Open Inquiry Investigations on Heat Transfer Performed by Undergraduate Engineering Students

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Abstract

Many researches have shown the pedagogical effectiveness of structured inquiry as a high performance tool in science education of undergraduate engineering students. In this paper we report the preliminary results of an extended investigation on the efficacy of the application of an open inquiry approach to the consolidation of the physics concepts regarding the topic of thermal energy transfer. We selected a sample of undergraduate mechanical engineering students, who passed the examination of the basic physics courses with good marks. Firstly, we investigated about resistant misconceptions in thermal physics by administrating a pre-activity questionnaire. Even the best marked students showed several deficiencies for what concerns, in particular, the practical knowledge of the physics of energy exchange by thermal radiation. Our open inquiry activity involved the students in a highly challenging learning environment, starting from the problem of projecting a thermodynamically efficient space base on Mars. Students were asked to work in groups and to perform scientific investigations regarding the best materials to use in the construction and the best design strategies to practice in order to collect as much thermal energy as possible during the Martian day. Students were stimulated to design and carry out their own laboratory activity by collecting, processing and analysing data, in order to discover new concepts and obtain more meaningful conceptual understanding of the physics underlying the process of thermal energy exchange by conduction, convection and radiation. All groups of students were invited to share the results of their explorative works within each other during the final discussion. Lastly, a final post-activity evaluation test was administered. Our open inquiry learning path has proved to be a great opportunity of enhancing the practical and reasoning skills of our engineering students. Here we discuss in detail the advantages and limits of the open inquiry-based teaching approach.

Keywords: engineering education, open inquiry learning, nature of science

Introduction

The emergence of an international network of social and economic systems and technology-related processes is rapidly changing the requests of the professional qualities of engineers, who are often asked to practice within interdisciplinary contexts and demonstrate flexibility, creativity, particularly in the design process, dynamism and innovation (National Academy of Engineering, 2012). Graduate engineers should be able to demonstrate both specialist-discipline knowledge, ability to solve practical engineering problems, and design skills based on innovative thinking (Nguyen, 1998; National Academy of Engineering, 2004, 2010). An effective and efficient engineering instruction, should be able to train students towards a deeper understanding of fundamental concepts and, at the same time, develop and strengthen their reasoning skills and transversal abilities, enabling graduates to immediately engage in engineering practice (see Borrego & Bernhard (2011) and references therein).

In the context of K-12 science education, many reports propose a new vision of scientific instruction, suggesting to switch from a passive lecture-style teaching to a more active and student-centred teaching strategy (American Association for the Advancement of Science, 1993; National Research Council, 1996, 2000; Rocard et al., 2007). Very recent updates of the American standards of scientific education strongly encourage the engagement in the practices of engineering design, which is considered equally important in the process of learning science as the engagement in the practice of science (National Academy of Engineering and National Research Council, 2009; National Research Council, 2012).

In this context, Inquiry Based (IB) science education represents the natural framework to develop opportunities of learning science concepts in terms of an active construction of meaningful knowledge and stimulate high levels of critical thinking skills (Llewellyn, 2002). In inquiry based learning, students are engaged in identifying relevant questions, searching information, collecting data and evidences, both in laboratory and real life environments, building descriptions and explanation models, communicating and sharing their findings. Depending on the amount of the information and support provided by the teachers, students may be involved in four levels of inquiry: Confirmation, Structured, Guided, and Open Inquiry (Schwab, 1964; Herron, 1971; Banchi & Bell 2008). In Confirmation Inquiry students are introduced to basic laboratory activities, such as collecting data, with the teacher providing both the question and procedure, and being the results known in advance. In Structured Inquiry the question and procedure are still provided by the teacher, but students generate their own explanations on the basis of their investigation results. In guided inquiry the teacher provides students only with the research question, and students design the procedure to test their working hypothesis. In Open Inquiry (OI) the teacher creates a context by presenting a multidisciplinary view of a theoretical or real-life phenomenon, after which the students start defining relevant questions, design and carry out their own investigations, communicate and share their results. In OI based instruction students have the purest opportunities to act like real scientists, reinforcing their reasoning skills and becoming aware of the process of scientific inquiry and of the nature of science (Schwartz, Lederman, Crawford, 2004; Flick & Lederman, 2006; Lindsey, Hsu, Sadaghiani, Taylor, and Cummings, 2012; Capps & Crawford, 2012).

While IB teaching strategies of science in K-12 grades of instruction are increasingly developing (e.g., Mooney & Laubach, 2002; Crawford, 2007; Minner, Levy & Century, 2010; Pyatt & Sims, 2012), at university level physics education is still mostly based on courses which are aimed firstly at introducing theoretical concepts and, only as a second, at developing practical skills through laboratory activities, which have often a pure demonstrative purpose and do not train the students to effectively inquiry the observed phenomenon. This approach is hardly successful, because, as it is well known, any mental construction, i.e. any mental model (Greca & Moreira, 2000), is deeply rooted on experience and students rarely fully understand a theory, even if currently accepted, if it is left far from a direct experimentation.

In this paper we address the problem of providing advanced engineering undergraduate students with a learning environment able to stimulate an effective understanding of the physics concepts underlying the complex world of thermal phenomena. Thermal science has always been considered a particularly tough discipline, because of the difficulties faced by the students at any level of education to overcome persistent misconceptions due to the common-sense experience of events governed by the intrinsic properties of matter (Streveler, Olds, Miller, & Nelson, 2003). Very recently, two studies confirmed the presence of robust misconceptions in undergraduate engineering students, even after having attended a semester or more of traditional instruction on thermal science (Streveler et al. 2011; Prince et al. 2012). Moreover, a recent study has shown the pedagogical effectiveness of guided inquiry-based activities, concerning the topic of thermal energy transfer, in courses for chemical engineering undergraduates, who achieved higher overall scores on the post-activity assessment of understanding critical concepts (Nottis, Prince, & Vigeant, 2010). While teaching strategies based on structured inquiry have shown their efficacy mostly when the target of instruction is the students' mastering of contents, guided inquiry appears to be the most appropriate approach for developing an effective understanding of critical concepts and a deeper awareness of the nature of science (e.g., Tabak et al., 1995). Concerning the OI approach, it has been shown that it can sometimes produce negative motivational effects, such as the frustration due to achieving undesirable results, that could affect the successful completion of the learning process (Trautmann, MaKinster, & Avery, 2004; Quintana, Zhang, & Krajcik, 2005). Other studies, on the contrary, assert that only the adoption of an OI approach makes possible the achievement of higher levels of critical thinking skills and a deeper understanding of the nature of science (Yen & Huang, 2001; Krystyniak & Heikkinen, 2007). Open inquiry is considered a dynamic learning process in which a continuous and renewed thinking involves flexibility, judgment, and contemplation, as part of the changes that occur in the course of inquiry (Zion et al. 2004). Moreover, the dynamic characteristics of an open inquiry process emphasize the perspectives of thinking about the process and affective aspects, such as curiosity, which are expressed in situations involving changes and uncertainty.

In this paper we present some preliminary results of an extended investigation regarding the study of the efficacy of an OI based learning method for a group of advanced engineering undergraduates, who persist to show conceptual problems and experience difficulties on applying the studied theories to solve practical everyday problems. To the best of our knowledge, an OI approach has never been adopted in advanced engineering education of undergraduates in the study of thermal phenomena. At the Mechanical Engineering Faculty of the University of Palermo (Italy) we have activated a pilot project, in which undergraduate students are involved in a high challenging research-like work on the topic of thermal energy transfer, oriented towards the practical application of the physics concepts which students should have learned in their previous traditional courses. The general objective of the project is to investigate the efficacy of an OI based learning environment for a sample of students, having college-level physics knowledge background, but still showing conceptual difficulties, in order to (a) correct resistant misconceptions, and (b) help them to overcome the difficulties that they experience in applying their theoretical background of knowledge to face practical everyday problems in thermal science. Finally, we also investigate on the opportunity for an OI based instruction to strengthen the reasoning skills of undergraduate engineering students and their abilities to carry out a scientific experiment.

Method

This study was carried out by selecting and motivating a sample of students to carry out independent OI-based research-like activities, within a framework provided by expert educators in the context of an effective learning of thermal science in engineering advanced students. In this paper, pre-instruction data, recorded by means of a questionnaire dedicated to investigate students' conceptual difficulties, are compared with post-instruction outcomes. Moreover, results are also drawn from the analysis of the students' logbooks of experiments, final scientific reports and oral presentations. The lab sections were also entirely video-recorded, but the results obtained from the video analysis will be presented and discussed in a subsequent paper.

Sample Selection

Our sample includes thirty undergraduate mechanical engineering students, being at the second or third year of their curriculum program. They have attended the first-year introductory physics courses and already passed the related examinations with marks greater or equal than 24/30. In particular, a first-year university background of knowledge includes a specific theoretical introduction to the concepts of thermal science and a more technical instruction on applied thermodynamics. All students were invited to join the project on a voluntary base after a brief presentation made by the authors at the Faculty Council for Engineering, where the general objective of the project was illustrated. Students involved in this study have never had specific instruction about the process of scientific inquiry and never participated to other OI-based learning programs.

During all the stages of the project, the students' learning activities were supported by two educators (N. P. and D. P. A.) having more than ten years of expertise in the field of scientific research and on teaching physics at both high-school and university level courses.

Activity Description: Mission to Mars!

Our OI activity involved the students in a highly challenging learning environment, starting from the problem of designing a thermodynamically efficient space base on Mars. The project was developed across four main phases described in the following.

Phase 1: Presentation (description and motivation) of the project. The students were invited to take part to an experimental project aimed at searching for design schemes and best materials to use for the construction of such a Martian base; more specifically, they were requested to point out the best design strategies to put in practice for collecting as much thermal energy as possible during the Martian day, and avoiding heat dispersions during the cold night. Students were supposed to work in groups and to perform scientific investigations devoted to the design, realization and testing of smart devices, having physical characteristics able to maximize the capture and storage of thermal energy from the Sun and high insulating efficiency. All groups of students were invited to carry out their own experimental work, by taking into account the physics underlying the process of thermal energy exchange by conduction, convection and radiation. Educators provided a brief description of the context in which students' work would have been developed and the motivation for an active participation.

At this stage, all students participating the project answered to a pre-instruction questionnaire containing fifteen open-answer questions, concerning everyday experiences on thermal energy exchange. The questionnaire was developed and content-validated (Jensen, 2003) by the authors in collaboration with twelve faculty professors having long experience on teaching physics at engineering, by following the standards for education and psychological testing (American Educational Research Association, American Psychological Association, & National Council on Measurements in Education, 1999). Moreover, the questionnaire was developed through a six-month long activity of interviews to first-year university students involving their common difficulties experienced in learning thermal science concepts. The main topics covered by the questionnaire concern the following physics concepts: absorption of visible radiation, emission of thermal radiation, heat, specific heat and heat capacity, transfer of energy by thermal conduction and convection. The questions report practical experiments or real-life problematic situations in which a thermal phenomenon is described and the students are asked to give their personal explanation, providing a convincing motivation grounded on the studied physics theories. As an example, we report here two selected questions:

#4. Two equal plastic bottles, the first one filled with water the second with sand, having almost the same weight, are exposed to the sunlight in the same way and for the same time interval (15 minutes); which of the two bottles reaches the higher temperature? Explain your answer.

#6. Two ice cubes are extracted from the freezer and placed on top of two plates, both left at room temperature and made of the same material (aluminum). The plates have the same surface area but one has double thickness with respect to the other. In which plate the ice melt faster? Explain your answer.

Phase 2: The planning. All student groups were asked to plan in advance a set of experiments to be carried out during four lab sections. They were preliminarily invited to explore the laboratory in order to verify the available materials and measurement facilities and, successively, to begin the design of their own experiences. The educators asked the students to plan in detail their experiments and to write the planning of all their experimental activities into a document, for subsequent analysis. At this stage, students were strongly encouraged to feel themselves free to explore, even leaving the laboratory to move outside, if needed, or to bring inside home-made resources.

Students were informed about the opportunity to use all campus libraries and internet resources to gather literature. The educators suggested a preliminary search for information, but always left the students free to plan the experiments by following their own procedure.

Phase 3: Execution of experiments. Students were stimulated to carry out their own experimental work in the most independent way they were feeling confident to do. On average, students spent about thirty hours to complete four cycles of laboratory activity, by collecting, processing and analyzing data. Students used logbooks to note the followed procedure, the difficulties encountered throughout the activity and the changes they made during the inquiry process. They acquired the data by means of a system of sensors connected to computer interfaces. In Figure 1 we show a collage of photos taken during the development of this phase of the project.

Phase 4: Outcomes and conclusive reports. Each group of students shared the results of their scientific investigations with all the other participants during the development of the project activities. A final report and an oral communication describing their most significant experimental results were presented by each group. At the end of all activities, the same pre-instruction questionnaire was re-administered.

Results

The analysis of student learning involved two main aspects: the first one related to their understanding of physical concepts, the second one related to their awareness of the scientific procedure concerning the different steps of their inquiry approach to the posed problem. The results reported in this paper are mainly based on the analysis of the students' answers to the questionnaire[1].

Before the beginning of the project, students were not informed about the duty to answer to the same questionnaire prior to and after instruction, so they answered to the test, during the first introductory meeting, by considering the questionnaire only an instrument for educators to assess their initial competences. After that, they planned the experiments they believed more significant by following only the aim of the research project and executed their activities not considering the opportunity to test in laboratory some problematic situations presented in the questionnaire. At the conclusion of all activities, they were invited to review their pre-instruction questionnaire with the chance to change the answers given at the beginning. The OI learning activities carried out by our students were not directly related to the experimental contexts proposed in the questionnaire. As a consequence, the questionnaire has been used to evaluate the effectiveness of an OI based learning method to help the students to overcome conceptual difficulties and improve their critical reasoning skills. In the following, two research questions are addressed with both quantitative and qualitative research methods.

Research Question 1:

Which cognitive constrains and conceptual difficulties affect the understanding of thermal phenomena in undergraduate engineering students facing practical problematic situations which require an effective application of their background of theoretical knowledge on thermal science?

Students' answers to the pre-instruction questionnaire were independently analyzed by the researchers, authors of this paper. A common finding was the evidence that, even after a semester of university level physics instruction, a significant fraction of students still show several problems in the understanding of basic concepts of thermal science, such as temperature, heat, thermal energy, thermal conduction, convection and radiation heat transfer. A comparative study has been performed by the researchers in order to achieve a global consensus on the classification of students' answers with respect to the conceptual problems detected. The inter-rater reliability was very high, reaching a value of about 96 %, since only in few cases different interpretations to a student response were proposed, while many other students' answers were similarly interpreted and classified. As a result, all students' problematic answers were accurately studied and grouped within eight clusters of main learning problems, which are listed in Table 1. Some of these problems are related to well known misconceptions, such as confusing heat with temperature or consider heat as an intrinsic storable quantity, while some others appear to be a sort of forgetfulness on taking into account important mechanisms of energy transport, such as convection or thermal radiation.

The percentage of students who completed the questionnaire by giving at least one of the problematic answers included in the clusters of Table 1, during the pre and post-activity administration, are compared in Figure 2. Engineering undergraduates, having received a traditional, transmissive and mostly theoretical instruction, continue to experience severe difficulties to manage everyday phenomena concerning the topic of thermal energy exchange. When facing the pre-instruction questionnaire, some students started by opening the handbook of engineer, trying to catch the right formula to be used in answering the questions. However, differently from usual engineering examinations, the questionnaire was developed with the specific aim to investigate the students' abilities to face and solve practical problems that could be encountered

1 A paper reporting the complete analysis (qualitative and quantitative) of all collected data is in preparation.

in real world contexts and students showed significant difficulties both to identify the dominant transport mechanism of thermal energy and/or the relevant physical quantity involved in the process.

The analysis of pre-instruction questionnaire answers shows four clusters with a percentage of students greater than 50 %, namely C1, C2, C3 and C8, with cluster C1 even reaching 72 % and cluster C3 83 %. While the problem associated to cluster C1 is a typical residual misconception of younger learners at lower grades of instruction, the problems of clusters C2 and C3 are symptomatic of students' difficulties to identify the dominant mechanism of energy transport (C2) or key physical quantity involved in the process (C3). Even cluster C7, with a percentage of 60 % of students, represents a problem of considering all the relevant heat transfer mechanisms. The problem of "forgetting" to mention convection or thermal radiation does not occur for thermal conduction, probably because this latter transport mechanism is better "known" by the students, though the other two are equally experienced by the students in their everyday lives, but without a real awareness. Thermal conduction needs a medium to transport the energy and students seeing the medium can easily imagine something (heat) that is traveling across it. Convection needs a medium too, but students have more difficulties to figure out the motion of the particles when the fluid is invisible, such as air. In this view, thermal radiation, being able to travel in the vacuum, is the transport mechanism most easily forgotten, even if students are, of course, aware of the heating by solar radiation. Our pre-instruction results confirm the inefficacy of a traditional lecture based courses of physics instruction even in advanced engineering education.

Research Question 2:

Is the open inquiry approach, adopted in a learning environment dedicated to the carrying out of scientific research-like activities, useful to help engineering students to overcome the difficulties that they experience in applying their theoretical background of knowledge to solve practical everyday problems in thermal science?

Questionnaire results collected at the end of the open inquiry project activities show a clear reduction in the percentage of students giving problematic answers (see Figure 2). In particular, the number of students answering within clusters C1, C2, C3 and C5 has decreased up to almost halve the corresponding percentage. The most significant improvement is observed in cluster C4, while the most resistant problem regards the underestimation of the effects due to the radiation heat transfer (cluster C7). By averaging over the all cluster data we find a global reduction of problematic answers of about 55 %, which corresponds to a significant improvement of students' effective understanding of the basic concepts of thermal physics.

Before this project, the majority of our students ignored the significance of carrying out activities in the context of a scientific research. Many of them experienced the science laboratory at the high school through some demonstrative activities performed by their teachers, but they have never been actively involved in a physics laboratory at university before. For more than a semester, these students have been instructed by following a traditional teaching approach and trained to solve specific problems on thermal physics, even more complicated than those proposed in our questionnaire. However, this teaching strategy has proved to be ineffective to prepare future engineers to face unexpected problematic situations, because students were trained only to mechanically apply some mathematical formula within a standard procedure to the problem resolution, without any reasoning effort in searching for the procedure itself.

Within this pilot project, students, for the first time in their academic studies, were left free to explore the world and find a solution by themselves to the proposed research problems.

Preliminary results, obtained by the qualitative analysis of the documents developed by the students during the OI project and partly by the detailed study of the videos, allow us to make some inferences about students' understanding of the procedures involved in the scientific inquiry. They learned how to conduct a scientific investigation, starting from an initial collection of information (literature) on the topic, and moving across a planning phase of activities, the design and realization of measurements, the gathering and analyzing of the data, the formulation of hypothesis and modeling, drawing conclusions. The choice made by the educators to drive the students' OI of thermal phenomena within the context of a space science challenge (Mission to Mars!) strongly motivated the students. They participated to the activities with excitement, being convinced of the importance of actively participate to a real research experience. This strong motivation avoided any negative psychological effect that could be observed in low-motivated open inquiry environments, such as frustration caused by mistakes or unexpected results, lack of curiosity or distractions.

The analysis of students' logbooks makes evident that students gained awareness of the importance of (a) the documentation, not only at the beginning but extended throughout the entire process, (b) the need of maintaining constant conditions during an experiment, (c) of observation reliability, (d) repetitions of measurements, using statistics, (e) taking the boundary conditions under control, and (f) interacting and sharing the results of their work with the other people involved in the same research.

Summary and Conclusions

An OI learning environment has been activated at the Faculty of Engineering of University of Palermo, Italy. Selected students, having attended college-level physics courses with traditional teaching approaches and being assessed with high grades in related examinations, participated to a pilot project on the application of an OI-based strategy to strengthen their practical and reasoning abilities and allow a more effective learning of the thermal physics concepts. Students spent a total amount of sixty hours to plan and realize a complete scientific research, concerning the experimentation of ideas, the design and practical realizations of smart devices, aimed at being useful in a hypothetical project about the construction of a thermodynamically efficient space base on Mars. Undergraduate mechanical engineering students were stimulated to design and carry out their own laboratory activity, with the aim of obtaining a more meaningful conceptual understanding of the physics underlying the process of thermal energy exchange by conduction, convection and radiation.

Even if already instructed by traditional courses on thermal science, the presence of residual misconceptions on basic concepts and several difficulties to face practical everyday problematic situation, in which a dynamic thinking is necessary to find a solution, were observed on a significant fraction of the students answering to a pre-instruction questionnaire. During the project activities, students faced some unexpected results from their experiments, but, being strongly motivated by the importance of conducting an experiment by themselves and within the attractive context of space science, they never experienced negative psychological feelings. They learned that unexpected results or failures are also results, because they help to rule out incorrect hypotheses and stimulate to think how to take into account real-world effects in the theory. At the end of all activities, the students answered to the questionnaire in a different way, by firstly inquiring on the described phenomenon and reasoning about the dominant transport mechanism and the most relevant physical quantity involved in the process. They achieved a global improvement of their conceptual knowledge and practical and reasoning skills, in terms of a 55 % reduction of problematic answers to the post-instruction questionnaire. We believe that teaching and learning strategies, within an open inquiry based learning environment, developed across experiences more extended in time, should bring about to even better results. An important component in implementing open inquiry is the teachers' ability to motivate their students to ask those questions that will guide them through their inquiry (Chin, & Chia, 2004). In this respect, a critical point is represented by the need of a good teacher training path.

Traditional methods of teaching science, mainly based on transmission of information and laws, bring about a not lasting and effective learning. Theoretical descriptions of the scientific method procedures oversimplified scientific activity and fails to engage learners in a deep understanding of contents. Research like activities, within an OI-based learning environment, should be included in standard curricula of engineering education for undergraduates, as a valid integration to traditional teaching. In this way, it could be possible to achieve a more useful and effective meaningful knowledge on difficult physics concepts, promoting the strengthening of the reasoning skills of future engineers and their vision of the nature of science.

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Table 1. List of main problems within which students' problematic answers were clustered.

Label	**Detected problem on physics concepts**
C1	Heat considered as a storable quantity
C2	Thermal conduction instead of thermal radiation
C3	Thermal conduction and insulation instead of specific heat or heat capacity
C4	Thermal radiation instead of specific heat
C5	Bigger object means greater heat capacity or resistance to change in temperature
C6	Temperature instead of heat
C7	"Forgetting" to mention thermal radiation
C8	"Forgetting" to mention convection

Figure 1. Collage of pictures taken during the work of the students involved in the OI-based learning environment dedicated to the pilot project “Mission to Mars”.

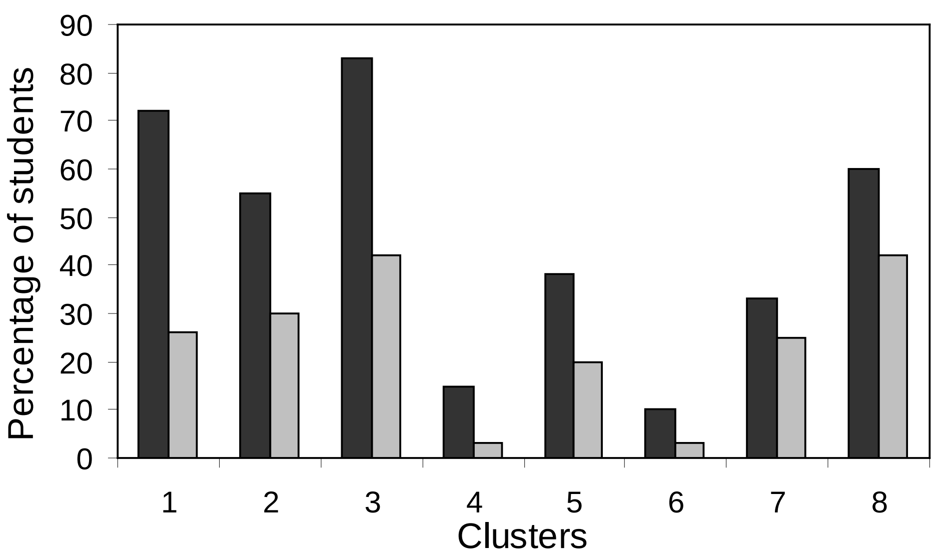

Figure 2. Percentage of students who answered the questionnaire by providing at least one of the problematic answers defining the clusters of problems listed in Table 1. Black and grey columns indicate pre-instruction and post-instruction data, respectively.