Upper secondary school students' understanding of adiabatic compression

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ABSTRACT

The present study refers to second year (16-17 years old) upper secondary school students' conceptions on elementary thermodynamics and especially the First Law of Thermodynamics (FLT). This paper focuses on students' explanations of a real situation representing an adiabatic compression and their forms of reasoning in providing explanations. We used descriptive statistics and hierarchical cluster analysis in order to process students' answers. The main results were that (a) the vast majority of the responses consisted of alternative frameworks, namely FLT is highly disregarded among the students, (b) the students provided confused explanations that entangle diverse physics models and/or referred to the phenomenology of the situation and (c) linear causal reasoning was the prevailing way for providing explanations, although it was inadequate for this physics level.

KEYWORDS

Secondary school, elementary thermodynamics, first law of thermodynamics, adiabatic compression, alternative conceptions, linear causal reasoning

RÉSUMÉ

La présente étude se réfère aux conceptions des élèves de 16-17 ans sur la thermodynamique élémentaire et surtout sur la première loi de la thermodynamique. L'étude met l'accent sur les formes de raisonnement qu'ils utilisent quand ils sont *invités à expliquer une situation réelle concernant le phénomène de la compression adiabatique. Les réponses des élèves ont été analysées en utilisant la statistique descriptive et la statistique basée sur le regroupement hiérarchique. Ces analyses ont conduit aux conclusions suivantes: (a) la grande majorité des élèves ont exprimé des conceptions alternatives au cadre conceptuelle de la thermodynamique et, surtout, la première loi a été fortement négligée parmi eux, (b) les élèves ont proposé des explications confuses se référant à la phénoménologie de la situation et/ou à différents modèles de la physique et (c) le raisonnement linéaire causal a été identifié comme leur raisonnement préféré mais insuffisant pour ce niveau de la physique.*

MOTS-CLÉS

Lycée, thermodynamique élémentaire, première loi de la thermodynamique, compression adiabatique, conceptions alternatives, raisonnement linéaire causal

INTRODUCTION

Thermodynamics is a significant part of physics, as it suggests a generic theory of energy that explains the differentiation between various forms of energy and specifies the conditions and the limits of physical phenomena and technical processes (Baehr, 1973). Therefore, it is customarily included in the secondary school curriculum and in several university courses in a variety of faculties such as physics, engineering and chemistry.

For both secondary and tertiary physics education, the First Law of Thermodynamics (FLT) is one of the most substantial concepts of thermodynamics. In a few words, FLT represents the conservation of energy for thermodynamic systems and describes the qualitative and quantitative conversions between heat, work and change of the system's internal energy (Baehr, 1973). A *system* is defined as "a quantity of matter or a region in space chosen for the study" and its *boundary* is "the real or imaginary surface that separates the system from its surroundings" (Çengel & Boles, 2011, p. 10). For the study of the FLT in particular, we focus on a *closed system*, which "consists of a fixed amount of mass and no mass can cross its boundary" (Çengel & Boles, 2011, p. 11), but it allows the transfer of energy between itself and its surroundings. Heat and/or work can be transferred into or out of the system, in contrast to the internal energy stored in the system, which does not cross the boundaries unless it is transformed to heat and/or work (Çengel & Boles, 2011).

One application of the FLT is the adiabatic process of an ideal gas, namely the compression or expansion of a gas subjected to the Ideal Gas Law (IGL) that is trapped in a heat-insulating vessel. The IGL, which is also known as the *equation of state*, involves the thermodynamic coordinates (state variables) of the pressure, the temperature, the volume and the amount of the substance we study. However, the IGL cannot be adequately used to qualitatively interpret the behavior of the gas, because during an adiabatic process none of the implicated variables remains constant, except the amount of the gas.

University students' understanding of the concepts of physics thermodynamics has been under investigation for several years (Rozier & Viennot, 1991; Loverude, Kautz & Heron, 2002; Meltzer, 2004; Kautz, Heron, Loverude & McDermott, 2005; Kautz, Heron, Shaffer & McDermott, 2005; Leinonen, Raesaenen, Asikainen & Hirvonen, 2009; Leinonen, Asikainen & Hirvonen, 2012). The pertinent research indicates that students present numerous alternative explanations in order to describe phenomena and process related to the FLT. The adiabatic compression, especially, has proven a valuable tool for investigating students' conceptions on FLT.

In this ground, limited research has been conducted during the last two decades in secondary education level. Because of the elementary level of thermodynamics in school, preceding studies focused on fundamental issues, such as students' understanding of basic concepts like temperature and heat (Johnstone, MacDonald, & Webb, 1977; Erickson, 1979; Kesidou & Duit, 1993; Arnold & Millar, 1994). The aim of the present study is to expand the field of concern regarding upper secondary school thermodynamics. These courses ordinarily integrate complex concepts and laws that are very close to those taught in introductory physics courses in university. Therefore, it is in our intention to investigate upper high school students' reasoning and the frameworks they create regarding FLT.

THEORETICAL FRAMEWORK

Students' causalities and reasoning

When students are presented with a physical situation that calls for an explanation, the spotlight is on their types of interpretation, namely the learners' theory and associated models (Tiberghien, 1994). Tiberghien (1994, p. 76) suggests that the learners' explanative system depends on causality, which is an important aspect of the theory they construct. Aristotelian causalities are a sufficient frame of reference in order to identify the causality involved in students' explanations. In fact, Aristotelian causalities can be considered as invariants, that is to say they remain constant with different students at the same age or level of instruction as well as with a same student for a set of situations. These invariants are common for students at the beginning of middle school and after five years of university (Tiberghien, 1994, p. 77).

According to Kuhn (1971), the Aristotelian causalities are (a) material, (b) efficient and (c) formal/final. *Material causality* is used when students provide explanations in regard to the properties of the involved materials. *Efficient causality* is involved when students notice a change that they attempt to interpret. The students use *formal/final* *causality* when they give justifications in terms of purpose, aim or end of the situation they try to explain. Particularly in the field of thermodynamics, we can use these causalities, especially efficient causality, as reference for both secondary school and university level students' explanations (Rozier & Viennot, 1991; Tiberghien, 1994).

The theory and the models constructed by the students are directly related to the specific situation they deal with, therefore they are vastly connected to the observed objects and facts. However, efficient causality can activate a theoretical construction that includes a variable, which is not directly noticeable in the original perception of the situation. This variable acts as a "mediator" between a cause and an effect and is probably the only element of students' modeling that is not associated with the subjective existence of objects and facts (Tiberghien, 1994; Tiberghien, Psillos, & Koumaras, 1995).

According to Walton (1990, p. 404), "*reasoning* can be defined generally as a sequence of steps from some points (premises) to other points (conclusions)". Linear causal reasoning is the most elementary form of relation that can be developed to link a cause to its effect. Linear causality, which is basically indistinguishable from the Aristotelian efficient causality (Tiberghien, 1994), is the main reasoning source for the justifications the learners have to offer (Tiberghien et al., 1995). Within this type of reasoning, a modification to the quality or quantity of the surroundings equals to a modification to the physical system we study. However, linear causal reasoning is usually inadequate because, more often than not, a single cause can trigger various effects or a single effect can be the result of several causes (Halbwachs, 1971; Koliopoulos, 2008).

Rozier & Viennot (1991) conducted a study with second year university students in a course of thermodynamics and they came to the conclusion that the participants used the variables of the given tasks in a simplifying way that led to the reduction of the number of variables; in other words, the students did not take into account all the necessary parameters. The researchers noted that the students:

a) neglected some variables at will,
b) used a preferential relation between two variables and/or
c) ignored the symmetry in implications.

These simplifications led students to creating numerous alternative explanations. Some vivid examples of type (a) simplification are presented by Leinonen et al., (2012). Their sample consisted of second year university students and about 25% of them neglected or misused some variables implicated in an adiabatic compression task. As for instance, a student claims that the increase of the pressure inside the system causes the temperature to rise, completely ignoring the role of the volume in the process.

Kautz, Heron, Loverude, et al. (2005) conducted a research with university level students and recognized several simplifications that fall into type (b). One of them is the reverse analogy between pressure and volume during an adiabatic process, as the students assumed that the temperature remained constant. Alternatively, some students argued that pressure and temperature were directly proportional, supposing that the volume would remain unchanged.

In regard to point (c), Rozier & Viennot (1991) mention that the students were familiar with the fact that temperature and volume of an ideal gas are proportional, but they would apply it only in an unidirectional way. In isobaric processes (constant pressure), the vast majority accepted that the increase of the temperature of an ideal gas resulted to the increase of its volume too, but 22% of the participants did not acknowledge that a volume increase would lead to the increase of its temperature.

Students' alternative frameworks

Students' physical theories and models are usually quite differentiated from the scientific ones and their inadequate linear causal reasoning lies in the core of their pre-scientific alternative frameworks. The present study focuses on the students' conceptions on the FLT; more specifically, we concentrate on the way students conceptualize the phenomena (Driver, 1989) involving the FTL, especially through tasks of adiabatic processes that help in bringing out their own explanations. As Driver (1989, p. 481) mentions, research provides "intriguing insights into a child's conceptual world –a world often reflecting a compelling reasonableness". However, investigations in specific domains, like thermodynamics, have brought to light some homogeneity in the models that students construct in order to interpret various physical situations (Driver, 1989). The pertinent research reveals a few distinct categorizations in university students' frameworks regarding the FLT.

Leinonen et al. (2012) review students' explanations in an adiabatic compression task. They claim that students' responses fall into 4 classes; however, these classes are not exclusive, since they often overlap. These categories and the approximate percentages of the respective answers are (a) a desirable approach based on the first law (7%), (b) microscopic models (28%), (c) ideal gas law (30%) and (d) something is ignored or misused (34%). The first class includes explanations related to the FLT, more specifically references to the concept of work and the different forms of energy. Microscopic models in students' reasoning suggest the second class; these models can be accurate for describing the phenomenon, but they can be very puzzling for the students' level. They mostly referred to the kinetic energy of the particles, but they made incorrect assumptions about the collisions between them. In the third category the students provided explanations related to the IGL. Answers within this fourth class included incorrect assumptions about the relations of the variables, that is to say one or more variables has been erroneously used or omitted.

Another research that came to similar conclusions was conducted by Leinonen et al. (2009), in order to analyze university students' pre-knowledge of thermal physics. The adiabatic compression task revealed that students are mostly focused on the IGL rather than the FLT, because in upper secondary school they had been more acquainted with the first than the latter. That also stands for microscopic models and, in fact, a combination of the equation of state and the micro-level was very appealing to the students. In their effort to utilize these to models, they referred to collisions between the particles to explain the increase of temperature. Finally, some participants faced difficulties in telling the difference between adiabatic and isothermal processes (constant temperature). This confusion can be partially resulting from university students' vague ideas about the concepts of temperature, heat and even internal energy, as has been well documented over the years (van Roon, van Sprang, & Verdonk, 1994; Loverude et al., 2002; Meltzer, 2004; Kautz, Heron, Loverude & McDermott, 2005; Barbera & Wieman, 2009).

Kautz, Heron, Loverude, et al. (2005) and Kautz, Heron, Shaffer, et al. (2005) in their two-part study on university students for the understanding of the IGL, confirm that they had trouble handling macroscopic variables such as the thermodynamic coordinates. This was due to the mix-up of the concepts, but also because the macroscopic level explanations seemed to be rooted in incomplete microscopic models. This research has added another finding: difficulties with mechanics limited students' ability to correctly interpret the phenomena, including an adiabatic process task. In a preceding work of the same researchers (Loverude et al., 2002), once again it has been noted that the FLT was severely disregarded or mistreated during the adiabatic processes, as IGL and microscopic models were more favored by the participants.

Research objectives

As demonstrated on the above paragraphs, the relevant literature focuses on the tertiary education students' reasoning and frameworks regarding FLT; the respective field of secondary education still remains largely unmapped. Not only we do not know what the immediate effects of our teaching are, but we also do not know what the long-term consequences are as soon as our students have to deal with thermodynamics at university level. As a matter of fact, some researchers suggest that we should carefully examine where the emphasis in secondary school is, in order to illuminate the reasons students provide inaccurate explanations of thermodynamics in university introductory courses (Leinonen et al., 2012, 2009).

More specifically, this study examines the following research questions:

a) What are the upper secondary school students' conceptions of an adiabatic compression?

b) What types of reasoning do they deploy in order to support their explanations?

METHODOLOGICAL FRAMEWORK

The sample

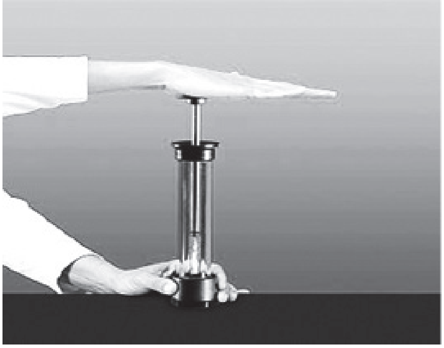
This study was conducted at a Greek upper high school in Kastritsi, which is a suburb of Patras city in Greece. The sample was consisting of 54 students (28 boys and 26 girls) in their second year of upper secondary school, namely around 16-17 years old. They were alphabetically separated in 3 classes of 15, 18 and 21 students, with no remarkable differences in their average school performance. All of them had already studied physics for 4 subsequent years as a compulsory lesson and, for the year in discussion, they took by choice 3 more hours of physics (and 2 hours of mathematics) in their weekly curriculum.

The procedure

This research was conducted during the elective physics course, because thermodynamics is a substantial part of its syllabus at all. By the time the present study took place, the students had already been taught the IGL, microscopic models and the FLT (including isothermal, isochoric, isobaric and adiabatic processes) in that order.

The school's regular physics teacher permitted one of the authors, who also is a physics educator, doing the didactical intervention in his classes. The researcher made some introductory comments to remind students what an adiabatic compression of an ideal gas is and then demonstrated a simple real situation of an approximate adiabatic compression (Figure 1): a glass tube was containing a small piece of inflammable cloth and it was sealed with a piston; after a rapid compression, the cloth was on fire. The students were given a paper with the definition of the adiabatic compression, an image of the real situation they had just observed and a request for them to explain *"why there was an ignition of cloth in the vessel"*. The papers were collected, as soon as the students filled their answers.

FIGURE 1



The demonstrated real situation of an approximate adiabatic compression

The analytic procedure

The authors analyzed the students' responses in the following order: the author who did not take part in the intervention extracted the classes of the explanations and devised a preliminary categorization of them. Following, the other authors conducted a second categorization that induced some differentiations to the original classes. The researches came to an agreement on the classes and revised their categorizations from scratch; after that, the consonance was around 81,5%. After further discussions, they settled on the final categorization.

The students' responses were recorded in binary variables with values of 0 (absence of response) or 1 (presence of response). The final data was transferred to SPSS Statistics (v. 21) in order to perform descriptive statistics and cluster analysis. Through cluster analysis, the students have been placed in groups regarding the consistency of their answers. For the classification we used the method of Hierarchical Cluster Analysis (Basics & Sambamoorthi, 1978). This method works hierarchically, in the sense that it begins by using every response as a group and, as it progresses, groups with similar responses cluster together. We used Jaccard coefficient as a similarity measure for asymmetric binary variables (Choi, Cha & Tappert, 2010) and, within groups, linkage as hierarchical clustering methods.

RESULTS

Students' explanations of adiabatic compression

In this section we attempt to answer our first research question. On one hand, we examine the emerging categories from students' explanations of the adiabatic compression they observed and we quote relevant examples. On the other hand, we investigate the patters that have been created due to these categories, depending on their exclusive or shared use, and also the clusters of students that result from their preference of interpretations.

Emerging categories

The major categories that emerged are six; two of them are separated to subcategories of Correct/Complete and Incorrect/Incomplete (Table 1). In Table 1 we record the frequencies for each category and subcategory. One should note that the majority of the students' explanations did not fall into merely one category, that is the reason the sum of the responses is way more than the number of our sample. In the following paragraph we describe the particularities of each category with respective examples.

TABLE 1

Categories of students' explanations and respective frequencies (n=54)

Categories	First Law of Thermodynamics		Ideal Gas Law		Micro-level	Phenomeno-logical	Chemical	Other
Sub-categories	Correct	Incorrect/ Incomplete	Complete	Incomplete				
Subcategory frequencies	2	14	5	19				
Category frequencies	16		24		15	23	12	3

First Law of Thermodynamics. Within this category one can find responses that are energy-related. Students' utilize concepts of heat, work, internal energy or they refer more vaguely to energy transfers and changes. As "Correct" we characterize those explanations that accurately describe the phenomenon using a qualitative form of the FLT and as "Incorrect/Incomplete" the ones that have an error or one or more variables have been omitted. The main problem appears to be in the concept of internal energy, which was used by just three students; work was also low rated, as only eight students referred to this concept. As for instance, a Correct explanation was the following: *"The piece of cloth was burned because the gas in the vessel got compressed, absorbed energy from the surroundings through work and increased its internal energy, therefore it got hotter"*. On the other hand, we have an Incorrect/Incomplete explanation: *"Because of the fast kinetic energy we applied on the air through the piston, it was converted to internal energy and the latter, in the form of heat, burned the cloth in the vessel"*.

Ideal Gas Law. This category includes explanations related to the IGL. Upper secondary school students are very well familiarized with the equation of state not only in physics context, but also in chemistry, for more than one school year. School thermodynamics begins with the laws of ideal gases and IGL, introducing at that point isothermal, isochoric and isobaric processes. It seems that students utilize it for adiabatic processes as well. As we have already mentioned, the change in the variables of an adiabatic compression cannot be accurately predicted by the equation of state. However, some students have managed to use IGL in a well-rounded manner in order to interpret the increase or the decrease of the involved thermodynamic coordinates ("Complete"). Most of them failed to do so ("Incomplete"). For example, as Complete explanation we consider the following: *"The ignition of the piece of cloth in the vessel happened because of the compression of the air, namely the volume was decreased, therefore the pressure and the temperature were increased; the moles of the gas remained constant"* and as Incomplete: *"The cloth ignited because of the temperature increase. More specifically, the pressure of the piston increased the temperature in the vessel"*.

Micro-level. In this category we included all those explanations that refer to microscopic descriptions of the gas. The students who used this model tried to interpret the increase of the temperature using microscopic models, which were mostly related to the kinetic energy of the molecules and the collisions between the molecules of the air and the cloth. Here is an example of the latter: *"The energy of the gas in the vessel and the molecules gained greater kinetic energy; as a result the collisions between them are also increased. From these collisions occurred the ignition of the cloth"*.

Phenomenological. Within this category there are those responses that are merely a description of the observed real situation with no other justification. The students mention that the piston was pressured, the cloth was on fire, the volume of the air in the vessel was minimized etc., namely scattered observations with no apparent physical model underneath. As for instance, oversimplified explanations were similar to the following: *"Because the temperature in the vessel was abruptly increased"*, while more elaborate justifications were like this: *"In vessel there was ignition of the piece of cloth because the compression happened very fast, resulting to the increase of the temperature. Hence, there was ignition of the cloth and it burned"*.

Chemical. There were a significant number of explanations that sought for the chemical reactions to interpret the fire on the cloth. Naturally, most of the answers in this category referred to combustion. For example: *"Due to the abrupt compression we induced, the result is that the molecules of the air, which contain oxygen, would move faster, ergo the collisions between the oxygen and the cloth would increase, resulting to the burning of the cloth, since there is oxygen"*.

Other. This category includes the responses that cannot be integrated in one of the others or they just do not make sense. As for instance: *"There was an ignition because the pressure increased rapidly and abruptly when we pressed the piston rapidly and abruptly. Therefore, by changing the pressure, the physical constants also changed, resulting to the burning of the cloth in a lower temperature"*.

Exclusive categories, overlapping categories and cluster analysis

The above categories, as we have already mentioned in the previous paragraph, are not used exclusively in students' explanations, but, more often than not, they appear in combinations of two or three. Only 21 of the students used solely one model, 27 used two and the remaining 6 used three. The diagonal of Table 2 includes all those explanations that belong in merely one category. The numbers below the diagonal count the frequency of responses that fell into two categories. In Table 3 there are the answers that fell into three different classes.

TABLE 2

Frequencies for exclusive and two overlapping categories (n=48)

	Correct FLT	Incorrect/ Incomplete FLT	Complete IGL	Incomplete IGL	Micro-level	Phenomenological	Chemical	Other
Correct FLT	1				1			
Incorrect/ Incomplete FLT		2	1	4	3	2		
Complete IGL			3				1	
Incomplete IGL				3	1	4	2	1
Micro-level					3	3	1	
Phenomenological						8	3	
Chemical							0	
Other								1

TABLE 3

Frequencies for three overlapping categories (n=6)

	Correct FLT	Incorrect/ Incomplete FLT	Complete IGL	Incomplete IGL	Micro-level	Phenomenological	Chemical	Other
Correct FLT **Chemical**					1	1		
Incomplete IGL **Phenomenological**							1	1
Micro-level **Chemical**				2				

The exclusive use of a single type of explanation is more frequent for Phenomenological category, that is to say that 8 students were content by the description of their observations as an explanation. Regarding the most commonly overlapping categories, in Table 2 it is noticeable that students combine Incorrect/Incomplete FLT with Incomplete IGL, namely they tangled some of the energy concepts with some of the thermodynamics coordinates in an inaccurate way. Another combination preference we notice for Incomplete IGL and Phenomenological; in this case, the students attempted to blend their portrayal of the observation with elements of the IGL, which seems rather natural because these two forms of explanations superficially belong to the same framework in terms of concepts. In regard to the utilizing of three categories at the same time, Table 3 shows that 6 students were not satisfied with their two-folded explanations unless they integrated some kind of microscopic and/or chemical concepts in them.

In order to define the number of students' clusters in reference to their interpretations, we used only those categories/subcategories that had efficient discriminant ability. These categories/subcategories were the following four (out of eight): Complete IGL, Incomplete IGL, Micro-level and Chemical. Three clusters emerged (Table 4). The first cluster consists of 21 students and the majority of them focus on the micro-level category (with combinations). The second cluster of 17 students has an absence of responses in our discriminant categories, because students' answers were mostly placed in Incorrect/Incomplete FLT (with combinations) and Phenomenological. The last cluster consists of 16 students, who chose Incomplete IGL (with combinations). These clusters vividly sketch the students' inclinations; they drive away from the correct form of FLT and they perplex microscopic models, energy-related explanations and variables of state.

Table 4

Clusters of students based on their explanations (n=54)

		Frequency of agreement per category			
Number of students	**Cluster**	**Micro-level**	**Complete IGL**	**Incomplete IGL**	**Chemical**
21	1st	15	1	5	10
17	2nd	0	4	0	1
16	3rd	0	0	14	1

Students' reasoning on adiabatic compression

In this section we engage with our second research question; the examination of the students' forms of reasoning when they try to interpret the adiabatic compression they observed during the demonstration. In particular, we seek for Aristotelian causalities and especially efficient causality, namely linear causal reasoning, in their explanations.

Material causality. The substantial number of students that used chemical reasons (Table 1) took mainly into consideration the involved materials and substances. Most of them thought that the cloth was on fire because it is flammable and/or because the presence of oxygen in the air leads necessarily to combustion. They actually did not reflect on the fact that flammable objects are constantly in touch with oxygen and they still do not burn. Apparently, in this case students' reasoning is limited by the properties of the materials and substances.

Efficient causality/Linear causal reasoning. The students make extensive use of this type of reasoning regardless of the category their explanations belong to. Commonly, their interpretations create a chain of variables; each of them induces a change in the next one in a linear way, like domino effect. In case they have another, complementary idea, they do not integrate it into the existing causal reasoning, but they start a new linear chain, alongside the first one. We particularly examine the simplification of variables noted by Rozier & Viennot (1991).

In regard to the first simplification, namely the neglecting of variables, students' explanations are full of it. This is mainly the reason why there are so many answers falling into the Incomplete subcategories of FLT and IGL. For the FLT, the missing variables of internal energy and/or work completely ruined the interpretation of the adiabatic compression. For the IGL, the most absent variable was the volume of the gas. The same stands for the microscopic models; a number of variables was missing, leading to a sum of inaccurate explanations. As for the second type, the preferential relation between two variables, we notice the simultaneous increase of pressure and temperature (IGL and Phenomenological classes) and also the increase of temperature and heat (almost in every category). Regarding the third type, that is to say ignoring the symmetry in implications, we had no opportunity to examine it because of the nature of the observed real situation and the specific question we asked the students that did not provoke them to "reverse" the phenomenon or the variables.

Formal/final causality. This causality form did not generally occur in our samples' reasoning. Only one student suggested that we used the specific real situation *because* we wanted to put the cloth on fire. The rest of them thought of the combustion as a side effect of the compression and not the other way around.

CONCLUSIONS

In this study of second year upper secondary school students, we found more diverse explanations of an adiabatic compression in comparison to those noted in the relevant literature for university students. Our belief is that more categories emerge because upper high school students use their imagination more freely than university students, without realizing the contexts they should be restrained in. Nevertheless, among the various students' explanations, there was a common underlying theory: the cloth was on fire as a result of temperature increase. Therefore, the majority of the students did not try to directly interpret the existence of the flame, but the rise in the temperature.

It does not come as a surprise that the majority of explanations does not fall into the category of FLT; it a was rather expected outcome judging from the results of preceding studies (Loverude et al., 2002; Leinonen et al., 2009, 2012). Although adiabatic processes are taught exclusively as applications of the FLT and the students were reminded of that fact at the beginning of the didactical intervention, this model was still not enough appealing. The vast majority of the students who used energy-related explanations did not involve the internal energy, because the latter does not seem to be connected to temperature. In this context, another underlying theory comes to light: temperature increase can only occur if heat was transferred to the system. Temperature and heat are often interchangeable for students' minds and in some cases identical; this fact is widely mentioned in pertinent studies, but the Greek language creates an additional obstacle for our students, as etymologically the words are barely different ("thermokrasía" and "thermótita" respectively).

The IGL explanation is students' most preferable. This was predictable, considering the pertinent literature (Loverude et al., 2002; Kautz, Heron, Loverude & McDermott, 2005; Leinonen et al., 2009, 2012). State variables such as temperature, volume and pressure are more manageable, because students can actually "see" their variations, in comparison to energy concepts and the microscopic world. However, students often use microscopic models as the ultimate explanation of phenomena that they observe at the macroscopic level (Meltzer, 2004; Kautz, Heron, Shaffer & McDermott, 2005). When they are asked to interpret the flame, they "dig deeper" than the level they can directly observe. Students have been learning microscopic models every year starting from elementary school and, especially for thermal phenomena, they were acquainted with them before the FLT. It is possible that they feel more confident "handling" molecules than macroscopic magnitudes. Additionally, answers that fall into the Chemical category are an extension of this perspective. The underlying conceptions of micro-level and chemical models are not that far apart. They both discard macroscopic variables and focus on the level lying underneath the obvious.

Special attention should be given in students' second favorite category: Phenomenological. This class includes responses that are hardly an interpretation of the phenomenon, but rather a description of the real situation; nevertheless, many students believed that they truly provided an efficient explanation. We take into consideration the way the phenomenon was presented to them: they made an observation of a real situation. As Hodson (1986, p. 382) states, "*theoretical interpretation is* part *of the observation, not subsequent to it*". The students had already been acquainted with and reminded of the scientific theory that interprets the adiabatic compression and the demonstration was carried out in order to trigger them in providing their own theories. However, judging from the results, observation itself could have created an obstacle; in several cases, the students explained *what* they observed and not *why* they observed it. One the other hand, the absence of a cohesive personal theory maybe hiding behind this type of response.

Considering the forms of students' reasoning, our results confirmed the views of Rozier & Viennot (1991) and Tiberghien (1994) regarding the similarities between secondary school and university students. In both educational levels, the participants of the pertinent studies utilize Aristotelian causalities and especially linear causal reasoning to interpret an adiabatic compression. It appears that these types of causalities and reasoning are rather restrictive for the students, as they commonly lead them to inaccurate explanations and, subsequently, to alternative frameworks that do not communicate with the scientific ones.

RESEARCH IMPLICATIONS

The conclusions of this research could affect relevant aspects of high school physics, but also university level physics, especially thermal physics and thermodynamics for both educational levels. They could give prominence to the direct and also the long-standing effects of our teaching in this field.

School educational systems, like the Greek one, that consider the FLT as a physics model with explanatory power as good as any other's related model, may have to revisit this perspective. In addition, the students believe that the models they learn long before the FLT, such as IGL and microscopic, have the same or even greater explanatory capability in comparison to the FTL in both qualitative and quantitative perspective and therefore they can be applied indiscriminately. This fact usually conceals the importance of the FLT, which is left aside, although it can actually interpret a wider variety of phenomena for this level. More specifically, we consider the use of the FLT and especially of its qualitative elements could result to more effective learning of the respective physics field. The FLT could not only be a proper introductory framework for thermodynamic, but also a "conceptual umbrella" which can hold complementary explanatory models underneath it.

Another implication arises in regard to students' reasoning skills. They do not seem to realize that physics tasks need more than a linear causal scheme to be answered correctly. Therefore, physics educators should distinctly present the concepts and the laws and also spend time revealing their interplay and respective limitations. Furthermore, they could overcome students' linear causal reasoning by introducing intermediate schemes that connect the qualitative level of the various models with their quantitative aspects in a meaningful way (Meli, 2015). A solid example of such transitional schemes is the energy chain, which could be highly applicable while teaching the FTL in particular.

Finally, the methodology we used in order to pick on students' minds, namely the observation of the adiabatic compression, brought to spotlight two facts: (a) students could not relate their theoretical knowledge of FTL with an actual situation and (b) in several cases the observation itself was proven to be an obstacle for their interpretations (Bachelard, 1938). These remarks could lead, on the one hand, to a more systematic research of the role that the given representation of a real situation plays in various tasks that the students are asked to explain and, on the other hand, a revision of the role of demonstrations and related observations in science teaching and introduce alternative ways of physical representations (Meli, 2015).

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