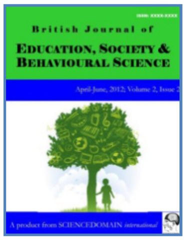

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The Effect of Conceptual Difficulties of Undergraduate Chemistry students' Understanding of Energy

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Authors' contributions

This work was carried out in collaboration between all authors. Author MMW. designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author, HIA and TE managed the analyses of the study and extensively reviewed and edited the manuscript. All authors read and approved the final manuscript.

Original Research Article

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ABSTRACT

Much of the research into student's conceptions of chemical ideas has focused on school age students. This study aimed at identifying specifically undergraduate chemistry student's difficulties in determining the concepts of Energy. Data were collected from 87 undergraduate chemistry students at Dire-Dawa and Haramaya University in Ethiopia during 2011-2012 academic years. Data collection performed through two different instruments in order to determine undergraduate student's difficulties in determining the concepts of energy in chemistry: First A diagnostic test composed of five open ended questions was specifically developed for this study; After this Thirteen participants (out of 87) were also interviewed in order to gather more information in addition to the written responses. The analysis of the result showed seven major conceptions difficulties at macroscopic level of learning, nine at molecular level and four at the quantum mechanical level. Undergraduate students attempt to interpret Energy phenomena explicitly but from

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our study result chemistry requires that these three approaches be integrated, but often they are separated into distinct section of the courses and are not explicitly connected. The findings reported here may contribute to conceptual development of undergraduate's difficulties and can be utilized in research that develops teaching strategies to overcome such difficulties.

Keywords: Energy; chemistry students; macroscopic; molecular; quantum mechanical.

1. INTRODUCTION

In chemistry Thermodynamics is concerned with the study of the transformation of energy, and in particular the transformation of energy from heat into work and vice versa. That concern might seem remote from chemistry. "Energy" is a complex scientific concept central to all scientific disciplines. Here we describe three approaches often used to address energy in the context of college level courses: the macroscopic, which involves thermodynamic and mathematical treatments, the molecular, which describe the origins of energy changes in terms of bonds, and the quantum-mechanical, which provides the basis for understanding periodic trends, bonding and interactions of matter and electromagnetic radiation. Chemistry requires that these three approaches be integrated, but often they are separated into distinct sections of the course and are not explicitly connected. Moreover, prior instruction that does not explicitly address energy concepts at the molecular level likely adds to student challenges.

Indeed, thermodynamics was developed during the nineteenth century by physicists and engineers interested in the efficiency of steam engines. Thermodynamics, which is a science of the macroscopic world, not only deals with the energy output of chemical reactions but it help to answer questions that lie right at the heart of everyday chemistry, such as why reactions reach equilibrium, what their composition is at equilibrium, and how reactions in electrochemical (and biological) cells can be used to generate electricity [1,2]. Energy concepts are critical to understanding how molecules form and behave and quantum-mechanical important focuses' of energy instruction is the idea that at the atomic-molecular scale energy is quantized.

Despite the importance of Energy as the foundation of chemistry, most students pass chemistry courses with several conceptual difficulties about these subjects [3-12] Physical chemistry courses, where students tackle more advanced ideas of Energy are perceived by many students to be one of their most difficult courses [11] so from this study we need to provide students with a relevant energy concepts that integrates the three level and allows students to make sense of energy phenomena.

1.1 Purpose and Research Question

Although several studies cited above investigated students' conceptual difficulties of ideas related to Energy, no systematic study focused on identifying students' conceptions of Energy. Energy concepts such as heat, temperature, equilibrium are widely studied both at elementary and secondary levels and students' alternative concepts are well documented. However, there is a shortage of research to provide guidance on how to improve the teaching of Energy at the tertiary level. The present study may provide some guidance for teachers by identifying undergraduate chemistry student conceptual difficulties in determining Energy and providing recommendations on how to address these conceptual difficulties. Consequently, the research question investigated in this study was:

- What are Ethiopian chemistry undergraduates' conceptual difficulties in determining the concept of energy? What is the source? What are the suggested solutions?

2. METHODOLOGY

2.1 Sampling

The present study employed a descriptive approach in order to achieve the aim described above. Data was collected from eight – seven undergraduate students. All of them were enrolled to Dire – Dawa and Haramaya University, Ethiopia to Bachelors Degree in Chemistry during 2011-2012 academic years.

2.2 Data Collection Tools

Two different instruments were used to collect data. In order to determine undergraduate student's conceptions in determining energy concept a diagnostic test composed of five open-ended questions was specifically developed to test undergraduate student's knowledge of Energy. Such as

a) $H_2(g) + ½O_2(g) \rightarrow H_2O(g) \qquad \Delta H = -242\ \mathrm{kJmol^{-1}}$

This thermochemical equation tells us that 242 kJ of energy are released as heat at constant pressure when 1 mol H_2 molecules reacts with ½ mol O_2 to form 1 mol H_2O.

Explain as carefully as you can why energy is released in this reaction.

b) $N_2(g) + 2\,O_2(g) \rightarrow 2\,NO_2(g) \qquad : \Delta H = 68\ \mathrm{kJ\ mol^{-1}}$

This thermochemical equation tells us that heat is required at constant pressure when 1 mol N_2 reacts with 2 mol O_2 to form 2 mol NO_2.

Explain as carefully as you can why heat is required in this reaction.

C) The potential energy of perfect gas molecules is zero. Why? Explain as carefully as you can.

The researchers' previous experiences in teaching helped them to identify the undergraduates' difficulties in Energy. In order to maintain the content validity of the test, it was given to four lecturers who were asked to assess the content, ideas tested and the wording of the questions. All questions were piloted with third year undergraduates taking physical chemistry course. Undergraduates' views about the content and wording of the questions were taken immediately after they completed the test and required modifications were made prior to the administration of the test.

The test was administered under normal class conditions without previous warming two months prior to students' graduation. Respondents were given a normal class period of 50 minutes to complete the test. Students were informed that the results of the test would be used for research purposes and would be kept confidential.

Based on the initial coding of the responses, prevalent conceptual difficulties were identified. These conceptual difficulties articulated how these undergraduate students differentiate the concepts of Energy, but did not provide in dept explanations of their personal views. To address this limitation, thirteen undergraduate students were interviewed in order to clarify their written responses and to further probe conceptual understandings of the questions asked in the test. Interviewees were selected on the basis of their responses on the written test. If a student's written test response demonstrated conceptual learning difficulties without providing an in-depth or clear explanation of his or her response, we requested interviews with them. The interviews lasted approximately 20-30 minutes. All the interviews were audio recorded (with the interviewees' consent) and then transcribed for analysis. The interviews did not go into great detail; instead they were used to elucidate the students' conceptual learning difficulties based on their written responses.

2.3 Data Analysis

Students' responses to the diagnostic questions were analyzed, conceptual learning difficulties were determined, and percentages were calculated for the responses. Conceptual learning difficulties held by over 25% of the subjects are reported here. Interview data were not subjected to a rigorous analysis but rather was used to support the diagnostic test results.

3. RESULTS

Research in science education has focused on studies which ensure the affective construction of knowledge, and prevent the formation of misconceptions. The present study was the determination of sub-concepts underlining for of meaning full learning the basic concepts related to energy, and an investigation the effectiveness of them on student's achievements. For this purpose, the basic concepts for the targeted unit for learning were correlated with the concept of Energy with macroscopic, molecular and quantum mechanical perspective. According to the result of this study we identified conceptual difficulties of energy with suggested solution related to the three perspectives.

3.1 Macroscopic Perspective

1. From a macroscopic perspective, observable energy changes can be measured and calculated as a result of temperature changes. Although temperature change is a physical manifestation of the energy changes that take place on the atomic-molecular level, most college- level instructional approaches do little to emphasize these origins: they do not explicitly connect the macroscopic (temperature) to the microscopic and molecular. Instead energy topics are introduced under the general heading of "Thermo chemistry" and later on more Generally "Thermodynamics".
2. Thermo chemistry is concerned with the energy changes that take place when a chemical system undergoes change, and for most students this topic will involve calculations using specific heats and temperatures. Subsequently thermodynamic functions such as enthalpy (H), entropy (S) and Gibbs energy (G) are introduced. However, it is common to find that instruction and assessment are focused on rote calculations of these functions rather than an understanding of the meaning of these

thermodynamic functions and how changes in state functions are linked to changes at the molecular level.

3. There is evidence that students approach mathematical representations of thermodynamic functions, such as enthalpy or entropy, in an algorithmic fashion and that even advanced chemistry students can fail to grasp what these mathematical representations of thermodynamic functions represent. [15] Found that students enrolled in an upper-division physical chemistry course struggled to interpret the expression $U = q + w$ as related to energy conservation
4. Students believed that $\Delta S < 0$ for spontaneous (that is, thermodynamically favorable) processes, suggesting that students did not interpret results in alignment with the Second Law of Thermodynamics. This is troubling given that Gibbs energy is one of the most important and useful thermodynamic functions for many scientists, yet its meaning is poorly understood. For example, biologists use it to determine the direction of change in biological systems and to understand how coupled reactions can drive thermodynamically unfavorable processes (that is, changes that alone lead to a decrease in total entropy or a positive Gibbs energy change). Yet, there is little evidence that students understand that the change in Gibbs energy is a proxy for the Second Law of Thermodynamics. Such difficulties may reflect a lack of an accurate underlying understanding of exactly what specific thermodynamic variables represent
5. Students enrolled in a university-level physical chemistry course viewed the change in Gibbs energy (ΔG) as related to the amount of heat transferred in or out of a system.
6. [9] noted that students believed that the magnitude of ΔG determined the rate of a reaction while [8] observed that students often view entropy as a form of energy
7. Furthermore, there is evidence that even university-level students may have foundational misunderstandings about the nature of heat and energy. For instance, some students view energy as substance or material quantity [16] or as a driving force or causal agent in a chemical reaction [17].

3.2 Suggested Alternative Approaches for Teaching

At the heart of challenges surrounding heat and work may be the fact that the terms such as “energy” or “heat”, and that the language used to discuss them often contains implicit metaphors comparing heat and work to quantities that can be found in everyday life[12,14,18] In transitioning to discussions of energy in science contexts, students must come to appreciate energy as an abstraction and as a tool for reasoning, which may be in conflict with everyday language. Clearly these findings are problematic; the use of mathematical resources to model and represent systems is a key scientific practice that has the potential to facilitate students’ understanding of energy transfer and conservation in more complex systems. However, if an appreciation of the concepts underlying thermodynamic functions does not exist, it becomes nearly impossible for students to appreciate energy as a tool for reasoning which they may then use in appropriate ways to explain and predict the outcomes of chemical processes. Generally a thermodynamic treatment of energy and energy changes does not build on students’ prior knowledge (for example from physics), but rather introduces new set of ideas that may appear to the student to be introduced solely for the purpose of doing calculations. Given that most students in a general chemistry course are not chemistry majors – but rather biology or engineering majors, it is necessary for them to transfer a conceptual rather than an algorithmic understanding to these subjects.

3.3 The Atomic Molecular Perspective

1. Energy concepts are critical to understanding how molecules form and behave. These are generally introduced during discussions of the structure and interactions of matter. These ideas may be taught introduced either before or after thermo chemistry, but are required to make sense of thermo chemistry. Only at the atomic-molecular level can the interactions responsible for the observable manifestations of energy changes be observed.
2. Bonding and intermolecular interactions are foundational parts of chemistry in that they enable predictions of molecular properties at the macroscopic level. It is possible to explain most of the properties and interactions of matter, from the sizes of atoms to their interactions along the spectrum, from London Dispersion Forces to covalent bonding, in terms of kinetic and potential energy.
3. To understand bonding at a conceptual level in terms of energy, students must recognize that such interactions are based on attractive and repulsive forces, and that a constant interaction is formed when there is a balance between these forces, an "energy minimum"[19]. Developing such an understanding, however, may be challenging for students. Since covalent bonds, ionic bonds and intermolecular forces are often treated as different entities; many students consider bonds as distinct from intermolecular forces, despite the fact that both are types of electrostatic interactions [27]
4. In reasoning about bond formation and stability, students may rely on heuristics such as the octet rule, rather than an understanding of how electrostatic forces contribute to the minimization of potential energy through bond formation [27]. Similarly, the topic of bond energies is also a source of difficulty– even after instruction typically over 50% of students believe that bonds release energy when they are broken [20,21]
5. Most students bring with them prior knowledge that is more likely to anchored in the macroscopic level, and may have great difficulty in translating macroscopic concepts to the atomic molecular level. For instance, the construct of potential energy is most often introduced in reference to gravitational potential energy in high school coursework. It has been noted that students may struggle with understandings of gravitational potential energy. For instance, [22]noted that undergraduate non-science majors enrolled in an introductory physics had difficulty in describing variables upon which gravitational energy depends, and that many students used definitions of potential energy in which they seemed to believe that potential meant the "potential" for movement energy It seems plausible that students might have similar difficulties in interpreting potential energy in other contexts, discussing intermolecular forces and bonding but rarely is the relationship between potential energy at including chemistry.
6. In introductory chemistry courses, potential energy is often referenced when the molecular level and gravitational potential energy elaborated. While electrostatic potential energy can be considered somewhat analogous to gravitational potential energy in that both depend on an object's position within a field, electrostatic potential energy is more complex since there are two types of charges and therefore both attractive and repulsive forces, in contrast to the solely attractive force active in a gravitational field. Students may be left to interrelationships between macroscopic and molecular ideas for themselves
7. In studies of high school and university-level students' explanations of electrostatic phenomena it has been found that despite instruction, students tend not to use energy and field-based explanations and instead appeal to explanations that deal

with the interaction of charge, or the movement of charged particles when explaining observations of properties related to electrostatic interactions and potential energy[23,24]

8. This finding may be understandable if one considers the abstract nature of electrostatic fields; reasoning about electrostatics requires students to reason about particulate-level objects (like electrons) and abstractions such as field and potential energy [25]
9. In our studies of what students understand by the term “potential energy”, we find that almost uniformly; from beginning level students to upper level chemistry majors and graduate students tend to fall back on their first introduction to the term to explain it. Their depictions of potential energy include “balls rolling down hills”, and are almost always concerned with gravitational potential energy, rather than molecular level explanations. There is almost no mention of fields, or the idea that a system of objects must be defined to understand these ideas. Similarly, in our own preliminary work related to students’ understanding of potential energy, when explicitly asked about potential energy as it refers to chemical systems, we find that undergraduate students are unable to articulate a coherent response, despite the fact that the terms “potential energy” and “potential energy minimization” are central to a wide swath of chemistry concepts.

3.4 Suggested Alternative Approaches for Teaching

We suggest that students must understand the origin of potential and kinetic energy changes at the atomic-molecular level before they can understand bases of thermodynamic ideas that are in common use. If students do not know how energy is transferred and stored at the atomic molecular level, it is likely they will struggle to understand (for example) the origin of “chemical energy” - how or why chemical reactions can be used as a source of energy (from food to batteries). We must do more to reinforce appropriate interpretations of energy as related to these forces at both macroscopic and atomic-molecular scales and to help students translate ideas of energy across scales.

3.5 The Quantum-mechanical Perspective

1. The third important focus of energy instruction is the idea that at the atomic-molecular scale energy is quantized. For most students (and for most people!) this idea is entirely counterintuitive; it has no counterpart in their lives, and is often taught in introductory courses only in connection with atomic structure
2. Typically emphasis is placed upon easily assessable ideas such as the recitation of electron configurations, rather than an understanding of why energy quantization is important within chemical systems
3. Seldom addressed are topics such as why carbon, the building block of life, forms four bonds rather than six (or two) bonds, why materials emit or absorb electromagnetic radiation of particular wavelengths, or why we can use solar energy only when mediated by appropriately designed materials that can capture and transfer the energy.
4. Not surprisingly, there are a number of reports in the literature about student problems with the concepts of quantum chemistry [10,26,28] which is hardly surprising given the nature of the construct. There is strong evidence that despite instruction within university-level chemistry courses, students may fail to see the relationship between energy quantization and orbital ideas [10,13]

3.6 Suggested Alternative Approaches for Teaching

As a result, quantization of energy and the uncertainty principle have been described as "threshold concepts" due to their challenging nature [13] In fact [10] indicated that quantum mechanical concepts present a "*genuine pedagogic problem: capable and motivated students struggle to learn from experienced and knowledgeable teachers.*"

4. CONCLUSION

Introductory chemistry courses typically "cover" these three approaches to energy but the coverage is fragmentary, not connected to students' earlier knowledge, and typically not set in a meaningful context. The three core energy ideas are not well connected, and there is often no attempt to make an explicit connection between them. Most assessments for introductory chemistry courses still emphasize rote problem solving and factual recall rather than understanding, and there is little opportunity for students to synthesize and connect the energy ideas. There is ample evidence that students lack a coherent framework of energy concepts on which they can hang their understanding of energy changes associated with chemical change. In fact many of the leading textbooks introduce these topics in different orders, so it is clear that there is no consensus on how to develop and connect energy concepts or ever why it is important.

Energy should be an integral component of introductory college-level chemistry courses. It should help   provide a framework for understanding both how and why chemical changes occur. Unfortunately, it is common to find that discussions of energy are fragmented and do not explicitly connect across the domains. This makes it more difficult to build on students 'prior knowledge since most of the ideas that students have are based on macroscopic understandings of energy and energy changes, which unless they are explicitly connected to the molecular level can significantly impede student understanding. We propose a learning progression for energy that explicitly connects the three domains and builds from a discussion of atomic structure to networked reactions that drive thermodynamically unfavorable processes. The development of this learning progression and the assessment of student learning outcomes are ongoing, with data collected from student performances and interviews being used to refine and revise this approach.

An ongoing challenge in creating a new focus on energy in the chemistry curriculum is that it must not only be coherent but also must explicitly address students' experiences in learning energy ideas in other course contexts. What is clear is that in chemistry we cannot continue to treat energy concepts as if students already have a robust framework to build on. We must take time to ascertain what students already know, and reconstruct and re-develop energy ideas beginning at the molecular level. We must design and construct meaningful activities and assessments that encourage students to relate understandings of energy across the curriculum.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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