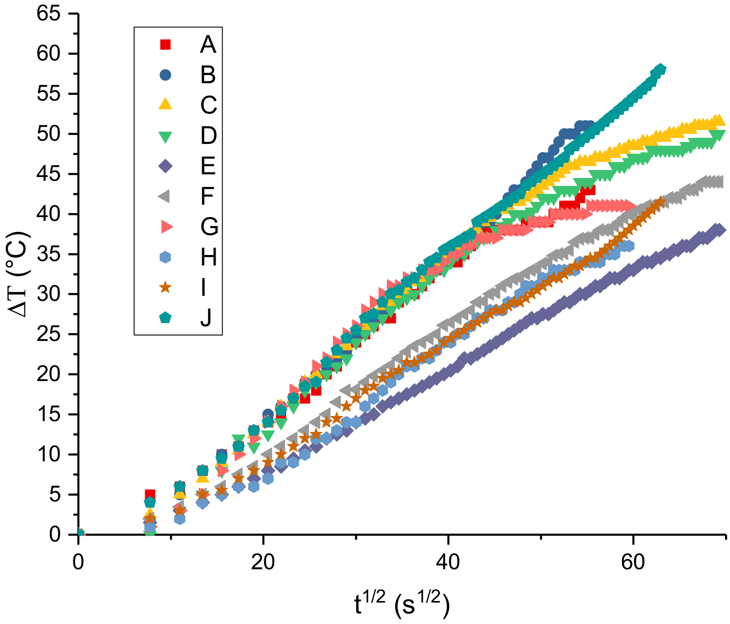

FIG. 5: Thermometer data: plot of the temperature variation of the ten cans vs. the square root of time. The symbols are the same as in Figure 4 (colours online).

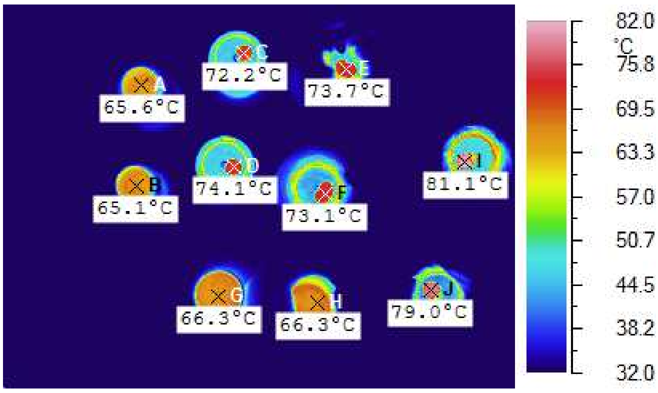

FIG. 6: Thermal picture of the top of the cans shown in Figure 3. Data refer to the water temperatures collected by the thermal camera during the experiment (see Figure 8) (colours online).

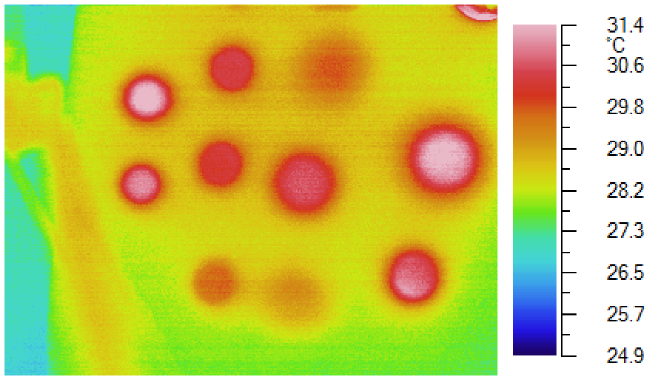

FIG. 7: Heat prints left by the ten cans on the cardboard shown in Figure 3 immediately after they have been removed. The colours of the prints (colours online) show the different temperature of different areas of the cardboard due to heat leakage through the bottom of the cans.

with the temperatures of the thermal prints. Note that, also for thermal camera measurements, at high times some of the plots stop being linear, as expected when the temperature of the water gets close to that of the surrounding air. Only the linear part of the plots (again chosen by hand by the students) was therefore used for the fitting, resulting in correlation indexes (R^2) very close to 1 for all plots (less than 1% deviation). These results were then interpreted in a guided discussion among the students with the aim of defining a first interpretative model. A few considerations emerged:

1) As expected, the highest slopes, corresponding to a faster cooling, were for the cans with no insulation (C, D and G);

2) The lowest number of data used for the fitting was for samples G and H that showed a marked downward curvature of the relative plots. It was observed that the top side of both these cans was completely open. Students therefore hypothesized that, besides heat conduction through the walls of the cans, also water evaporation, enhanced

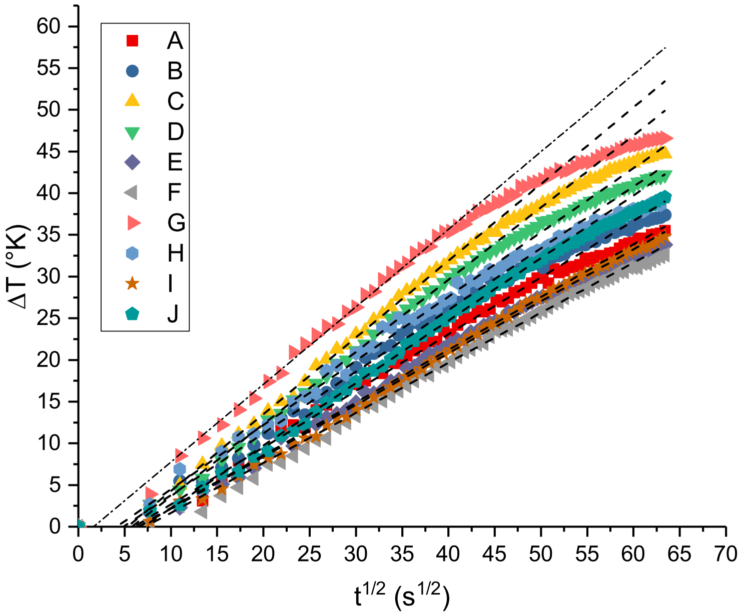

FIG. 8: Thermal camera data: plot of the change of temperature of the ten cans vs. the square root of time. The symbols are the same as in Figure 4. The straight lines represent the linear fits giving the slopes listed in Table II (colours online).

by the large size of the holes, plays a significant role in the transfer of heat, and leads to a faster temperature decrease of the water. They also considered that other modes of heat transfer, such as convection (of the air surrounding the cans) and radiation would have affected all the cans in a similar way, therefore are not responsible of the faster cooling of cans G and H;

3) The effect of a marked downward curvature is less evident for samples A and B, which were also completely open on the top, but had a much stronger dissipation from the bottom of the can, as can be seen from Figure 7. One can suppose that, for these cans, evaporation is not competitive with conduction;

4) The question emerged of what would have been the final temperature of the water if we had not stopped the measurements. The answer came principally from the analysis of the plot of temperature versus time (Figure 4). A general agreement was reached that the final temperature would have been the room one. Therefore a downward curvature of all the curves was understood as a general feature, and the linear part of each plot interpreted as describing a process with little heat exchange;

5) Additional spontaneous comments of the students concerned the difference between the regularity of the results obtained using the thermal camera with respect to those obtained using thermometers. First of all, it has been noted that, while the thermal camera data were obtained using the same instrument on all cans at the same time and in the same place, the thermometers were read by different groups of students in different parts of the school lab, at different times. Moreover, while the thermal camera is a passive instrument (non invasive) with respect to the cans, thermometers are not: the interaction of the thermometers' bulbs with the water in the cans could produce a systematic error;

6) The previous comments triggered a brief discussion on the necessity to consider errors in measurements.

Finally, the students presented reports on their work and findings.

III. RESULTS

For the evaluation of the effectiveness of the learning process, we considered the following steps:

1) The multiple-choice test on thermovision presented above, whose results are shown in Figure 2;

2) The level of the students' contributions to the discussion in the laboratory;

3) The comments given by the students when presenting the results obtained in the various phases;

Sample	Slope ($K/s^{1/2}$) thermal camera	Slope($K/s^{1/2}$) thermometer	Thermal print temperature (C)	Additional significant heat losses
E	0.62 (65)	0.79 (50)	29.0	
F	0.64 (60)	0.79 (50)	30.9	
I	0.66 (67)	0.72 (50)	31.4	
J	0.75 (57)	1.02 (50)	30.8	bottom of the can
A^*	0.75 (32)	0.84 (52)	31.3	bottom of the can and evaporation from open top
B^*	0.81 (27)	1.06 (49)	31.0	bottom of the can and evaporation from open top
H^*	0.82 (32)	0.64 (51)	28.7	evaporation from open top
D	0.92 (30)	0.94 (50)	30.2	
C	0.93 (36)	1.22 (20)	30.2	
G^*	0.95 (29)	0.97 (50)	29.2	evaporation from open top

TABLE II: The slopes obtained by linear fit of the plots in Figure 8, the slopes of the analogous plots obtained from the data in Figure 4 and the temperature of the thermal prints. The last column indicates identifiable additional significant heat losses. The cans marked by (*) were completely open on the top. In parenthesis, next to the slopes, we give the number of data points used for the linear interpolation. The cans are ordered by increasing slope (decreasing insulation level).

Question \ Evaluation level	1	2	3	4	5	6
Satisfaction level compared to expectations	1.5 %	0 %	9.2 %	25.2 %	43.7 %	20.4 %
Evaluation of laboratory equipment	1.5 %	2.4 %	5.8 %	21.8 %	44.2 %	24.3 %
Activity organization and planning	0.5 %	1.0 %	8.3 %	18.9 %	29.1 %	42.2 %
Contents and clarity of exposition	1.5 %	1.5 %	7.3 %	20.4 %	44.7 %	24.8 %

TABLE III: Summary of the results of the questionnaire for students' evaluation of the activity. Percentage of answers for each evaluation level from minimum (1) to maximum (6). The sample was of 206 students.

4) The outcome of a multiple choice questionnaire on the students' personal evaluation on the whole project. The questionnaire included questions about the student's satisfaction level compared to expectations, the tools at their disposal, their perceived comprehension of the treated contents, etc, with space provided for personal comments.

We can notice that the results of the test on thermovision were remarkably good for the first three questions, less for the last two (see Figure 2).

We have observed that students' contribution to the discussion in the laboratory was very satisfactory. This was especially true for the least motivated students in physics who have been very active not only in doing handwork, but also in participating to discussions on issues that were not to be studied before in the text-book. For what concerns the final reports of their experiments, more than 80% of the students got positive assessments by their class teacher.

We received positive comments coming from the group discussions concerning the work environment and the methodology. A summary of the students' evaluation of the experience, coming from the questionnaire answers, is given in Table III.

The personal comments were all positive, and we report here some extracts from a couple of them:

"The experiment was interesting also because it helped me to find out and learn formulas which are useful to understand many extremely important concepts ... I could see that all the students in the class were really involved". "The experiment on the whole was very clear and I could understand more about it". "... it raised my interest I felt I had more curiosity to do a better job".

IV. DISCUSSION AND CONCLUSIONS

The path presented above consisted in a sequence of guided enquiry activities about heat conduction settled in the interdisciplinary technical context of building inspection through thermography. Physics provided the ways to ask questions and seek the answers with practical lab work, but the landscape was the students' near environment, while the start kick came from professional technologies. Driven by the analysis of real images related to the presence of thermal bridges in their school, the students, through an elaborated experimental activity, were, at the end, able to discover a way of defining and measuring a physical quantity clearly related to thermal properties of insulating materials; namely the proportionality factor $C = \frac{2Q}{\sqrt{\pi \rho c k}}$ between the temperature variation and the square root of the time elapsed. It is a coefficient that, in the words of students, measures the "insulation capability of a substance". The physical relation we are speaking about is not present in students' text-books, nor it can easily be found in internet. Therefore, the activity allowed students to make a real research experience, although they had only a poor physical knowledge. In the ten hours plus the time devoted to homework, students worked in a new and intriguing way in which the emphasis was no longer on "the study of physics", but on "the study of the world through physics". Students were invited to organize, interpret and understand their own practical work; they started with an intuitive research for possible insulating materials and, using simple facilities of the school physics lab, together with suitably chosen low cost objects, they did a first quantitative measurement of thermal variations in a fixed, given situation. Nevertheless, they were still not able to understand the physical meaning of the acquired data, but only of a simple elementary description of the graphs obtained. The hint coming from a practical question: "How can we scale up insulating materials from the best to the worst?", let them make a step forward. The use of a thermal camera allowed them to refine their understanding of the heat dissipation phenomena involved in the experiment. In particular, they understood that heat can flow following other paths besides the simple conduction through the side walls of the cans: for example evaporation or conduction through the bottom of the cans. This finally led them to develop a critical understanding of the assumptions of the quantitative phenomenological model adopted. The thermal camera, initially presented as a work instrument for building inspection, was then turned into a cognitive tool for the description of their experiments. In this way students moved on from a hands–on introduction to the scientific methodology and to the use and limitations of approximations, being able to understand the wide scope of the methodology itself. Last, but not least, in the climate of participation that was created, students developed also a friendly approach to mathematical contents that they were used to manage (hardly) only in abstracts and/or formal contests. This helped to reduce their disaffection towards the formal aspects of physics modeling.

V. ACKNOWLEDGEMENTS

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