ENERGY EXCHANGE BY THERMAL RADIATION: HINTS AND SUGGESTIONS FOR AN INQUIRY BASED LAB APPROACH

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ABSTRACT: In this paper we present some laboratory activities developed in the framework of an inquiry-based, context-to-content teaching/learning approach to the study of energy exchange by thermal radiation. These activities have been developed in the context of “Establish”, a FP7 European Project aimed at promoting and developing Inquiry Based Science Education in European Secondary Schools. By starting from real life, meaningful situations, students are engaged in designing and carrying out laboratory activities by collecting, processing and analysing data. Particular attention is paid in building data interpretation by taking into account the effects of parameters like the environmental temperature, that, if not correctly considered, can lead to the application of wrong approximations and to an incomplete understanding of the physics underlying the analyzed situations.

1. Introduction

Several researches in science education support the view that teaching science as inquiry enables students to obtain an experience that is similar to that of scientists, making their learning more meaningful and improving their scientific understanding (Minstrell and van Zee, 2000; Windschitl and Thompson 2006). By inquiry we refer to learning experiences that engage students in various integrated activities of identifying questions, collecting and interpreting evidence, formulating explanations, and communicating their findings, that are consistent with science standards and recent reports (Duschl et al, 2007; Singer et al, 2005). In the majority of the developed Inquiry Based (IB) approaches, a relevant role is played by laboratory activities where students are directly engaged in finding answers to their questions, developed in appropriate contexts, as well as in developing investigative competences. On the contrary, in traditional content-to-context based physics education, the focus of laboratory activities developed by students is mostly dedicated on verifying information previously transferred by the teacher.

It is well acknowledged that science education has to make students aware that science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. Both elements, knowledge and practice, are essential (NAS, 2011).

In all IB approaches to science teaching, students are themselves engaged in the practices and do not merely learn about them second-hand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves. However, many problems exists in integrating contents and practices.

In this view, we are developing a teaching-learning sequence regarding the investigation of energy exchange by thermal radiation, conduction and convection, within the context of ESTABLISH (http://www.establish-fp7.eu), a FP7 European Project aimed at promoting and developing IBSE in European secondary schools. Our teaching-learning sequence is organized by firstly engaging students by means of scientifically oriented questions about real life situations, such as thermal insulation of houses and the use of energy saving materials. Students are invited to design and build by themselves a scale model of an energy-efficient house, through the understanding of relevant concepts regarding the energy flow in thermal systems. Then they are directly involved into modelling and practical activities and are stimulated to carry out their own experiments.

As a part of this inquiry-oriented teaching/learning sequence, here we present a laboratory activity for secondary school level students, or even first-level university ones, aimed at investigating the physics of energy transfer by thermal radiation. A scientific investigation on the energy exchange between a powered resistor and its surrounding environment during the heating and cooling processes is proposed. Students are stimulated to plan and carry out their own laboratory activity by collecting, processing and analysing data, in order to learn new concepts or laws and obtain more meaningful conceptual understanding of the physics underlying the process of energy exchange by thermal radiation. In particular, we report as problems and experiments have been developed in a workshop for engineering students attending the second year of their university curriculum.

In the following section, we present the theoretical framework that grounded the organization of the workshop. In Sections 3 and 4 we describe an example of inquiry-lab learning path where engineering students are directly involved in experimental activities and in the related investigations aimed at giving theoretical meaning to their experimental results. Finally, we discuss the pedagogical experiment by drawing conclusions about the way to improve its efficacy.

2. Theoretical Background

The term “inquiry,” has been interpreted over time in many different ways throughout the science education community. For this reason, many new documents better specify what is meant by inquiry in science and the range of cognitive, social, and physical practices that it requires.
The new Framework for K-12 Science Education (NAS, 2011) describes a set of practices for K-12 students derived from those that scientists and engineers actually engage in as part of their work. It is recognized that students cannot reach the level of competence of professional scientists and engineers, as well as that to give students opportunities to immerse themselves in these practices and to explore why they are central to science and engineering is critical to appreciate the skill of the expert and the nature of his or her enterprise.
Eight practices are considered to be essential elements of the K-12 science and engineering curriculum:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics, information and computer technology, and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information.

These may be, a fortiori, considered relevant for undergraduate students. However, typical pedagogical methods used in introductory physics courses mainly engage students in lectures and the related laboratory experiments can be grouped into two categories:

- A theoretical relationship between two or more variables is already known (or at least suspected) and an experiment is needed to verify or quantify this relationship.
- A theoretical relationship between two or more variables is not available but rather sought through an experiment.

Such kind of activities obscure the inquiry characteristics of scientific investigation and very often students perform experiments by slavishly following the recipes supplied by instructor.
Many papers have pointed out the fairly general process that one can follow to design an experiment under any circumstances (Winncy, et al., 2005; Hatzikraniotis et als., 2010). This process can serve as a tool for teaching students experimental design as well as to introduce in it many of the practices previously described (NAS, 2011).
Relevant elements of such a process have been considered the following (Winncy, et al., 2005):

1. Define the goals and objectives of the experiment.
2. Research any relevant theory (or idea) about what to expect from the experiment.
3. Select the dependent and independent variable(s) to be measured.
4. Select appropriate methods for measuring these variables.
5. Choose appropriate equipment and instrumentation.
6. Select the proper range of the independent variable(s).
7. Determine an appropriate number of data points needed for each type of measurement.

An easy solution, of course, is to intend all the information in steps 1 through 7 as a prescriptions by providing a “cookbook” lab. However, this types of approach should not supply an environment suitable to develop competences in experimental design as well as to engage students in inquiring. Our approach is aimed at defining and characterising practices in parallel at applying them at the solution of well posed problems. We think that this approach is relevant for making students aware of the involved practical/thinking process in a way that make them able to transfer these in different contexts.

Here, we describe a 4-hour Worksop (W) where students were put in a real problematic situation that made them face with a real problem, whose solution required the activation of the typical operative processes (theoretical and experimental) of scientific investigation.

3. Method

The W involved 60 engineering students that have completed their two courses of Introductory Physics mainly consisting in lectures and activities devoted to the solution of numerical problems. They participated to the W on a voluntary basis.

The lab activities have been introduced through a phase of topic exploration, mainly based on students' prior knowledge, that has been followed by a discussion about the relevant physical quantities which should be taken into account in a contest of a laboratory activity of measurements. From their previous studies, students should know that the energy exchange between an emitting body and its surrounding is caused by the processes of conduction, convection and radiation. By discussing between each other, students should gather that, in the absence of a medium, as in a vacuum system, the conduction and convection cannot take place. The inquiry–lab activity on thermal radiation proceeded as following:

1. A scientific investigation on the energy exchange between a powered resistor and its surrounding environment during the heating and cooling processes was proposed.
2. Students were stimulated to design experimental activities aimed at testing previously formulated hypotheses.
3. Then, they were introduced to the laboratory equipment and invited to adapt their plans about conducting the experiments with the available measurement facility for the study of energy exchange by thermal radiation.
4. Finally, they carried out their own experiments by collecting, processing and analysing data, by focusing on new concepts and laws and constructing models supplying a meaningful conceptual understanding of the physics underlying the process of energy exchange by thermal radiation.

4. The lab activities

At the end of the first two steps previously described, all students agreed that in order to eliminate effects due to conduction and convection, the cooling experiments have to be conducted in a vacuum environment. Moreover it is necessary to measure the variation of the resistor temperature as well as that of the environment (for example a glass tube surrounding the resistor). Figure 1 shows the proposed equipment.

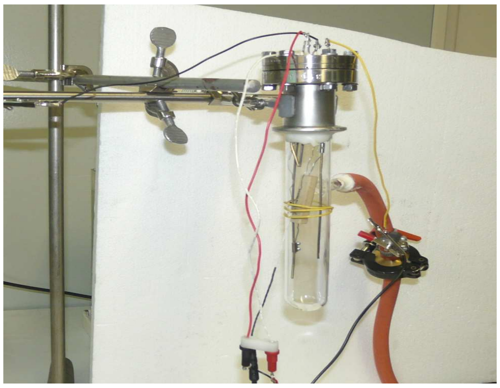
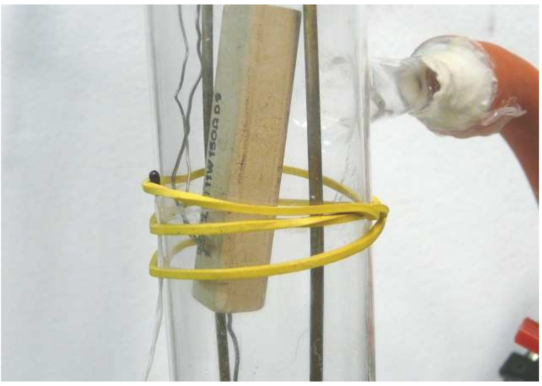

Figure 1. The vacuum tube containing the resistor and details of the ceramic-type resistor and the thermocouple.

The system is composed by a vacuum pump which is connected to the vacuum tube containing the resistor; the pump can lower the pressure inside the tube up to 0.1 mbar. The temperature of the resistor is measured by means of a thermocouple which is placed inside the vacuum tube and whose tip is in contact with the resistor surface. The thermocouple is externally connected to an amplifier module and interfaced to the lab computer. The resistor is a ceramic-type with the following physical characteristics: 11 W, 150 Ω. The temperature of the external surface of the

vacuum tube is measured by using a surface temperature sensor connected to a Vernier LabQuest computer interface. A power management system drives the electric current into the resistor.
The first experiment was carried out by the measuring the temperature of the resistor during the heating and cooling process. Figure 2 shows two typical results: the first one involving a modest variation of the environment temperature, the second one showing a relevant heating of the environment temperature.

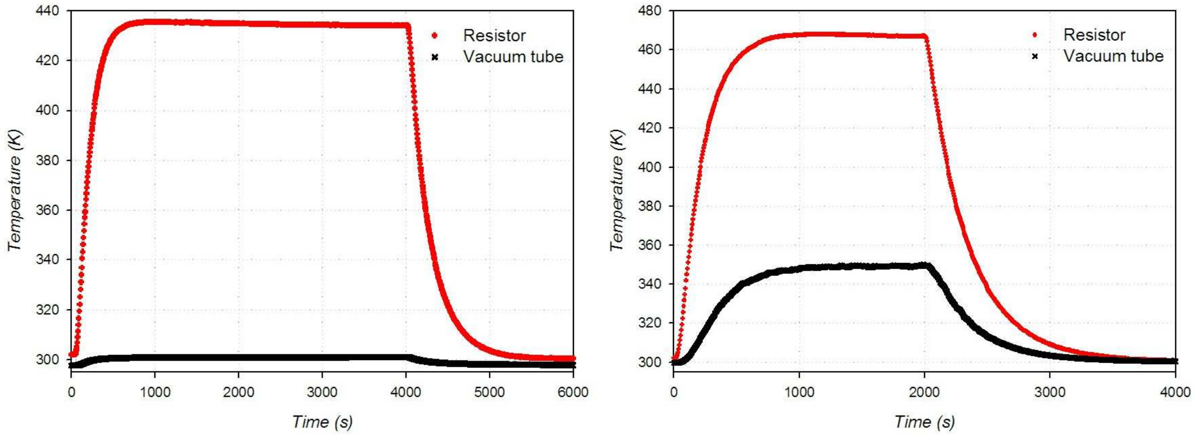

Figure 2. Heating and cooling curves of resistor and glass vacuum tube: on the left the temperature of the tube is almost constant; on the right the glass tube temperature increases and then decreases as the resistor temperature increases/decreases.

Students decided to investigate the cooling process following the saturation regime, just after the power supply has been switched off. They discussed about the collected data and tried to compare their experimental findings with the theory of thermal emission of radiation expressed by the Stefan law.

$$C\frac{dT}{dt} = -\varepsilon\sigma S\left(T^4 - T_b^4\right)$$

where T is the temperature of the emitting object, C the heat capacity, ε the emissivity, σ the Stefan constant, S the object surface and T_b the temperature of the surrounding ambient. Both the heat capacity and the emissivity are assumed to be equal to the constantLearning
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values C=1.5 J/K and ε= 0.9, respectively.
Students realised that, in order to perform such comparison, it was necessary to integrate the Stefan law or to approximate it (as reported in their textbooks) to an exponential law:

$$\mathrm{T}_b(t) = \left(T_{b0} - T_{\mathrm{inf}}\right)e^{-\frac{t}{b}} + T_{\mathrm{inf}} \qquad \text{(exponential decreasing)}$$

where T_{b0} is the maximum value of ambient temperature, T_{inf} is the equilibrium temperature and b is the time constant.
They tried to change these parameters in order to match the theory with the experimental data, and found that in the case of Fig. 3a a satisfactory agreement is not obtained for the exponential approximation, but the agreement is acceptable in the case of numerical integration of Stefan law. For the case of Fig. 3b students tried to identify the mean temperature of the glass tube as environment temperature during the cooling, but in both case the agreement is not satisfactory. They deduced that the problem needed further investigations. By analysing their thinking-aloud reasoning we verified that the experiment made students aware that the interpretation of experimental finding needs to put in action a lot of approximations, in particular the need to understand the importance of the boundary conditions. A group of students analysing the cooling of the glass tube and hypothesizing that in this case the effect of conduction/convection can be the most relevant factor tried to fit data by imposing also an exponential decreasing of the glass tube temperature by obtaining the curve 3) (see Fig. 3b) that fits well experimental data.

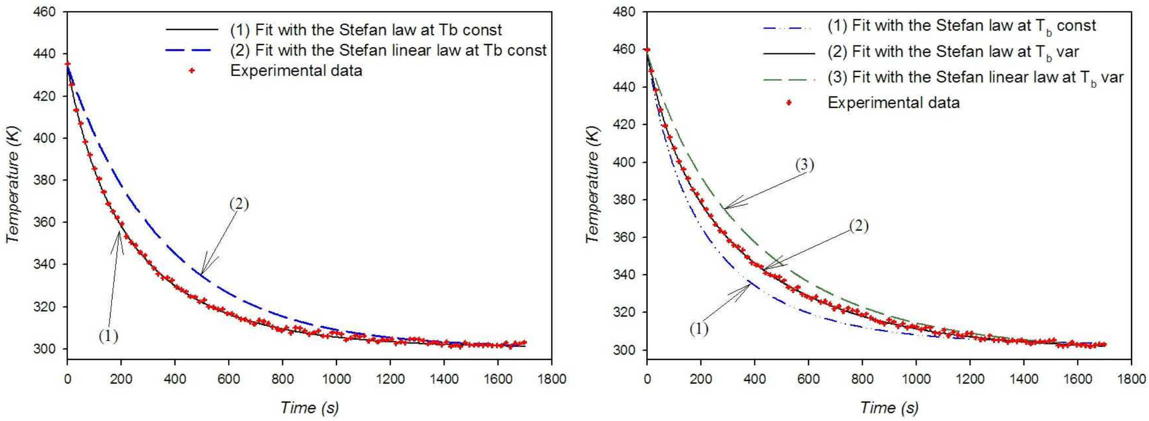

Figure 3. Fitting of cooling experimental data: on the left (the case of constant temperature environment), data are well fitted with the Stefan's law (curve (1)) and not with its linear approximation; on the right (the case with a decreasing temperature environment) curves (1) and (3) do not fit well experimental data that are well fitted with the Stefan's law when the environment temperature is supposed exponentially decreasing, curve (2).

5. Discussion and conclusions

In this paper we present a teaching/learning path based on a set of inquiry-laboratory activities aimed at driving students to the understanding of the physics underlying the process of thermal radiation. Students are, initially, engaged by questions regarding their everyday experience that lend themselves to scientific investigations and they are stimulated to design their own experiments. Such experiments are discussed in the classroom and adapted to the equipments at disposal. Students collect, process and analyse the data of a previously heated resistor, cooling in a vacuum system. The experimental findings are compared with the available theories and students discuss about the results of the comparison. The question is: "Do our experimental data meet the theory?". If the answer is "yes", everything is fine. If the answer is "no" (as usual) students should check their experiment and think about physical phenomena that can affect the data. Then, they can turn back to the theory, possibly modifying the previous one, and conduct a new comparison. In this way, students are involved into a real scientific research that can bring up to results unexpected even for the teachers, such as the importance of the temperature of the surrounding environment into the study of the energy exchange by thermal radiation. If the agreement between theory and collected data is still not completely satisfying, as the most usual case, students could argue that maybe they used a not perfectly correct value of heat capacity and/or emissivity in the numerical solution of the Stefan law and perform further investigations on how the accordance between data and theory can be improved by changing these parameters.

The results from the W described in this paper seem quite promising. Students showed to gain extensive experience in design of experiments by taking responsibility to define objectives, select appropriate methods to measure their variables, and analysing data.

The experimentation of a simplified version of this inquiry-lab learning path on high school students is under implementation and the results will be the subject of a forthcoming paper.

References

Duschl, R. A., Heidi A. Schweingruber, H. A. & Shouse, A. W. (2007) (Eds.), *Taking Science to School*: Washington, D. C: National Academies Press

Hatzikraniotis E, Kallery M, Molohidis A and D Psillos D (2010) Students' design of experiments: an inquiry module on the conduction of heat. *Phys. Educ*. 45 335-344.

Minstrell J and van Zee E (ed) (2000) *Inquiring intoInquiry Learning and Teaching in Science* (Washington, DC: American Association for the Advancement of Science)

NAS, (2011) *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, The National Academies Press at http://www.nap.edu/catalog.php?record_id=13165

Singer, S.R., M.L. Hilton, and H.A. Schweingruber, eds.(2005) *America's lab report: Investigations in high school science.* Washington, DC: The Nat. Acad. Press.http:// www.nap.edu/books/0309096715/html.

Windschitl M and Thompson J (2006) Trancending simple forms of school science investigation: the impact of preservice instruction on teachers' understandings of model-based inquiry *Am. Educ. Res. J.* 43 783–835

Winncy Y. Du, Burford J. Furman, Nikos J. Mourtos (2005) On the ability to design engineering experiments.*8th UICEE Annual Conference on Engineering Education, Kingston, Jamaica, 7-11 February 2005*