Investigating students' alternative conceptions in elementary thermodynamics and developing and testing activity-based modules to address them

Synopsis

Submitted in partial fullfilment of the
academic requirements for the degree of
Doctor of Philosophy
in
Science Education
by

Shirish R. Pathare

Thesis advisor: Savita Ladage

Thesis co-advisor: Hemachandra C. Pradhan

Homi Bhabha Centre for Science Education,

Tata Institute of Fundamental Research, Mumbai

May 2021

Abstract

The study of heat and thermodynamics is an important part of undergraduate physics students' education. Many basic concepts in this subject are related to everyday experiences. Yet in the formal study of the subject, these concepts take a rigorous form which students find difficult to cope up with. Due to these reasons, students misinterpret these concepts and often develop alternative conceptions about them.

In the present work, I have investigated students' alternative conceptions in elementary thermodynamics. At the initial phase, I developed and administered the questionnaires in topics like pressure, heat and temperature (N = 57), heat transfer mechanisms (N =57), thermal equilibrium (N= 291) and first law of thermodynamics (N = 135). These were first and second year of undergraduate physics students from different colleges in India. The analysis of students' responses presented a list of alternative conceptions in these topics. I felt that it would be more meaningful to develop ways to help students overcome some of these alternative conceptions rather than their mere identification.

It is evident from the physics education research (PER) literature that conventional instructional strategies are not sufficient to address such alternative conceptions. It is important to introduce active learning strategies to deal with them. In the Indian curricula, the theoretical courses are not supported by the practical course work in thermodynamics. In this context, I thought of adopting an activity-based approach and developed activity-based modules in two topics, namely, thermal equilibrium and first law of thermodynamics. The modules consist of a number of activities with experiments/demonstrations, designed with specific objectives along with structured activity-sheets. These modules were implemented using the predict-observe-explain approach (POE). The study indicates that the developed modules helped in enhancing students' conceptual understanding of the central concepts covered in the module and thus minimising the alternative conceptions. I believe that this approach can be adapted as a part of the laboratory curricula in undergraduate physics in India.

Publications related to the thesis

International

In Journal

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(2) **Pathare, S. R.**, Huli, S. H., Nachane, M., Ladage, S., Pradhan, H. (2015). Understanding Thermal Equilibrium Through Activities. *Phy. Edu.*, IOP, UK, 50(2), 146.
(3) **Pathare, S. R.**, Huli, S. H., Ladage, S. A., Pradhan, H. C. (2018). Understanding First Law of Thermodynamics through Activities. *Phy. Edu.*, IOP, UK, (53)2, 1 - 18.

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(3) **Pathare, S. R.** and Lahane, R. (2009). Understanding Thermal Equilibrium through Hands-on-Activities. Proceedings of the 6th International Conference on Hands-on-Science at Science City, Ahmedabad, India, 343 – 346.
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(5) **Pathare, S. R.**, Pradhan, H. C., Nachane, M., Huli, S. (2013). Understanding thermal equilibrium through activities. Paper presented at the International Conference on Physics Education, Prague, 108.
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In conference

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(2) **Pathare, S. R.**, Huli, S. H., Ladage, S., Pradhan, H. (2015). Students' understanding of the First Law of Thermodynamics. Presented at IAPT, Hyderabad, India.
(3) **Pathare, S. R.**, Huli, S. H., Pradhan, H. (2015). Enhancing students' understanding of Thermal Equilibrium. Presented at IAPT, Hyderabad, India.

Contents

Chapter 1: Introduction

The current synopsis reports on the investigation of students' alternative conceptions in elementary thermodynamics and on the development and testing of the activity-based modules to address the alternative conceptions. One finds in physics education research (PER) literature numerous studies on alternative conceptions as well as on activity-based instructional strategies. Majority of these studies are from mechanics, optics, electricity and magnetism and comparatively less work has been done in the area of heat and thermodynamics. This is especially true in the Indian context. Thermodynamics is a complex and conceptually rich domain that has numerous applications in everyday life and is an integral part of the physics/chemistry education. In Indian context, it occupies central position in the curricula especially at the undergraduate level. PER indicates that learners have several alternative conceptions in this area. Thus, it is still a fertile area of research in physics education.

1.1 Motivation

During my pre-university and undergraduate days, I found concepts in thermodynamics familiar to me from daily life and yet they were only seemingly simple. During my graduate coursework, I attended a course on Chemical Thermodynamics by a distinguished teacher. This course introduced the concepts of thermodynamics with different and deeper perspectives which helped me to realise the complexity of these concepts and also my inadequate understanding of this domain. Due to my own experiences at undergraduate level, this area always attracted my attention. Thus, I became interested in investigating students' conceptual difficulties in this topic and prepare material to help the students. In my exploratory work with undergraduate students from different colleges in Maharashtra, I found that several alternative conceptions prevailed. These observations further reinforced my idea to work in elementary thermodynamics. I felt that such a work should not be limited only to probing alternative conceptions but should also be extended to addressing these alternative conceptions. In India, at the undergraduate level, hardly any experiments on thermodynamics are included the curriculum. With my interest in experimental domain, I was keen on addressing the alternative conception through activity-based approach.

1.2 Research questions and objectives

Thus with my interests in investigating students' conceptual difficulties in elementary thermodynamics and adopting the activity based approach to address them, I formulated the following research questions:

1. What are the alternative conceptions in elementary thermodynamics of physics undergraduate students in India?

2. Is it possible to design activity-based modules and test their effectiveness to help students overcome the alternative conceptions?

In order to carry out systematic investigation, these research questions were further divided into following research objectives:

1. To review the syllabus of elementary thermodynamics which typically students in India at the senior secondary school level and the undergraduate physics level study, as part of their physics curriculum and on the basis of this review, prepare a list of concepts that these students are expected to be familiar with.

2. To conduct an open ended inquiry into the students' awareness of the concepts in the list prepared above and to analyse the responses and identify major areas of concern for understanding.

3. To develop short answer type / multiple choice type questionnaires in these identified areas and to arrive at the set of alternative conceptions through the analysis of students' responses.

4. To design and develop activity-based modules to address the alternative conceptions in a few typical areas and to bring them to a final testable form through several iterations.

5. To check the effectiveness of these activity-based modules, brought in the final form, to address students' alternative conceptions.

Working towards the first research objective, I began with the review of textbooks prescribed for class VII to XII of the Maharashtra State Secondary School Board as well as the Central Board of Secondary Education and the first year and second year undergraduate physics syllabus of University of Mumbai. From this review, I came up with a set of 70 concepts in elementary thermodynamics that students were expected to know. For the second research objective, a preliminary study was conducted on students' understanding of these concepts. The analysis of this study gave an idea about the concepts that the students have difficulty with and helped me to finalise the concepts that can be probed further. Along with this input and review of PER literature, a final set of questionnaires was developed. The work of investigating alternative conceptions, that is the third research objective, was conducted with first year and/or second year undergraduate students ($N \sim 50$ to 300) in different colleges studying physics as one of the subjects. The analysis of their responses/justifications helped in identifying a possible set of alternative conceptions which were further confirmed by the interviews with some of the students ($N \sim 10$ to 15 for each topic). During the interviews, the students were asked to elaborate their justifications in detail.

For working towards the fourth research objective, the activity based modules were developed. These modules were developed to explain the concepts to the students and in the process address their alternative conceptions that I found in my study. In view of the extended nature of the planned work, it was decided that it would be practical to restrict the development of modules only to two topics. The modules were developed and standardised through iterative cycles consisting of design - testing (with students)- modification based on students' feedback. The predict-observe-explain (POE) approach was used to administer the modules to students. The idea of cognitive conflict is central to this approach which helps students to reflect upon their own alternative conceptions. The outcome of the work on the fourth objective was a final version of the modules.

The fifth research objective, related to testing the effectiveness of these activity-based modules, was implemented by checking the students' understanding of the concepts through pre- and post-tests. The intervention between the two tests was the administration of the final version of the activities developed. Semi-structured interviews were conducted to support the quantitative analysis of the post-test responses.

Chapter 2: Literature Review

2.1 Introduction

This chapter presents a review of the literature in physics education research (PER) on alternative conceptions and particularly in the area of elementary thermodynamics. It then describes some of the instructional strategies aimed at challenging alternative conceptions. It briefly discusses the methodology adopted for developing the activity-based module to address students' difficulties.

2.2 Alternative Conceptions and physics education research

Students build their understanding about the world informally through their daily life experiences (Nussbaum and Novak 1976) and formally through school education. PER has a large number of studies exploring students' ideas in science. These ideas have been categorised and labelled by a range of different terms (Duit 2009) such as "naïve beliefs" (Caramazza, McCloskey, and Green 1980), , "misconceptions" (Clement, D. Brown, and Zietsman 1989, Driver and Easley 1978), "children's ideas" (Osborne et al. 1993), "conceptual difficulties (McDermott 1993), "phenomenological primitives" (diSessa 1993), "alternative conceptions" (Wandersee, Mintzes, and Novak 1994) and so forth (Gurel, Erylmaz, and McDermott 2015). Even if each of these terms have variations, they all focus on differences between the ideas that students bring to classroom and the scientifically accepted concepts. All these studies are aimed at understanding of students' variant conceptions that impede learning. Some of the common causes for alternative conceptions in physics (Council 1997 and Suprapto 2020) are preconceived notions, language related misunderstandings, conceptual misunderstandings and teacher driven. For students, the textbooks too are one of the major sources of information and, perhaps, alternative conceptions (H. Cho, Kahle, and Nordland 1985, Iona 1987).

2.3 Cognitive conflict strategy and alternative conceptions

Wandersee et. al.'s (Wandersee, Mintzes, and Novak 1994) extensive literature review on alternative conceptions claims that the alternative conceptions are often rigid and difficult to dislodge using conventional teaching strategies. The authors assert the need for conceptual change approach to address students' alternative conceptions and to develop scientifically accepted conceptual understanding.

Many researchers offer different views about the process of conceptual change (Chi and Roscoe 2002, diSessa 2002, P. Hewson and M. Hewson 1983, Hynd et al. 1994, Posner et al. 1982, Thagard 1992, Vosniadou 2012) and these models have emphasised the role of cognitive conflict as a central condition for conceptual change. Some researchers (Posner et al. 1982, Limón 2001) state that conceptual change is a gradual process and that in general, a dramatically radical change cannot be expected just after introducing anomalous data in a short instructional intervention.

One of the most accepted theory of conceptual change is presented by Posner (Posner et al. 1982) and this model of cognitive conflict has been widely used in many later studies (Basili and Sanford 1991, Costu, Ayas, and Niaz 2010, Calık, Ayas, and Coll 2007a, Calik et al. 2007b, Limón and Carretero 1997). For conceptual change to take place, Posner et. al. suggested four conditions: (1) students must become dissatisfied with their existing conceptions (dissatisfaction); (2) the new concept must be clear and understandable for students (intelligibility); (3) the current problem should be solvable by using the new concept (plausibility); (4) similar future problems can be solved by using the new concept (fruitfulness). The cognitive conflict strategy is based on the idea that by introducing discrepant events into learning, learners are led to a situation where they recognize the fact that their existing understanding is inadequate to explain the information presented. The cognitive conflict process occurs when a learner recognizes the anomalous situation, expresses interest or anxiety about resolving the cognitive conflict and therefore, engages in cognitive reappraisal of the situation to resolve the conflict (Lee et al. 2003). Clement emphasises the need to help students make sense of science content (Clement 1977) by representing the same in multiple modes (e.g., verbal, mathematical, concrete-practical, pictorial). In this work I too have tried to use multiple modes to improve students' understanding of the concepts.

2.4 Instructional strategies for addressing alternative conceptions

Several approaches have been used to bring about a conceptual change. These include Investigative Science Learning Environment (ISLE), Interactive Video Vignettes (IVV), Predict-Observe-Explain (POE), the Interactive Lecture Demonstrations (ILD) and others.

In ISLE (Etkina and Van Heuvelen 2007), students observe phenomenon/activity, look for patterns and then develop explanations for these patterns. Using these explanations they make predictions about the outcomes of testing experiments. Then they decide if the outcomes of the testing experiments are consistent with the predictions. If necessary they revise explanations. IVV (Wright et al. 2016), are designed as ungraded web-based assignments for introductory physics students in the form of online videos with video analysis. Each online vignette addresses a learning difficulty identified by PER. IVV, elicits predictions from a student, confronts student with experimental results, and helps the student resolve any differences between the prediction and observations (*https://www.compadre.org/IVV/research/PERbasis.cfm* 2021). POE places importance on students' reasoning (White and Gunstone 2014). The explanation that the students provide to resolve cognitive conflict is a result of their prior knowledge and the understanding developed through the activity. The POE tasks, therefore, are quite suitable for externalizing and addressing alternative conceptions (Bahar 2003). ILD (Sokoloff and Thornton 2004) engage students in activities that confront their prior understanding of a core concept. These demonstrations are aimed at creating active learning environment for large (or small) lecture classes using discovery based laboratory curricula supported by real-time microcomputer-based laboratory tools. It incorporates POE as a part of a pattern combination to improve the effectiveness of lecture demonstrations (Alexander and Winne 2006). Thus POE is an important instructional approach, used in creating cognitive conflict, to address alternative conceptions.

2.5 Predict-observe-explain approach

The POE approach involves introducing a demonstration of a scientific phenomenon, eliciting predictions, running the demonstrations, and asking the students to reconcile contradictions (White and Gunstone 2014). POE offers evidence that distinguishes students' thinking between prediction and what is observed during demonstration. The observation part of POE can induce conflict by enabling students to explain the observation. The explain phase in POE encourages learners to reconcile any discrepancies between their predictions and the observations. POE has the greatest benefit when students use evidence (generated from their observations) to analyse their predictions (Alexander and Winne 2006). Many extensions of POE tasks in terms of its integration with conceptual change model have been developed by researchers (Ebenezer et al. 2010, Savander-Ranne 2003, Costu 2008). Eryilmaz (Eryilmaz 2002) stated the following guidelines for conceptual change based activity sessions:

1. Use the conceptual question as an event that helps students to expose their conceptions about a specific concept or rule.

2. Allow students to make their own predictions, verbally and pictorially, even if they are

not correct and ask them to justify their predictions.

3. Give enough time to the students to think and respond to the questions.

4. Create a discrepant event, one that creates conflict between exposed preconceptions and some observed phenomenon that students cannot explain.

5. Make students aware of this conflict

6. Help students to accommodate new ideas presented to them. The teacher does not bring students the message, but makes them aware of their situation through dialogue.

7. Show explicitly where oversimplification, exemplification, association, and multiple representations have happened, if any. If not, provide exemplification, associations with other topics, and multiple representations for the topic.

I have used POE approach with these guidelines for my work on addressing alternative conceptions. Since the work is related to students' alternative conceptions in thermodynamics, it is important to look at the studies related to this area.

2.6 Alternative conceptions in thermodynamics

A large number of concept inventories have been developed to study alternative conceptions in physics. Various concept inventories in thermodynamics have been developed such as Computer as Learning Partner (CLP) (Linn 1997), Thermal Concept Evaluation (TCE) (Yeo and Zadnik 2001), Heat and Temperature Concept Evaluation (HTCE) (Thorton and Sokoloff 2001), Thermal and transport concept inventory (TTCI) (Nelson et al. 2007), Thermodynamic Conceptual Survey (TCS) (Wattanakasiwich et al. 2013), A survey of thermodynamic processes and first and second laws (STPFaSL) (B. Brown 2015). These concept inventories, when administered to students, bring out different alternative conceptions that students have in thermodynamics. Heat and temperature are the most commonly researched concepts in physics education research literature (Harrison, Grayson, and Treagust 1999, Sözbilir 2003, Paik, B. Cho, and Go 2007). One of the most fundamental confusions is due to the difference between the daily life experiences and scientific terminology used for heat and temperature (G. L. Erickson 1979, G. Erickson 1985). Many students hold conceptions very similar to the caloric theory of heat held by scientist in 8^{th} century (Brush 1976). Another prominent alternative conception is that heat is an intensive quantity and temperature is the amount of heat (Kesidou and Duit 1993). Students do not accept that different objects are at the same temperature when left in the same environment for a long time (Yeo and Zadnik 2001). Jacobi et. al. (Jacobi et al. 2003) observed that students were confident about conduction but less certain about convection and radiation. Majority of students confuse heat with internal energy (Granville 1985). Students' understanding of the first law of thermodynamics has been studied by different researchers (Meltzer 2004) which particularly focus on the compression and expansion of an ideal gas (Kautz et al. 2005a, Gonen 2014). Students experience difficulty in recognizing the difference between the important quantities in the first law of thermodynamics and the change in these quantities (Meltzer 2004). Due to this difficulty, they used inappropriate explanations rather than the first law of thermodynamics in the context of adiabatic compression.

2.7 Development of activities

Research has shown that active, discovery-based laboratory curricula bring about significant changes in students' understanding (Thornton 1998, Lucariello and Naff 2013). Activities, designed appropriately, engage and help students to establish relationships among various concepts, especially in a complex subject like thermodynamics (Stepans 2008). In Indian context, where thermodynamics is taught primarily as theory course, the activity based approach is likely to be of great significance. Therefore, it was decided to adopt an activity-based approach for addressing students' alternative conceptions. This was also a natural choice for the researcher who has expertise in developing experiments for the international physics olympiad programme. The development of such activities went through several iterative stages of modifications before it was finalized. These iterative cycles involves stages of design, evaluation, analysis and revision.

Chapter 3: Research Methodology

3.1 Introduction

This chapter discusses the research methodology adopted in both the parts of my work - 1. how I arrived at the topics of investigation and students' alternative conceptions in these topics, 2. the development and implementation stages of the activity-based module.

3.2 Selection of the broad topics of study

I decided to investigate students' alternative conceptions in four areas from elementary thermodynamics: heat and temperature, heat transfer mechanisms, thermal equilibrium and the first law of thermodynamics. The current section presents the discussion about the process that led to selection of broad topics/concepts related to elementary thermodynamics for the study. The topics in elementary thermodynamics that students study as part of their secondary/higher secondary level(class VII to XII) syllabi were looked at, followed by what they are expected to study at first and second year of undergraduate physics courses. For Class VII to XII, both the Maharashtra state board and the Central Board of Secondary Education (CBSE) syllabi were considered. For undergraduate level, I looked at the syllabi of University of Mumbai. A list of 70 core concepts in thermodynamics was drawn. This list was given to 100 first and second year undergraduate students from six different colleges in Mumbai, Delhi, Kolkata and Bangalore. In this open ended study, students were asked to give their explanation of these concepts supported by examples. This study was aimed at understanding students' level of awareness about these core concepts. The students' responses were categorised as "correct", "incorrect/inadequate" and "not attempted". I looked at how many students presented explanation and also the correctness of the explanation. Such analysis helped me to understand the concepts that are easy and difficult for the students. This analysis of students' responses gave a list of 44 concepts, which the students found to be the most difficult. This list of concepts was shared with four undergraduate college teachers, experienced in teaching thermodynamics and I discussed with them about their own students' understanding of these concepts. They also opined that their students do have difficulties with these concepts. I also consulted the book, Heat and Thermodynamics by Zemansky and Dittman (Zemansky and Dittman 2008), which is a standard reference prescribed for undergraduate physics education in India. Based on the analysis of students' response, discussion with experienced teachers and the reference book (Zemansky and Dittman 2008), I finalised the topics that are difficult for students and narrowed down the focus to the following six broad topics in thermodynamics: 1. Heat and temperature, 2. Heat transfer mechanisms, 3. Thermal equilibrium, 4. First law of thermodynamics, 5. Pressure, elementary kinetic theory of gases, 6. Second law of thermodynamics and related concepts

Second law of thermodynamics and related concepts like heat engine, entropy etc. being somewhat more advanced than the remaining topics deserve a separate detailed study. Further in the survey, it was observed that very few students presented explanation about the concepts related to this topic. Hence, it was difficult to have any perceptions about students' understanding regarding this topic. Thus, I decided not to investigate these topics. Out of the remaining five topics, pressure and kinetic theory seem to be rather separate from the other four, which would go together as a theme. I, therefore, decided to restrict the study of alternative conceptions to the following four out of the six topics given above: **1. Heat and temperature, 2. Heat transfer mechanism, 3. Thermal equilibrium and 4. First law of thermodynamics**

3.3 Development of questionnaires to identify alternative conceptions

On each of these topics, I prepared situation-based short answer questions, guided by the analysis of students' understanding of concepts studied earlier. These questionnaires then were administered to smaller groups (typical group size $\sim$ 30) in checking their effectiveness in probing students' understanding. The results of these pilot studies helped me to modify the questionnaires with respect to content, language and flow, for each topic, and therefore, to arrive at the modified version. These questions were also shown to two senior experienced teachers from undergraduate colleges in Mumbai and Bangalore and also to two subject experts. Their considered judgments as well as careful introspection on the part of the researcher led to further standardisation of the questionnaires leading to the final version. The analysis of short answer type questions with respect to these topics, provided me with different reasonings that students gave, revealing their alternative conceptions. Along with identifying the alternative conceptions I was keen on developing activity-based modules to address them. Thus, considering the vastness of the work, I further decided to pursue my work about students' alternative conceptions only for two topics, namely, thermal equilibrium and first law of thermodynamics. The first law of thermodynamics does cover concepts related to heat and temperature (topic 1). The topic - heat transfer mechanism was not pursued further.

To investigate how widely these conceptions were held and how frequently they were used, I decided to prepare multiple choice questionnaires (MCQ). The advantage of using MCQs was that it provided an opportunity to quickly analyse the performance of each test item and to use this information for future assessments (Scully 2017). This approach was similar to that used in the study by Panse et. al. (Panse, Ramadas, and Kumar 1994) about students' alternative conceptions in Galilean relativity. I designed the distractors for these multiple choice questions based on the responses which I analysed from the short answer type questions in the preliminary studies on these topics.

3.4 Activity-based modules

An activity module is a group of certain activities, involving experiments/demonstrations with structured activity-sheets, designed with a specific objective. My aim was also to generate activity modules that are usable by teachers in their undergraduate classes. Therefore, while developing the experimental activities, I used following criteria:

1. the temperature, pressure, heat flow sensors and measuring instruments used should be low-cost and easy to use
2. the entire experimental assembly should not be bulky and should be easy to tackle if faced with operational difficulties

The primary purpose of the activity modules was to address students' alternative conceptions. However both these modules can be used to introduce the topics in the classroom. Figure 3.1 gives a flow chart of the development and the implementation of the activity module. I developed the activities and modified them so that they help in addressing students' difficulties associated with the concept. Ideas like heat flow or an isothermal change or an adiabatic change have rarely become concretely observable to the students, especially in Indian classroom. So, the major thrust of the activity modules was to make the concepts observable to students. Further, the emphasis in the activity development was to generate conflicting situations for students and to critically study their responses to these situations as cognitive conflict is evident from these responses. In order to develop the activity-based modules, I adopted the iterative approach (figure 3.1). The module development process began with a preliminary apparatus design along with the activity sheets needed to address a particular conceptual problem faced by the student about given thermodynamic concept.

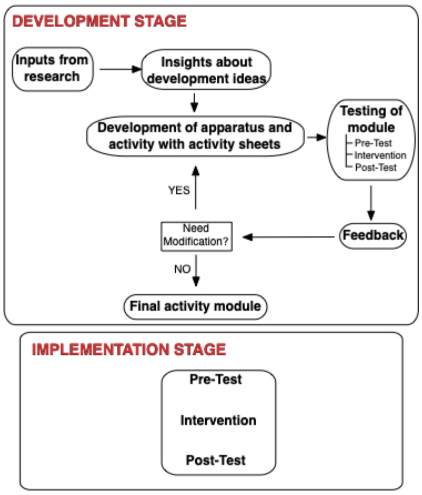


Figure 3.1: Stages of the Activity-based module

The entire development process consisted of multiple cycles of design, testing, and modification through feedback received from students' responses. These modified activity modules were tested every time to check students' responses and how it affected their reasoning. In order to check for the effectiveness of the module, I had to give a post-test. But one would really like to know where the students were earlier. So, I adopted a quasi-experimental design where a pre-test – intervention – post-test was administered to the students. The responses were collected from students, individually, as I was keen on studying the reasoning and understanding of each individual student. I felt that collaborative discussions would be a compounding variable and was thus avoided during the testing and implementation phase. The formative evaluation of the activity module that I carried out during the activity development stage was a kind of continuous validation of the module. The validity of the final activity module was further checked by showing the module to experts.

In the case of thermal equilibrium, I started with an idea to develop an activity-based module around alternative conceptions, but I felt that it was not adequate for students in terms of developing the module only around alternative conception. In order to even approach those alternative conceptions, it was important to discuss some prerequisite concepts. Therefore, I decided to develop an activity-based module for introducing the concept and in the process, also take care of alternative conceptions.

In the case of the first law of thermodynamics, I found that the basic understanding of the law was inadequate which gave rise to multiple alternative conceptions. Thus, the module began with explaining the law through different activities and in the process addresses various alternative conceptions that students have.

The activity sheets consisted of two parts - one that describes the apparatus/activity. The other presents questions which students were supposed to answer before and after the activity was carried out. The questions were designed to encourage the students to explore discrepancies between their responses and observations. Space was provided for writing down the justification for the discrepancy (if any) between their prediction and observations. These activity sheets were finalized after receiving input from each of the iteration cycles. The activity sheets evolved in terms of the description related to apparatus of the activity and the questions related to the activity.

3.5 Implementation of the modules

The modules were implemented with the first and second year students enrolled for the bachelors' programme of science colleges in different cities in India. The study was completely voluntary for both control as well as the experimental group. The control group was administered only the tests and the activities were not given to them. The experimental group was administered the complete module. The students worked on the activities for 3 hour immediately after the pre-test. The post-test was given to the students of both the control and experimental group 1 week after the pre-test. During this period of one week, the students from both control and experimental groups attended their regular academic physics courses, having almost the same content, which did not include thermodynamics. The experimental group was called to the laboratory in HBCSE for the module on thermal equilibrium whereas the module on first law of thermodynamics was administered at HBCSE laboratory as well as in the colleges in and outside Mumbai. The pre-test and post-test for the control group was given at their respective colleges. Typically it took 1 hour each for pre-test and post-test for both control and experimental group.

3.6 Data analysis for the modules

Independent sample t-test (Garret 1981, Foster et al. 2018) was carried out on pre-test scores of control and experimental group to test the equivalence between the groups. Correlated means t-test (Garret 1981) was conducted on pre-test and post-test of each (control and experimental) group to check the improvement in students' understanding due to the activity-based module. Students' qualitative responses from pre-test and post-tests, activity sheets were also studied to understand the improvement in students' understanding.

Chapter 4: Identification of Alternative Conceptions

In this chapter, I describe the findings with respect to students' alternative conceptions in the following four topics: 1. Heat and temperature, 2. Thermal equilibrium, 3. First law of thermodynamics 4. Heat transfer mechanisms. In this chapter, I present the findings of students' difficulties in these topics.

4.1 Heat and temperature

The pilot study was conducted with 31 second year undergraduate students from a college in Mumbai. A questionnaire consisting of 7 short answer questions related to this topic was administered to this sample. The questions attempted to probe students' understanding of 1. definition of heat and temperature, 2. thermal equilibrium between two objects, 3. change in internal energy of a system in a container moving with uniform velocity and 4. extensive/intensive nature of heat and temperature. The pilot study led to standardisation of these questions with respect to language. The modified short answer test was administered to a sample of 57 first and second year undergraduate students from colleges in Mumbai. Interviews were conducted with nine students from the sample to understand their responses in greater detail (Pathare and Pradhan 2005).

When asked to explain, what heat is, many students did not go beyond the statement "Heat is a form of energy" (Sözbilir 2003). Majority of students could not differentiate between "heat" and "temperature" and they used these terms interchangeably (Harrison 1996, Kesidou and Duit 1993, G. Erickson 1985). Some students referred to heat as the "energy content of the system" (Kartal, Öztürk, and Yalvaç 2011). They seemed to equate heat with internal energy (Zemansky 1970). For some students, "Heat always increases temperature" (Yeo and Zadnik 2001), and none showed awareness about the fact that heat might also lead to external work. Some students stated that temperature measures the 'heat content' of the body (Kesidou and Duit 1993). I found that some students equated temperature to its unit "degree Celsius" whereas some others used inverted reasoning like "temperature causes change in heat". The analysis confirmed that thermal equilibrium is an area where students had conceptual difficulties (G. Erickson 1985). Students seemed to consider temperature to be an extensive quantity proportional to volume (Kartal, Öztürk, and Yalvaç 2011).

4.2 Thermal equilibrium

It was observed that students were unable to provide scientifically correct answers to questions on thermal equilibrium. They seemed to have greater trust in their daily life experiences. I, therefore, decided to probe students' understanding on thermal equilibrium further. Also, when a system is in mechanical, chemical and thermal equilibrium then it is said be in thermodynamic equilibrium. Therefore, students' understanding of thermodynamic equilibrium was also probed. I finalized the questionnaire consisting of 11 multiple choice questions on the categories, 1. Understanding thermodynamic variables and thermodynamic equilibrium, 2. Confusion between adiabatic and diathermic walls, 3. Object size and thermal equilibrium, 4. Material of the object and thermal equilibrium, 5. Effective temperature of the mixture. The distractors were developed from the students' responses in prior studies. This questionnaire was administered to a sample of 291 undergraduate students (Bangalore - 251 and Mumbai - 40).

Understanding thermodynamic variables and thermodynamic equilibrium: Students were given a situation in which a cylinder (with a gas enclosed in it) fitted with a movable piston was kept on a moving platform. They were asked to identify a thermodynamic variable. About half of them regarded the velocity of any gas molecule to be a thermodynamic variable. They ignored that the velocity of all the molecules has a common component, which is the velocity of the platform as a whole. In elementary kinetic theory, students learn that the average velocity (in magnitude) of a molecule is related to the temperature of the system, which is a thermodynamic variable. Hence they seemed to think that the velocity of a gas molecule is a thermodynamic variable. They ignored the distinction between the velocity of an individual molecule and average velocity per molecule. Another question asked the students explicitly what a thermodynamic variable meant to them. It was rather surprising to note that some students said that any microscopic quantity describing the system is a thermodynamic variable. The correct answer that thermodynamics variable is a macroscopic quantity having a bearing on the internal state of the system, was given only by few students which might have even come through as a random choice. From the responses to another question, it seemed that for some students, equilibrium is "no change in time". So, they felt that in equilibrium not only the macroscopic but also microscopic variables do not change in time.

Confusion between adiabatic and diathermic walls: In one of the questions, the students were asked to categorize materials according to their suitability for adiabatic or diathermic wall. The materials given were plastic, glass, brass, paper, rubber, concrete, diamond, aluminum, gold and Teflon. Out of these, brass, diamond, aluminum, are suitable as diathermic and the others are suitable as adiabatic. This categorization activity brought to my notice the confusion that students had. Students relied heavily on their daily experiences while categorising the materials (For example, "in summer, concrete roof becomes hot… (which) makes us feel hot…" or another example is "… coffee feels hot through glass…".).

In both these examples, students should have considered the thermal conductivities of concrete and paper, which are very low. It is necessary to understand that for an adiabatic wall these low thermal conductivity materials will take longer time to pass heat through it as compared to diathermic materials like aluminum or brass. Having this practical sense of adiabaticity was absent in students' understanding.

Object size and thermal equilibrium: Students were given a situation in which two wooden cubes of different sizes (27 cm^3 and 125 cm^3 both initially at room temperature), were kept in a hot air constant temperature enclosure (maintained at 70°C) for a few hours. They were asked to comment on the temperature attained by each cube. A good percentage of them agreed that both the cubes attain a steady temperature but they felt that the temperature attained by each cube would be different. A sizeable number of students felt that the smaller cube will attain a higher temperature than the bigger cube.

Material of the object and thermal equilibrium: Students were given a situation similar to that given above with two cubes of equal sizes but different materials (copper and wood). The cubes were initially at room temperature and then transferred to a hot enclosure at 70°C and kept there for a sufficiently long time. Majority of students replied that the temperature attained by the copper cube would be greater than the temperature attained by the wooden cube as the thermal conductivity of copper is greater than that of wood. Only a small minority opted for the correct option that both the cubes will attain the same temperature as that of the enclosure. Students seemed to feel that since the rate of increase of temperature of copper will be higher than that of wood, the temperature attained by it will also be higher.

Effective temperature of the mixture: For a question, on the final temperature of mixture of two identical samples of liquid initially at different temperatures (34°C and 96°C), a very small number of students gave the correct answer (65°C). Almost an equal number of students gave the difference of two initial temperatures (62°C) as the answer.

4.3 First law of thermodynamics

I observed in the pilot study that for students, the first law is not more than a qualitative statement of the law of conservation of energy. They were unable to state and explain different energy terms involved in the law. A multiple choice test was prepared and administered to a sample of 135 undergraduate students. I decided to limit to the cases of adiabatic compression ($Q = 0$) and isothermal ($dU = 0$) compression processes leading to simple situation where only two energy terms become non-zero. Further both the adiabatic and isothermal processes are important processes by themselves in elementary thermodynamics. The students' responses were categorized separately for: temperature, heat, internal energy and sign convention. Students' written explanations for the selection of their choice to the items, supported by semi-structured interviews, are presented below.

Heat and Temperature: Students said that since in an adiabatic process, there is no transfer of heat, there should be no temperature change (Barbera 2009, Kautz et al. 2005a). Similarly, since the word isothermal means that the temperature remains constant, for many students there was no heat transfer either. They seemed to know that heat and temperature are not identical but intuitively took them to be inseparable. Among the arguments provided by the students, those based on the ideal gas equation were found to be quite common (Leinonen, Asikainen, and Hirvonen 2011). The students interpreted the ideal gas equation to mean that the increase in pressure due to compression, whether isothermal or adiabatic, would always be accompanied by an increase in temperature (Barbera 2009, Kautz et al. 2005a).

Internal energy: Students stated that in isothermal compression, as the work was done on the system, the 'heat content' of the system increased. They seemed to consider 'heat content' equivalent to internal energy (Meltzer 2004, Van Roon, Van Sprang, and Verdonk 1994, Loverude, Kautz, and Heron 2002). Some students said that since there was no heat transfer in adiabatic compression, the change in the internal energy would be zero (Meltzer 2004, Loverude, Kautz, and Heron 2002). I found that, for some students, in adiabatic compression, the internal energy of the system decreased. For them, there was some kind of 'natural' dissipation of internal energy over time and since there was no heat transfer, the internal energy did not get replenished. In the case of isothermal compression, many students predicted that the internal energy of the system would decrease. Perhaps they thought that since the system was open to heat transfer, as the piston moved 'heat was driven out of the system (Meltzer 2004, Van Roon, Van Sprang, and Verdonk 1994, Loverude, Kautz, and Heron 2002). Students seemed to be unaware about the fact that the change in the internal energy can be brought about by processes not only due to heating but also by the external work done on the system. Many students showed lack of awareness about how internal energy and temperature were related (Barbera 2009). Nowhere they used the argument that the gas in the container has been stated to be ideal and that for an ideal gas, the internal energy is dependent only on the temperature. Thus I thought that students' confusion about heat-internal energy equivalence affected their perception of work done as energy transfer mechanism.

Sign convention: The students seemed to be unsure of where to apply positive or negative sign to the work and heat terms in the first law of thermodynamics (Barbera 2009, Loverude, Kautz, and Heron 2002).

4.4 Heat transfer mechanisms

A short answer type situation-based questionnaire was prepared and then administered to a sample of 57 undergraduate students in which the students were supposed to label the situations presented as conduction, convection or radiation and justify their choice. I describe, below, students' prototypical explanations in each case (conduction, convection and radiation) (Pathare and Pradhan 2010).

1. *Conduction*: Students considered heat as a fluid. A typical response from one student: "…the hotness of the heated rod of the metal "expands" as there is space for expansion on the other side of the rod. .."

2. *Convection*: In natural convection, students attributed hotness to single molecules. A typical response from one student: "…cooler water molecules are heated by the warmer water molecules..."

The hot air blower is an example of forced convection. Most students did not realize this fact and reported this phenomenon as conduction. Since the hot air cannot be seen by the eyes and the hands at a distance are dried by the hot air blower, some students relate this phenomenon to radiation emanating from the blower.

3. *Radiation*: Students felt that heat transfer due to radiation necessarily needs a medium. A typical response from one student: "…There is some medium between the earth and the Sun and heat is transferred from the Sun to the earth by the molecules of this medium…"

4.5 Conclusions

From this study, students' difficulties can be summarised as follows:

1. Students do not distinguish between heat and temperature.

2. Students have difficulty in relating internal energy and temperature.

3. Students consider heat and internal energy to be equivalent.

4. Students disregard the external work as a mechanism by which the internal energy can be changed.

5. Students have difficulty in understanding the energy terms in the statement of the first law of thermodynamics.

6. Students think that the equilibrium temperature of objects, kept in a constant temperature enclosure, depends on size and material of the objects.

7. Students consider heat as a fluid while explaining the process of conduction.

8.In case of natural convection, students attribute hotness to a single molecule.

9.In case of artificial convection, some students confuse it with conduction and some students can not distinguish convection from radiation.

10. Students feel that heat transfer due to radiation necessarily requires a medium.

I observed that students' difficulties (statements 7 to 10) in the topic "heat transfer mechanisms" are rather disjoint from those listed in statements 1 to 6 pertaining to the first three topics. I felt that it requires separate study for the topic of heat transfer mechanisms and therefore it was not pursued further. Students' difficulties in the first three topics formed a basis for the further work on developing the activity-based modules.

Chapter 5: Module on Thermal Equilibrium

Developing activity-modules for all the alternative conceptions discussed in Chapter 4, would have required considerable time and therefore I decided to limit the development to only two of the areas, namely, thermal equilibrium and the first law of thermodynamics. This chapter discusses the activity-based module on thermal equilibrium.

5.1 Development of instrumentation

One of the important aspects of the activities in the modules was the measurement of the parameters such as temperature, heat flow and liquid flow.

Temperature: For the range of temperatures that were required to be measured, a chromel-alumel thermocouple already available in the laboratory was quite suitable.

Heat flow indicator: I used a Peltier device, which is available in the market as a cooling device in electronics, as a heat flow indicator in its thermoelectric generator mode (McKinnon et al. 2010).

Liquid flow indicator: I developed in-house a low-cost liquid flow indicator using commonly available materials like plastic tube and ball pen refill springs. Later, during the development of the module on the first law of thermodynamics, a low-cost liquid flow sensor based on Hall effect was procured from the market.

5.2 Development of the module

The apparatus and software developed for this module are: (a) constant temperature water bath with stirrer, (b) as the increase in temperature in one of the activities was rather quick, data interfacing unit was developed for recording temperature variation, (c) LabView interface for observing comparative temperature variation, (d) a container with two compartments separated by a graphite (diathermic) wall and fitted with two thermocouples and a heat flow sensor.

My work indicated that students had difficulties in predicting the final temperatures of blocks of different material but same sizes as well as blocks of same material but different sizes, immersed in hot water bath. I, therefore, decided to design an activity, to show the real time variation of temperature of the blocks from their initial to final values when they were placed in a constant temperature enclosure. The variation was compared i. when the blocks are of different materials but of same size and ii. when they are of different size but of same material. The activity module development went through 4 iteration cycles. These activities were tested for their effectiveness by administering them to a different samples of students in each cycle.

5.2.1 Cycle 1

Activity 5.1: Thermal equilibrium between two cylinders

The apparatus consisted of two copper blocks of different sizes and similarly two wooden blocks of different sizes, a constant temperature water bath, chromel alumel thermocouples to monitor the temperatures of blocks and the water bath, a data-interfacing unit to feed the outputs of these thermocouples to a desktop computer. The LabView interface showed the temperature variation corresponding to the large copper block, the large wooden block, the small copper block, the small wooden block and the water bath.

This activity was administered to a group of 25 undergraduate students using POE approach. Informal interviews were conducted to understand students' written responses.

It was observed that after the post-test, 13 (out of 25) students were still of the opinion that the copper block would be at a higher temperature than the wooden block. At this point the students' responses were analyzed and following problems were identified as possible reasons of students' incorrect responses.

1. Six separate windows for showing the temperature variation made it difficult for students to compare the temperatures.
2. Some students took even small temperature differences (even of the order of 0.1°C) between the blocks (arising due to small fluctuations in the water bath temperature or problems in thermocouple calibration) as genuine temperature differences between the blocks and concluded that the two blocks would be at different temperatures at all times.
3. Wood being a porous substance, water would enter into the block through the pores and this resulted at times in a faster temperature rise for the wooden block.

5.2.2 Cycle 2

In Cycle 2, I improvised the activity with respect to the problem areas identified.

1. The wooden block was replaced by a delrin cylinder because delrin is both, insulating and non-porous. Further, the copper block was replaced by a brass cylinder as brass is a softer material and allows ease in shaping the cylinders of required size.
2. The plots of temperature variation were combined in pairs as:

i. Window 1: Big brass cylinder and big delrin cylinder (different materials)

ii. Window 2: Big delrin cylinder and small delrin cylinder (different sizes)

3. The displayed least count was increased from 0.1°C to 1°C so that the small fluctuations in temperatures (less than 1°C) were smoothened. All the thermocouples were calibrated,

using the slider on the interface, to show the same temperature.

This modified version of activity was administered to another group of 25 undergraduate students. It was observed that the majority of students stated that both the cylinders should finally attain the temperature of the water bath. During the interview sessions, when asked the students said that two bodies would be at thermal equilibrium if their temperatures were equal. On further probing, some of them mentioned that since there is no instrument to measure heat flow, its role with respect to thermal equilibrium is not known. Such answers indicated that it was important to introduce students to the relationship between heat flow and thermal equilibrium.

5.2.3 Cycle 3

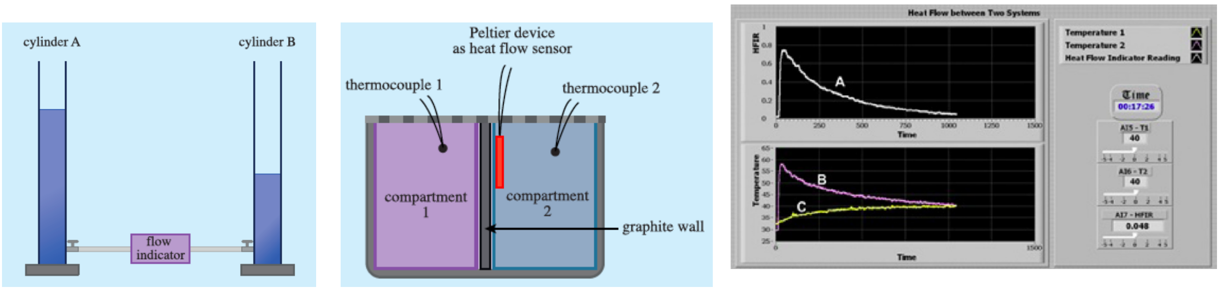
I began with a liquid flow analogy to enable students to understand thermal equilibrium by extending the concepts in hydrostatic equilibrium to thermal equilibrium. The reason for choosing the liquid flow analogy is that the students are familiar with the concepts of liquid flow and hydrostatic equilibrium from their school days and from everyday experience. For thermal equilibrium, I used two compartments separated by a diathermic wall, with a Peltier device attached to the wall, as heat flow indicator.

Hydrostatic equilibrium between two hydrostatic systems is characterized by net liquid flow being zero. Similarly, thermal equilibrium between two systems is characterized by zero net heat flow between them. For simplicity I have taken the hydrostatic systems to be two liquid containers connected with a pipe. In hydrostatic equilibrium, the heights of the liquid columns measured from a common reference point in the two containers are equal. For thermal equilibrium the quantity corresponding to height (in hydrostatic equilibrium) is temperature.

Activity 5.2: Liquid flow model of thermal equilibrium

In this activity, two 250 ml measuring cylinders, A and B, were filled up to different levels initially (figure 5.1a). Cylinder B was covered so that the level of water was not seen. The flow control valves were then opened, allowing flow between the two cylinders as indicated by the flow indicator. When the flow stopped the cover of cylinder B was removed. The students were asked to predict the level of the water columns in cylinders A and B, before cylinder B was uncovered.

Most of the students predicted rightly that the heights of the water column in the cylinders would be equal.



(a) Liquid flow model

(b) Heat flow model

(c) LabView interface - heat flow model

Figure 5.1: Liquid flow and heat flow model

Activity 5.3 Heat flow model of thermal equilibrium

The apparatus used in this activity consisted of two compartments separated by a diathermic wall in the form of a graphite sheet (figure 5.1b). The heat exchange through the diathermic wall was monitored using the Peltier device used as a heat flow indicator (McKinnon et al. 2010). Compartment 2 was filled with water at room temperature and compartment 1 with water at 60°C. The output terminals of thermocouple 1, thermocouple 2 and the heat flow sensor were connected to a data acquisition system. The output of thermocouple 2 was not shown to the students. They were asked to predict the final temperature of the water in compartment 2. They were also asked to predict, by drawing, the nature of the graphs for variation in the outputs of thermocouple 1, thermocouple 2 and the heat flow sensor.

Most of the students could see the correspondence of the heat flow in this activity to the liquid flow in activity 5.2. The nature of the graphs drawn by them was correct. They also predicted that the temperature of the water in compartment 2 would be equal to the temperature of the water in compartment 1 as the heat flow sensor reading reached zero. Students were then shown the activity. Figure 5.1c shows the output screen of this activity. The upper graph (graph A) showed the output of the heat flow indicator. The lower graph showed the outputs of the thermocouples in compartment 1 (graph B) and compartment 2 (graph C), respectively.

The students were asked to explain the nature of graphs A, B and C. From their explanations, it was clear that they understood that as the heat flow between the two systems approached zero, thermal equilibrium was established. At this point the temperatures of water in the two compartments were equal. Since the students were exposed to both the liquid and the heat flow models, they were asked to match the concepts from the two

Liquid flow model	**Heat flow model**
Liquid flow	Heat flow
Control valve in closed state	Adiabatic wall
control valve in the open state	diathermic wall
liquid flow rate	heat flow rate
height of the liquid column	temperature

Table 5.1: Concept matching between two models

models (Table 5.1). Most of the students could relate the concepts from one model to the other.

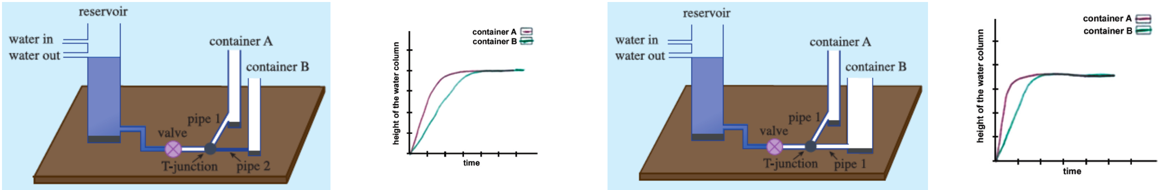
Activity 5.4 Liquid flow analogy of activity 5.1

For hydrostatic equilibrium, the instantaneous rate at which the hydrostatic equilibrium is attained, that is, the rate at which the height difference between the liquid levels in the cylinders reduces, depends on the instantaneous height difference itself (activity 5.2). The height difference here decreases exponentially with a characteristic time constant. The larger the time constant, the slower will be the attainment of equilibrium. In the hydrostatic equilibrium the time constant depends on the parameters of the flow tube, namely, its length (l), the radius of cross-section (r) and the viscosity of the liquid (η). By analogy, the rate of attainment of thermal equilibrium at any instant will depend on the instantaneous temperature difference between the two systems exchanging heat. In case of thermal equilibrium, the time constant thus involves the thermal conductivity, the specific heat and the density of the object (material factors) and also size of the object. In this activity, a measuring cylinder (1000 ml) used as a reservoir, had the water level in it maintained at a constant value. This is analogous to the hot water bath maintained at a constant temperature in activity 5.1. In this activity the reservoir was connected to two cylindrical containers through connecting pipes. The two parameters that were varied to change the time constant for attaining hydrostatic equilibrium are (a) the radius of the cross-section of the connecting pipe (part I), and (b) the base area of the receiving container (part II).

Part I: Studying effect of the radius of cross-section of the connecting pipes

In this part, two containers of equal volume (500 ml) were connected to the reservoir through connecting pipes of equal length but of different radii of cross-section. Container A was connected using a pipe of inner radius of 5 mm and container B using a pipe of inner radius 1.5 mm (figure 5.2a). The students were asked to predict, by sketching the graphs for the rise of water levels in both containers when the water was allowed to flow from the reservoir to the containers.

Most of the students could correctly predict that the level in container A would rise faster than the level in container B and finally the levels in both containers would be equal to the level in the reservoir (figure 5.2b).



(a) Schematic diagram of the apparatus - Part I

(b) Student's drawing - Part I

(c) Schematic diagram of the apparatus - Part II

(d) Student's drawing - Part II

Figure 5.2: liquid flow model of main activity

Part II: Studying effect of the base area of the receiving container

In this part, the two containers A and B were of different base area (the diameter of the base of container A was 4.3 cm and that of container B was 6.9 cm). They were connected to the reservoir through connecting pipes of equal length and equal radius of cross-section (5 mm) (figure 5.2c).

Students could correctly predict the nature of the graphs, considering the effects of base area on the rise of water levels in containers (figure 5.2d). After the activity, on being asked, students could find a similarity between activities 5.4 and 5.1. They could infer from what they observed in this activity that the time constant in activity 5.1 would depend on the material and the size of the object kept inside the enclosure. On further probing, during the interviews, students said that the situation in figures 5.2a and 5.2b would correspond to blocks of same size but of different thermal conductivities in Activity 5.1. Similarly, they said that the situation in figures 5.2c and 5.2d would correspond to blocks of same material but of different sizes in Activity 5.1.

In order to further test their understanding about thermal equilibrium, I added another activity-based post-test.

5.2.4 Activity on method of mixtures

I developed an extension activity to test students' understanding developed through the above four activities. Students were presented with a situation in which two substances with different specific heats and maintained at different temperatures are brought in contact with each other. A brass cylinder (19.7 g) was kept in a kettle in which the temperature of the contents (water and the brass cylinder) was maintained at 85°C. The brass cylinder was then taken out from the kettle and immersed into the water (20 ml water initially at room temperature) in the test tube. The water was continuously gently stirred. The students were asked to predict how the temperatures of the brass cylinder and the water in the test tube would change. Majority of the students could predict correctly that the brass cylinder would lose heat and its temperature would decrease and the water would gain heat and its temperature would increase. They also predicted that the final temperature attained by both would be the same and this would be intermediate between their initial temperatures. Their prediction was confirmed by the activity.

During the development of cycle 3 and 4, 41 students (first and second year undergraduate students) from 3 different colleges in Mumbai were administered the entire module (including modified activity 5.1).

I decided to finalize the module with these 5 activities (Activities 5.1, 5.2, 5.3, 5.4 and 5.5) including the questionnaires and the activity sheets.

5.3 Implementing the module

I selected a sample of students from the first and second year of the bachelors' programme of science colleges in Mumbai, India. The control group with 131 students was administered only the tests and were not exposed to the activities.

The final version of the module was administered to a sample of 112 students (experimental group) from different colleges in Mumbai.

Figures 5.3 and 5.4 summarize the students' pre- and post-test responses for control and experimental groups for material dependence and for size dependence.

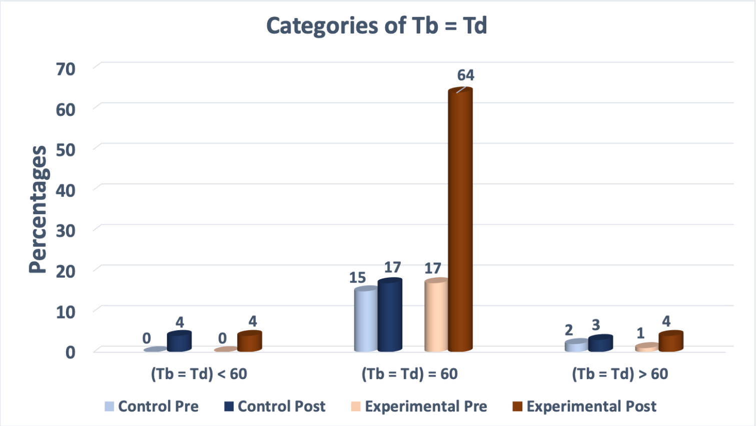


Figure 5.3: Percentage of students' responses for material dependence

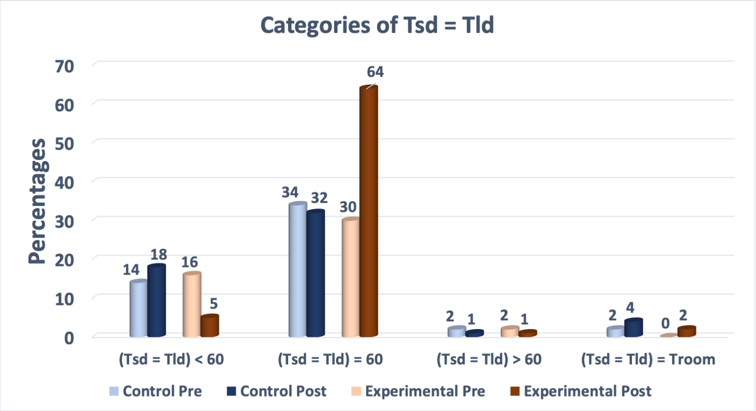


Figure 5.4: Percentage of students' responses for size dependence

5.4 Results and discussion

Out of 112 students, initially (in pre-test) only 17% answered that both delrin and brass cylinders would attain the temperature of the water bath which increased to 64% in post-test. In the case of size dependence, the percentage of students giving correct response increased from an initial 30% to a final 64%. In the activity on method of mixtures, 83% students could predict correctly that two bodies, initially at different temperatures, when brought together and allowed to exchange heat, would come to thermal equilibrium with a final temperature intermediate between the two initial temperatures.

I also scored the tests with each correct answer carrying one mark and incorrect answer, carrying zero. The total scores, for both pre and post-tests, material dependence and size dependence were obtained for each student. The mean scores were calculated for control and experimental groups for both, material and size dependence. I compared the pre-test mean scores of the control and the experimental groups by an independent sample t-test (Garrett, 1981). The t-test scores confirmed that the two student groups were equivalent for both material and size dependence. I compared the pre- and post-test mean scores of both the control and the experimental groups using a correlated means t -test (Garrett, 1981). For the control group, the mean scores did not differ significantly even at 5% level. For the experimental group the mean scores differed significantly even at 1% level. Thus, I can infer that the implementation of the activity module improved the performance of students from the experimental group, in the post-test.

Chapter 6: Module on First Law of Thermodynamics

The current chapter is about the development of activity module for first law of thermodynamics. In the earlier study, I found that most of the difficulties of the students pertained to the nature of and relations among heat, temperature and internal energy. I, therefore, developed activities to explain the role of heat, work and internal energy in the first law of thermodynamics as applied to adiabatic and isothermal processes (Pathare, Huli, et al. 2018).

6.1 Development of the module

The module was standardized through 3 iteration cycles of development. It includes pre and post-tests to check the students' understanding of the law along with the designed activities. The activities were implemented using POE approach. In Cycle 1, I developed the apparatus of adiabatic and isothermal processes which replicated the pre-test situations. In cycle 2, the apparatus for both the processes was modified and a heat flow indicator was used to make the heat flow visible. In cycle 3, fire syringe was used to demonstrate and quantify the adiabatic process and a steel cylinder of larger dimension was used in isothermal process.

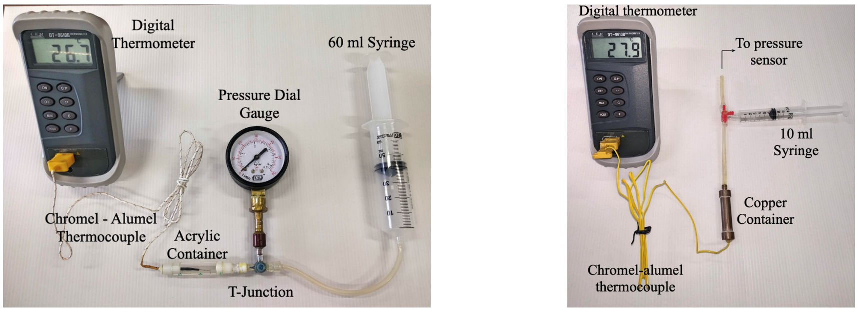
6.1.1 Cycle 1

Cycle 1 describes activities on the adiabatic and isothermal processes which were tested with 37 undergraduate students from two colleges in Mumbai.

Adiabatic process

In adiabatic process, since $Q = 0$, the activity aimed to show students that the work done on the system can change the internal energy of the system. The set-up involved an insulating container made up of acrylic, connected to a plastic syringe through a silicon tube. The container was fitted with a chromel-alumel thermocouple for the measurement of temperature of air inside the container and a pressure dial gauge for pressure measurement (Figure 6.1a). In order to achieve adiabaticity, the piston of the syringe was pressed swiftly. Students were asked to record the pressure and temperature of air before and after the compression process in the activity sheet. The corresponding change in the volume also was noted as the syringe was calibrated for volume. The graph of pressure against volume for the syringe obtained by the researcher was provided to the students so that they could calculate the work done by measuring the area under the curve.

Students realized that work done on the system resulted in change of temperature of the air in the syringe. They were aware that for an adiabatic process the heat flow is zero.



(a) Adiabatic process (b) Isothermal process

Figure 6.1: Apparatus for adiabatic and isothermal processes

During the interview, I found that majority of the students were unaware of the relation between the change in temperature and the change in internal energy. Hence, they could not relate the work done on the system to the change in internal energy of the system. When asked to calculate the change in temperature by equating the work done on the system to the change in internal energy of the system, students observed a much smaller change in temperature during the actual activity than the expected. On closer inspection, I found that this was due to an air leakage through the T-shaped silicon pipe which connected syringe, acrylic tube and pressure gauge (Figure 6.1a).

Isothermal process

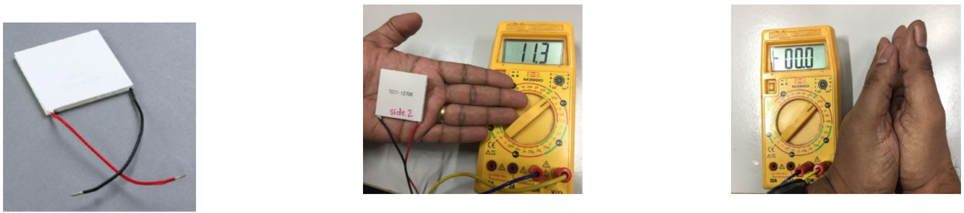
In this activity, I wanted to show that since $\Delta T = 0$ (implying $\Delta U = 0$) the work done on the system would result in the heat flow. A metallic container made up of copper was connected to a plastic syringe through a silicon tube. The container was fitted with a chromel-alumel thermocouple for measurement of the air temperature inside the container (Figure 6.1b). A digital pressure sensor set up (Motorola IC, MPXM2010) was assembled in the laboratory for measurement of the air pressure in the container. Students were asked to press the piston of the syringe very slowly in such a way that the air inside the container remained at a constant temperature. They were asked to note the pressure-volume observations in the activity sheet. A graph of P against V was provided to the students as in the adiabatic case. This allowed them to calculate the work done in the compression process by the area under the curve. They were also provided with the necessary formula in the activity sheet for the work done in the isothermal process. The students could understand the isothermal process in practice when they found that the temperature of air inside the container remained constant when the piston was slowly pushed in. They noticed from their calculations in the activity sheet, that the work done was non-zero, but the change in temperature was zero. During the interview, however, they could not infer that the internal energy remained constant and majority of them were confused about what happened to the heat flow, as the heat flow in or out of the system was not visible. Most of the students still equated the internal energy as *heat of the system*. The activity was unable to explain the relation between change in internal energy and the change in temperature of the system in the processes. The students found it difficult to remain consistent with the sign convention in respect of the work done and heat flow in the expansion or the compression process.

6.1.2 Cycle 2

With respect to observed difficulties in cycle 1, the following modifications were made.

1. *Activity on familiarizing with the heat flow indicator*:

I provided, to the students, a Peltier device in this activity to make heat flow observable (Figure 6.2a). The Peltier device generates voltage across its terminals proportional to the temperature difference between its two surfaces, indicating the heat flow through the device.



(a) Peltier device as heat flow indicator

(b) Voltmeter reading with one palm touching the device on one side

(c) Voltmeter reading with both palms touching the device each one on one side

Figure 6.2: Peltier device as heat flow indicator

Students were asked to touch a specimen device only on one side by their palm and note the voltage (Figure 6.2b). This voltage reversed when the palm touched the other side of the device. When they pressed both the sides of the device with their palms, the voltage indicated was almost zero (Figure 6.2c). Thus, the voltage across the device was a measure of the net heat flow through it.

A Peltier device was used as an indicator of heat flow, both in adiabatic and isothermal processes. Students were asked to note their observations in the activity sheets.

2. *Information sheet on internal energy – temperature relation and sign convention*:

In this cycle, an information sheet was provided to the students explaining to them what internal energy was and how change in internal energy ΔU is related to ΔT for an ideal gas. Also, they were reminded of the sign conventions for heat and work done.

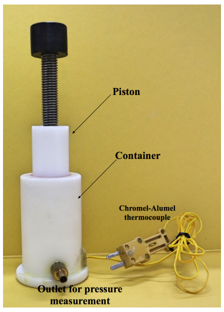


Figure 6.3: Modified piston-container

3. *Air leakage problems*:

For the adiabatic process, the acrylic container used in Cycle 1 was replaced by a Delrin container and piston (Figure 6.3)which reduced the number of connecting parts and their joints, considerably reducing the air-leakage. Additionally, the analog pressure sensor was replaced by a digital pressure sensor which measured the intermediate values of the pressure from a minimum to maximum. The heat flow indicator was attached to the wall of the Delrin container. For carrying out the adiabatic compression, the piston was pressed swiftly by hammering it. The entire process was video recorded such that the piston displacement, pressure and temperature readings were clearly visible in video frame and their values at any instant could be measured using TRACKER software (https://physlets.org/tracker/). Students were also asked to note the change of temperature of air in the container and they were asked to calculate the work done in the activity sheet for the plotted PV graph.

For carrying out the isothermal compression, the apparatus used for isothermal compression in Cycle 1 was not changed except the addition of the heat flow indicator. The activity module with these activities were given to 28 undergraduate students from a college in Mumbai. Due to the information sheet students could use the internal energy – temperature relationship in their explanation of the processes. They could apply the appropriate signs to work done in both adiabatic and isothermal processes.

Heat flow indicator played an important role in understanding the presence or absence of heat flow. Students could clearly see $Q = 0$ for the adiabatic process. But some students also mentioned that since $Q = 0$, the change in the internal energy should also be zero. When reminded of the internal energy-temperature relationship (information sheet)), students, during the interview, said that change in temperature of air should also be zero. But what they observed in the activity was a finite temperature change. They were not able to resolve this discrepancy. Some students, in the interview, justified their "zero temperature change" response by saying that without heat flow, no change in temperature can take place and work done on the system by itself cannot change the temperature of the system. They argued that the observed change in temperature was some kind of experimental error.In spite of the changes made in the design of the piston-container assembly for the adiabatic process, the expected temperature change corresponding to work done could not be achieved during the process.

In isothermal compression, students could see that the temperature of air inside the container remained constant. But students could not observe any noticeable heat flow reading and hence some of them mentioned that as there is no temperature change heat flow is zero. This was possibly because of lesser contact between the surfaces of small sized cylindrical container and the flat shaped heat flow indicator. Therefore, at the end of cycle 2, students still could not differentiate between heat and internal energy in adiabatic process and also could not relate work done with heat flow in isothermal process.

6.1.3 Cycle 3

Based on the problems faced in cycle 2, I modified/added activities in cycle 3. Activity on familiarizing with the heat flow indicator from cycle 2 was retained as the first activity along with familiarisation with digital thermometer. These modified activities were administered to 66 students (a typical group size $\sim$ 15 students). The changes introduced in cycle 3 are as follows.

1. Understanding work done as a mechanism by which internal energy can be changed:

In this task, I built an analogue of Joule's apparatus in which a stirrer was rotated not by falling weights but by a DC motor (figure 6.4). This task was developed to address following alternative conceptions i) in the adiabatic process no heat transfer corresponds to no change in temperature, ii) heat— internal energy equivalence. The activity demonstrated that the internal energy of the system can be changed even in the absence of heat transfer and it can be seen as the change in the temperature of system. This change is brought about by work done. The apparatus consists of the plastic container surrounded by Teflon sheets. The lid of the container is fitted with a specially designed stirrer and a high-speed DC motor. The container is filled with water at 16°C.

The temperature of water was measured by inserting a thermocouple in the water. A heat flow indicator was attached externally to the walls of the container to display adiabatic nature of the container.

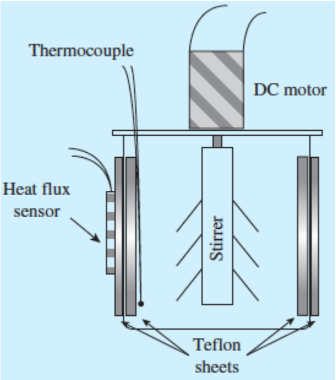


Figure 6.4: Work done as mechanism by which internal energy can be changed

The students observed that the temperature of the water increased as it was stirred. But the heat flow sensor showed no heat transfer. The students realized that even if the net heat transfer between water and surrounding was zero, the temperature of the water could be changed. Students appreciated that the stirrer did work on the water and in this process, energy would be gained by the water. At this point students were reminded of the first law of thermodynamics and internal energy - temperature relation. During the interview, students said that since there is no heat flowing into the system, the energy pumped in due to work done has to result in change in internal energy. At this point they seemed to realize that the work done is also an energy transfer mechanism responsible for changing the internal energy of the system.

2. Adiabatic compression – achieving expected temperature change

In order to achieve the expected temperature change in the adiabatic compression, it was necessary to build an apparatus which is frictionless as well as free of leakages. I used a fire syringe (Jackson and Laws 2006) instead of a Delrin piston-container assembly. Prior to the fire syringe activity, another activity (a) for helping the students to appreciate the variation in temperature generated due to the varying speeds of piston was introduced.

a. Getting introduced to the adiabatic process: I used a 25 ml plastic syringe, a chromel—alumel thermocouple and a digital thermometer. The piston was pulled out to 25 ml mark. The thermocouple was inserted from the open end of the syringe. The open end was then closed tightly with thumb. The piston was pushed with varying speeds and the corresponding temperature changes were to be observed and noted in the activity sheet.

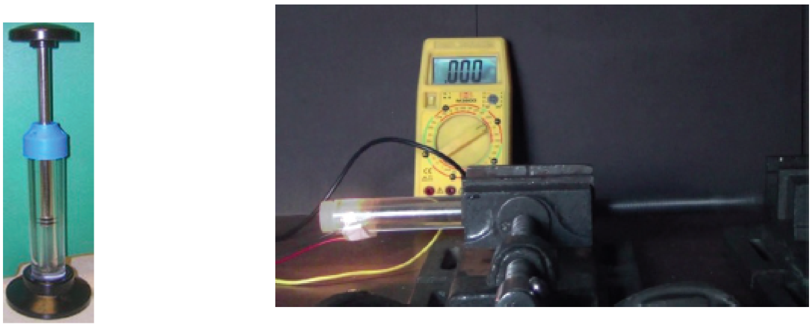
Followed by the activity, I introduced a discussion session to understand what can make a process adiabatic, in practice. The discussion started with the equation of the Fourier law of heat transfer, namely,

$$dQ = (kA\frac{dT}{dx})dt \tag{6.1}$$

where, dQ/dt is the rate at which heat is transferred, k is the thermal conductivity of the syringe wall, A is the surface area of the syringe available for heat transfer, dT is the temperature difference between air inside the syringe (system) and the air outside the syringe (surrounding), dx is the thickness of the syringe wall.

Since in equation (6.1), the proportionality constant $(kA\frac{dT}{dx})$ is finite, it is obvious that if dt is small, then dQ will be small too. As a result, by making dt to be small, the process can be made adiabatic, which means that the process should be carried out very rapidly.

b. Activity using Fire syringe: A fire syringe (Figure 6.5a) is a thick walled transparent acrylic cylinder with a snug–fit piston. A small cotton piece is placed at the bottom of the syringe. When the piston is pushed, the air inside the cylinder gets compressed resulting in an increase in its internal energy and temperature. If the piston is pushed with a sufficiently high speed, the temperature increase is sufficiently high to burn the small piece of cotton. The low thermal conductivity of the acrylic cylinder walls allows practically no heat transfer over this time interval.



(a) Fire syringe

(b) Adiabatic compression with heat flow reading displayed

Figure 6.5: Adiabatic process - using fire syringe

c. Quantification of fire syringe activity: In order to give students a quantitative idea for the fire syringe demonstration, I fitted a spring over the piston. This modified fire syringe was tightly held in a bench-vice. The spring-piston was stretched and held in another bench-vice. A heat flow indicator was attached to the external wall of the acrylic container of the fire syringe. When the piston was released, a glow due to cotton-burning was observed (figure 6.5b).

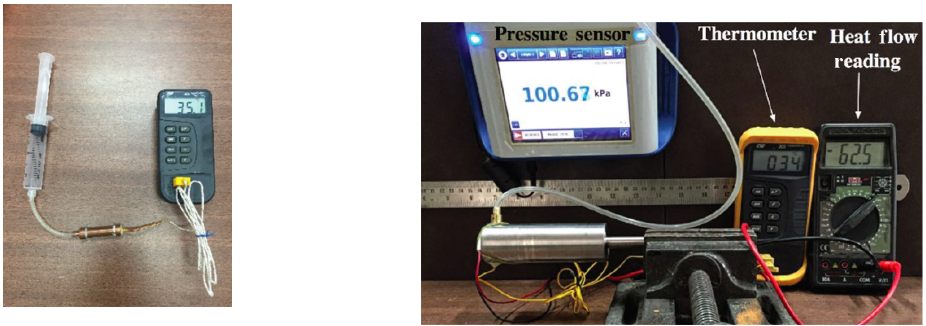
A video of this process was recorded. I asked 15 students to measure the piston positions using TRACKER and after multiplying the net piston displacement by constant area, calculate the change in volume of air during compression. They were asked to calculate the work done using this volume change and equate it to the internal energy of the ideal gas and determine the temperature of cotton plug when it catches fire (Mungan 2003, Guemez, C. Fiolhais, and M. Fiolhais 2007). The calculated value for temperature of burning of cotton was consistent with auto-ignition temperature range for cotton (Lewin 2007). For the later batches of students, explaining them the procedure used, I only showed and discussed these calculations.

Students noted in the activity sheet that the process needs to be carried out very quickly to make it adiabatic. In the fire syringe activity, students observed the cotton burning in the process. The observation indicates considerable change in temperature. On being asked in the interview, students explained that the only source of energy that would generate this high temperature would be the work done during compression. They were reminded of the first law $Q = \Delta U + W$. Q being zero $\Delta U = -W$. Further they stated that since temperature change is proportional to internal energy change, the internal energy of the system increased. Unlike the activity on adiabatic compression from Cycle 1 and Cycle 2, this activity convinced students about the magnitude of work done in the process matching with the change in the internal energy of the system.

3. Isothermal compression

a. Getting introduced to isothermal compression: In this task, students were given a small, hollow, thin walled copper cylinder with a thermocouple already inserted in it (Figure 6.6a). A 10 ml syringe was connected to a small opening on the copper cylinder using a tube. Students were asked to press the piston with varying speeds and note the change in temperature of the air in the cylinder and check for the speed necessary to keep the temperature constant.

b. Observing heat flow reading in the isothermal compression: I replaced the small copper container with a bigger steel cylinder with a snug-fit piston (Figure 6.6b). The heat flow indicator was attached to the base of the steel cylinder as it ensured larger surface contact with the heat flow indicator. A thermocouple was inserted in the cylinder. A pressure sensor was also attached to measure the pressure of the air inside the cylinder during this process (Figure 6.6b). The cylinder was then pushed slowly (by holding the piston in a vice). For avoiding heat conduction by contact with hands, a non-conducting acrylic pipe was used to push the cylinder. A video of this activity was recorded and was shown to the students. Using discussion about heat conduction(equation 6.1), the students stated in the



(a) Understanding isothermal compression

(b) Complete set up for isothermal process

Figure 6.6: Isothermal process

activity sheet that to maintain the temperature of the system constant, the process should be carried out at an adequately slow rate to allow necessary heat transfer. Students also observed that during the compression, the heat flow indicator showed a negative reading. At this point they were reminded of the first law $Q = \Delta U + W$. They could infer that the heat is transferred from system to surrounding while work is done on it. ΔU being zero $W = Q$. At the end of Cycle 3, I finalized the module with following activities:

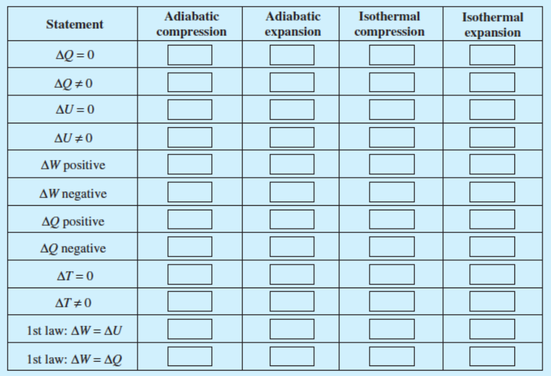
Activity 6.1	Familiarizing with digital thermometer and heat flow sensor
Activity 6.2	Work done as a mechanism by which internal energy can be changed
Activity 6.3	Adiabatic compression
Task 1	Getting introduced to the adiabatic process
Task 2	Fire syringe activity
Task 3	Quantification of the fire syringe activity
Activity 6.4	Isothermal compression
Task 1	Getting introduced to isothermal compression
Task 2	Isothermal compression – activity through video

Table 6.1: Final activity sequence in the module

The pre and post-tests

The pre-test consisted of 10 multiple-choice questions. The first five questions were for adiabatic compression. The other five questions were similar questions for isothermal compression except the difference that for adiabatic process it was mentioned that the piston and the walls of the container do not allow heat transfer whereas for isothermal process they freely allow heat transfer. Also, for the isothermal case it was mentioned that the temperature of the gas was constant and the piston was moved down slowly. The students were asked to predict changes in temperature, pressure and internal energy during the processes and also sign convention for heat transfer and work done.

The post-test consisted of 20 questions: (i) 10 identical questions on compression as the pre-test, (ii) 10 similar questions on expansion and (iii) Table completion task (figure 6.7).



Statement	Adiabatic compression	Adiabatic expansion	Isothermal compression	Isothermal expansion
$\Delta Q = 0$	☐	☐	☐	☐
$\Delta Q \neq 0$	☐	☐	☐	☐
$\Delta U = 0$	☐	☐	☐	☐
$\Delta U \neq 0$	☐	☐	☐	☐
ΔW positive	☐	☐	☐	☐
ΔW negative	☐	☐	☐	☐
ΔQ positive	☐	☐	☐	☐
ΔQ negative	☐	☐	☐	☐
$\Delta T = 0$	☐	☐	☐	☐
$\Delta T \neq 0$	☐	☐	☐	☐
1st law: $\Delta W = \Delta U$	☐	☐	☐	☐
1st law: $\Delta W = \Delta Q$	☐	☐	☐	☐

Figure 6.7: Table completion task

Table completion task

Following the post-test, a table-completion task was administered to check the overall understanding of different quantities in the four processes: adiabatic compression, adiabatic expansion, isothermal compression and isothermal expansion. The table consisted of five columns: the first column listed 12 expressions pertaining to different quantities and the next four columns consisted of four processes. Students were asked to tick the check-box across each expression in the processes where the expression was applicable.

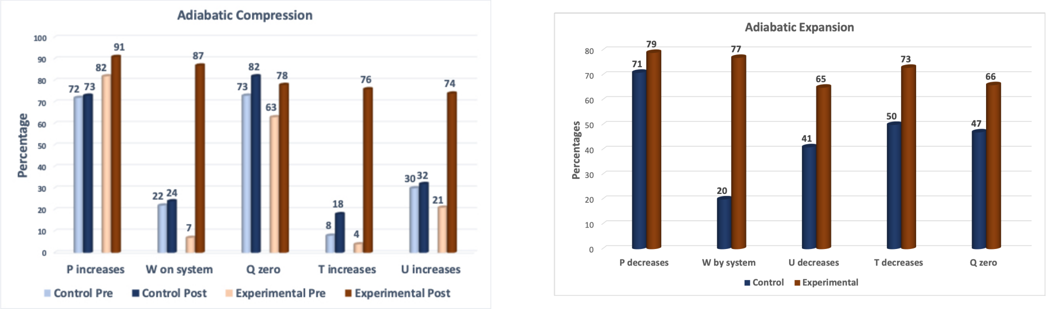
6.2 Implementing the module

The experimental group (124 students) was administered with various components of the module in the following order: 1. Pre-test on adiabatic and isothermal processes, 2. Activities, 3. Post-test on adiabatic and isothermal processes, and Table-completion task. In the experimental group, students worked on activities for 5 hours immediately after the pre-test. However, 18 students later dropped out for various reasons and only 106 were available for tests on isothermal component. The control group with 99 students, was administered only the tests. The table completion task included in the post-test could be given only to 98 students in the control group and 90 students in the experimental group. The post-test was given to both the groups a week after the pre-test and the administration of the activities.

6.3 Results and discussion

Adiabatic process: In case of adiabatic compression (figure 6.8a), there was a significant increase in percentage of students saying that temperature of the gas would increase and also in the percentage of students stating that the internal energy increased. Their understanding of role of work done on/by the system, seemed to have improved substantially.

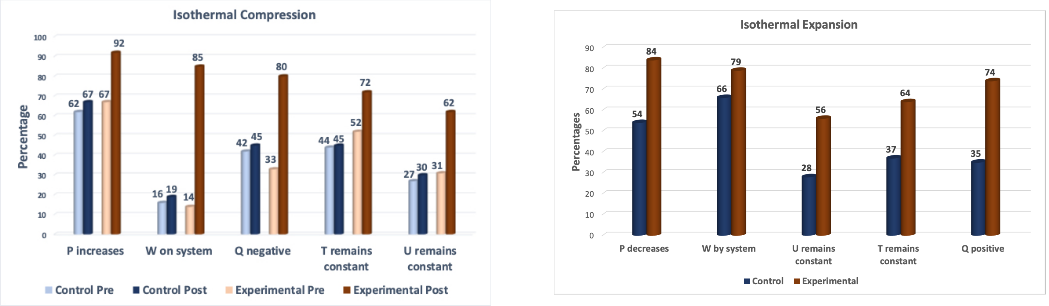
Isothermal process: For isothermal compression (figure 6.9a), the percentage of students stating that the temperature remains constant increased. Also I observed that the percentage of students stating no change in internal energy increased. The percentage of students for whom the heat transfer was negative during the isothermal compression also increased.



(a) Students correct responses about compression process (post-tests)

(b) Students correct responses about expansion process (post-tests)

Figure 6.8: Adiabatic process



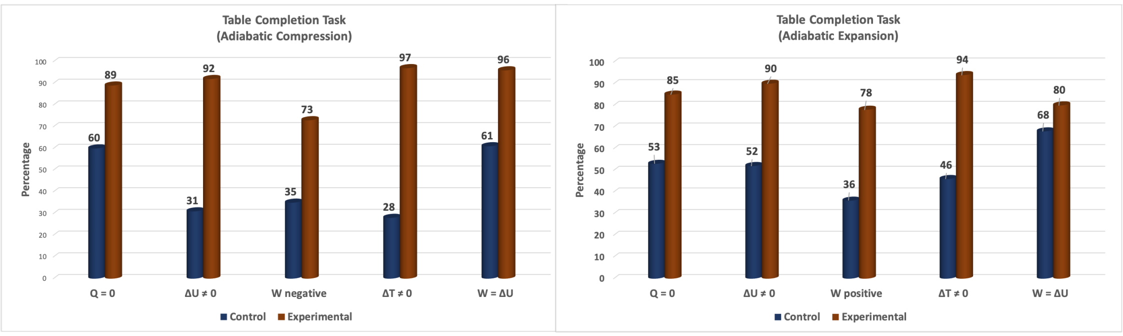
(a) Students' correct responses about compression process (post-tests)

(b) Students' correct responses about expansion process (post-tests)

Figure 6.9: Isothermal process

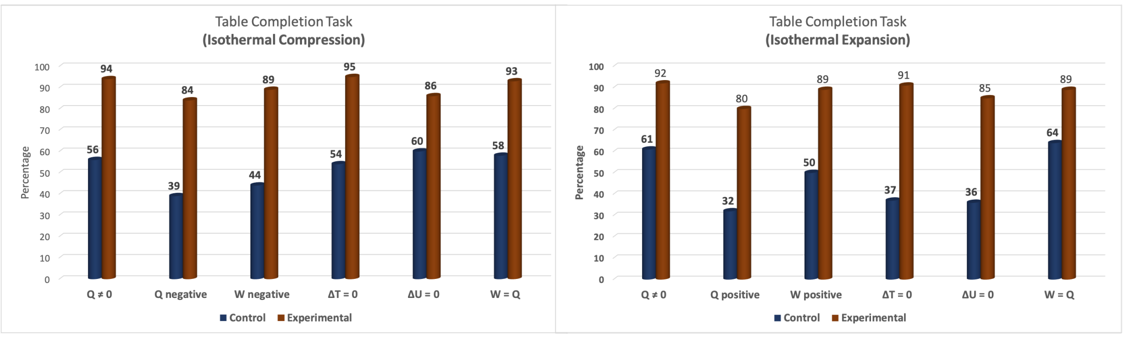
However, in both adiabatic and isothermal expansion (figures 6.8b and 6.9b), the percentages were consistently less, indicating that the students were not sure whether to extrapolate the results from compression. This may be due to the fact that for the compression process they had done a concrete activity and seen the results for themselves, whereas for expansion they had not done any such activity and had to rely only on abstract reasoning.

Table-completion task results: Figures 6.10 and 6.11 summarize the results of the table-completion task for both control and experimental group which shows that the number of students giving correct responses in experimental group is more than that in the control group. Figure 6.10 indicates that most students from the experimental group confirmed zero heat transfer in case of adiabatic compression and expansion processes. Similar numbers were observed in the case of work done and $\Delta T \neq 0$. In case of internal energy, the percentage of students who responded is less, indicating the continuation of confusion about the concept. However, among those who responded, majority wrote it correctly.



(a) Adiabatic compression (b) Adiabatic expansion

Figure 6.10: Table completion task - Percentage of students giving correct responses



(a) Isothermal compression (b) Isothermal expansion

Figure 6.11: Table completion task - Percentage of students giving correct responses

In the case of isothermal compression as well as expansion (figure 6.11), most students confirmed that $\Delta T = 0$. In case of $\Delta U = 0$, the number of students who responded was less as compared to students responding to $\Delta T = 0$. Out of those who responded, a sufficient number could confirm $\Delta U = 0$. A similar trend was seen in case of other quantities/relations. It was found that those who responded could answer it correctly.

I compared the mean scores of the control and the experimental groups for the pre-tests using an independent sample t-test (Garret 1981, Foster et al. 2018). Since there was no significant difference between the mean scores as indicated by t-test, I infer that both the control and the experimental groups were equivalent in terms of performance.

I also compared the pre- and post-test mean scores of both the control and the experimental groups using a correlated means t -test (Garrett, 1981). The results show that the performance of the experimental group was significantly better on the post test as compared to control group for both adiabatic and isothermal cases. The effectiveness of the activities for helping students to overcome their alternative conceptions can therefore be said to be established.

Chapter 7: Conclusion

This chapter presents conclusions of my work on identification of students' alternative conceptions in elementary thermodynamics and developing and testing activity-based modules to help students overcome the alternative conceptions. In the later part of the chapter, I also discuss the pedagogical implications of the work, possible limitations of the work and suggestions for future work.

7.1 Summary of the work

7.1.1 Identification of alternative conceptions

I began with a survey of the topics, taught under elementary thermodynamics in typical undergraduate physics courses and secondary school physics studies in India. Having identified the concepts, I prepared open ended questionnaires to gauge students' level of understanding of the concepts. From the analysis of the open ended questionnaire I came up with following six topics which were difficult to understand: 1. Heat and temperature, 2. Thermal equilibrium, 3. First law of thermodynamics, 4. Heat transfer mechanisms, 5. Pressure and elementary kinetic theory of gases, 6. Second law of thermodynamics and related concepts. Second law of thermodynamics and related concepts like heat engine, entropy etc. being somewhat more advanced than the remaining topics deserve a separate detailed study. Out of the remaining five topics, pressure and kinetic theory seem to be rather separate from the other four, which would go together as a theme. I, therefore, decided to restrict the study of alternative conceptions to the following four topics: 1. Heat and temperature, 2. Thermal equilibrium, 3. First law of thermodynamics and 4. Heat transfer mechanisms. I carried out the investigations in students' alternative conceptions in these topics. The students' difficulties observed in the study, are summarised below:

1. Students do not distinguish between heat and temperature.
2. Students have difficulty in relating internal energy and temperature.
3. Students consider heat and internal energy to be equivalent.
4. Students disregard external work as a mechanism by which internal energy can be changed.
5. Students have difficulty in understanding the energy terms in the statement of the first law of thermodynamics.
6. Students think that the equilibrium temperature of objects, kept in a constant temperature enclosure, depends on size and material of the objects.
7. Students consider heat as a fluid while explaining the process of conduction.

8.In case of natural convection, students attribute hotness to a single molecule.

9.In case of artificial convection, some students confuse it with conduction and some students can not distinguish convection from radiation.

10. Students feel that heat transfer due to radiation necessarily requires a medium.

The alternative conceptions represented by statements 7, 8, 9 and 10 (related to heat transfer mechanism) are disjoint from the first six statements. These six statements are related to topics - heat and temperature, thermal equilibrium and the first law of thermodynamics. These three topics together form a unit pertaining to elementary thermodynamics. Therefore, for designing the modules, it was meaningful to consider the first three topics rather than the fourth one. In view of the extended nature of the planned work, I further restricted the scope of the work and decided to develop the activity-based modules related to 1. Thermal equilibrium and 2. First law of thermodynamics. I believed that the topic of "heat and temperature" is naturally covered under these two topics. The findings about students' alternative conceptions in the first three topics (statements 1 to 6) formed the basis for the development of these activity-based modules.

7.1.2 Designing the modules

I observed that the alternative conceptions were related to understanding of various prerequisite concepts related to central concept. Thus, I realised that it was not enough to develop an isolated activity only addressing a central alternative conception. It was equally important to consider all the interlinked concepts and their interconnections for building adequate conceptual understanding, which will help students to overcome the central alternative conception. Therefore, the activity-based module consisted of a central activity addressing the central alternative conception supported by various sub-activities, each addressing the interlinked prerequisite concepts. My another aim was to come up with a comprehensive activity-based module for a particular central alternative conception, in a form adaptable either as a lecture-demonstration or as an activity for the laboratory course. Overall, my approach can be considered as incremental in developing the understanding that is necessary for the students to overcome the central alternative conception. The design and development of the modules planned this way went through several iterations. When I observed the students' responses with respect to each of the activity at a given stage of iteration, I could identify the areas of improvement and suitable refinements were made with respect to 1. design of the activities, 2. the proto-type instruments and

3. the activity sheets.

Both the modules were administered to the students using the predict-observe-explain approach and along the guidelines for conceptual change based activity sessions (Eryilmaz 2002). The module began with a conceptual question describing a situation. It was made sure that each student makes a prediction. The central activity provided a concrete experience related to the situation presented as a part of conceptual question. The activities were demonstrated to the students in the module on thermal equilibrium whereas students performed some of the activities in the module on the first law of thermodynamics. The perceptible experience and questions in the activity sheets helped in generating cognitive conflict for students. The supporting sub-activities and discussions conducted by the researcher generated opportunities for students to engage with cognitive reappraisal of the situation so as to resolve the conflict (Lee et al. 2003).

Module on thermal equilibrium

Here the central alternative conception is that the students relate the equilibrium temperature of the objects, kept in a constant temperature enclosure, to the size and the material of the objects. They do not necessarily think that this steady state temperature should be the temperature of surroundings. The central activity, therefore, was designed to show students how the temperature of objects, with different material and size, vary and finally reach the same steady state temperature equal to the temperature of the enclosure. I found that the students did not understand the concept of thermal equilibrium itself. Therefore, I looked for possible analogy which could be demonstrated and such a experience could be harnessed to enable students for developing understanding of thermal equilibrium (Treagust and Duit 2009). The key point in understanding thermal equilibrium is the zero net heat (energy) flow across a boundary surface between two bodies. Since heat flow is rather difficult for the students to grasp as it is not directly amenable to perception, I considered hydrostatic equilibrium which is familiar to the students. The analogous net fluid (material) flow across an interface between two liquid systems can be demonstrated and is perceptible. Thus, the demonstration of the base domain (hydrostatic equilibrium), would make it easier for students to compare the sub-concepts of base domain and target domain (thermal equilibrium) and hence, help them extend their understanding to the target domain. Further, the equilibrium depends on certain factors related to the process of exchange. Thus, such factors are important and when they are different, then the approach to the equilibrium may be different. This key aspect was demonstrated by developing the liquid flow analogy model for the central activity. I had to take care that students didn't take the analogy literally. I emphasised that in one case the quantity involved was matter whereas in the other case it was energy.

Module on first law of thermodynamics

The first five students' difficulties found in my study, pertained to the first law of thermodynamics. The statement of the first law of thermodynamics involves three terms, ΔU, Q and W. The crux in the understanding of the whole law rests on students' understanding of each of these terms. It is important to note that the internal energy can be changed by Q or W independently. A situation where the change in internal energy comes about by contribution from both Q and W, in my opinion, would be rather difficult for students to grasp. In order to emphasize the independence of these two processes (Q and W), I thought of two simpler processes, namely, adiabatic compression and isothermal compression, in which one of the three terms is zero. The important factor in the activity-module was quantitative representation of different energy terms. The information sheet, explained students, the relation between change in temperature and the change in internal energy, the sign convention of work done and heat flow in compression and expansion processes. I began with adiabatic process, as students were aware that the net heat flow is zero for such a process. In this process, making $\Delta T \neq 0$ visible to the students, would prove useful in addressing students' difficulty of not distinguishing between heat and temperature. This change in temperature that is change in internal energy with $Q = 0$, would help students realise that heat flow and change in internal energy are not the same. In the isothermal compression, students were shown that though $\Delta T = 0$, heat flows from the system to the surrounding. This would reiterate our addressal of students' difficulties pertaining to not distinguishing between heat and temperature as well as considering heat and internal energy to be equivalent. In adiabatic compression, the external work during compression process in fire syringe was equated to the change in internal energy. This would be useful in dealing with their difficulty of disregarding work done as a mechanism to change the internal energy of the system. In isothermal compression, the same could be shown through the presence of heat flow when the external work is done.

7.1.3 Testing the effectiveness of the modules

The final modules were tested for their effectiveness, using a quasi experimental pre-test - intervention - post-test design. The entire module was given to the experimental group, whereas the control group was given only the pre-test and post-test. The activities were implemented using the POE approach. The students' responses in the pre- and post-tests as well as in activity sheets were analysed. The changes that I observed in students' responses with respect to their difficulties are given below:

1. Students do not distinguish between heat and temperature

In adiabatic process, students realised that temperature change need not always result in heat flow which could be clearly seen from an increase in percentage of correct responses. Similar change was observed in isothermal process wherein students indicated presence of heat flow even if the temperature of the system remained constant.

In the case of adiabatic compression, the percentage of students saying increase in temperature increased from mere 4% to 76%. The table completion task confirmed students' realization of $\Delta T \neq 0$ (97%), even if $Q = 0$ (89%). In case of isothermal compression, the percentage of students agreeing to negative heat flow increased from 33% to 80%. Even in the table completion task, students realized that though the $\Delta T = 0$, $Q \neq 0$.

2. Students have difficulty in relating internal energy and temperature

During adiabatic compression about equal percentage of students agree that both temperature (76%) and therefore the internal energy of the system (74%) increases. In isothermal process, equal percentage of students say that both temperature (72%) and internal energy of the system (62%) remains constant. This indicated that students related change in temperature with the change in internal energy of the system.

3. Students consider heat and internal energy to be equivalent

In the table completion task, in case of adiabatic compression, 89% students mark $Q = 0$ and 92% students agree to $\Delta U \neq 0$. In case of isothermal compression 86% students mark $\Delta U = 0$ and 94% students mark $Q \neq 0$. For adiabatic compression (where majority of students are aware of $Q = 0$), the percentage of students saying $\Delta U \neq 0$ decreased. In isothermal compression, students realized that even though $\Delta U = 0$, $Q \neq 0$. Thus students made a clear distinction between heat and internal energy.

4. Students disregard external work as a mechanism by which internal energy can be changed.

In the table completion task, students could equate the work done on the system 1. to the change in the internal energy of the system in adiabatic compression (96%) and 2. to the heat flowing out of the system in isothermal compression (93%). Students' response during interviews, "...energy pumped in due to the work done..." gave the evidence of their realization of external work as a mechanism by which internal energy can be changed.

5. Students have difficulty in understanding energy terms in first law of thermodynamics

The table completion task collated students' understanding by making them identify the correct locations of the energy terms with respect to different processes in the table. This showed that students could perceive different energy terms in the statement of the law.

6. Students think that the equilibrium temperature of objects, kept in a constant temperature enclosure, depends on size and material of the objects.

Students realised that thermal equilibrium is attained when net heat flow between two objects becomes zero, leading to equal final temperature of the objects. Students were convinced that the time taken to attain thermal equilibrium depends on material and size, but the final temperature reached, is independent of these factors and equal to the surrounding temperature. Students could apply this understanding to the activity on method of mixtures to correctly predict and calculate equilibrium temperature.

These findings showed the effectiveness of both the modules to address students' alternative conceptions which was also confirmed through a statistically significant change in the percentage of correct responses of the experimental group compared to the control group.

7.2 Pedagogical Implications

In India, students are introduced to thermodynamics primarily through theory classes. There are almost no experimental activities related to elementary thermodynamics at the undergraduate level. Often the synchronization of laboratory work with the theory classes is missing in Indian context. Under such situations activity-based approach, which can be adopted directly in the classroom, is a promising alternative. The modules developed can be adapted for the same. The smaller units of these modules can also be prepared and used to cater students of different grades. During interviews, students indicated the need for such activities in their elementary thermodynamics classes. These activities, therefore, can be a part of concept-based demonstrations at the undergraduate physics classrooms and laboratories. Another important aspect of the module development was to look at the possibility of replication of these activities in present college system. The sensors which have been chosen are low-cost and are easily available either in the electronic shops or online websites. I also developed some activities with alternate design enabling manual data collection, which otherwise use data-logging instruments in the module. These alternate apparatus were later tested in different teacher workshops. The purpose of these low cost apparatus development was to convince the teacher community about the feasibility of such development in their college setting. I have also developed videos of these activities. However, performing activities is always much more effective than watching videos of those activities. But at certain places where it is very difficult to get the required sensors and material to develop the activities, one can use these videos. Such carefully designed activity modules present opportunities to revisit thinking and reflect on the same which is a crucial step in advancing the conceptual understanding. Over the years, these activities were introduced to teachers through workshops at HBCSE and outside which were appreciated by the teacher participants. They were given videos related to the activity modules to be used for their own classrooms.

7.3 Possible Limitations

The present work is restricted to colleges located in urban areas of India like Mumbai, Nagpur and Tehri. I believe that the alternative conceptions will not be substantially different if the data collection would have been carried out in colleges located in semi-urban or more interior parts of the country. I am aware that reaching out to students studying in such colleges will make the results richer and more generalisable. The nature of the alternative conceptions observed in my study with Indian students are similar to those listed in the PER literature across the globe. While implementing the activities to the students, the number of students that I could handle at given time was restricted, as I had limited copies of the apparatus. I tried to overcome this limitation by implementing the module to several batches of students. Both the modules were developed and implemented by the researcher. It is important to study the effects when the modules are implemented by teachers in their classrooms. In the present study, the post-test was administered with a gap of one week after the intervention, so as to understand the improvement in students' understanding and its retention. It is important to check whether the improvement is retained by students over time, by administering similar tests over time. However, access to the same sample on continuous basis is a practical difficulty and hence, this aspect is not explored as part of the current study.

While considering the activity-based approach, I felt that it is important to look and consider those concepts which are amenable to concrete perceptible experiences and make them accessible to students. Even while working with these concepts, some theoretical concepts need to be presented to the students along with the activities. In my opinion, discussions about relevant theoretical concepts can not be omitted as it will affect the interlinkages among various concepts. Thus, reflection on nature of concepts is crucial while adapting the suitable approach. For example, it is not possible to develop activities for the relation between change in temperature and change in internal energy.

In the module on first law of thermodynamics, the activities were related to the compression process. In the post-test, along with the questions on compression, questions on expansion process were given to the students. It was observed that this extrapolation though was attempted by many students, the percentage of correct responses for expansion process was lower as compared to that obtained for compression process. Thus, transferring the learning from one context to another, for some students, was difficult.

7.4 Suggestions for future Work

Activities developed on thermal equilibrium and first law of thermodynamics in this thesis are small units related to some of the core concepts in elementary thermodynamics. The activity modules developed as part of current study are appreciated both by teacher/student communities, which is an encouraging response. In order to implement this activity-based approach in the present undergraduate college system, it is important to closely interact with the teacher community. Therefore, I am keen on observing the classes where the activity modules are implemented by teachers. The unit on first law of thermodynamics that included adiabatic and isothermal processes is already extended to other thermodynamics processes like isobaric and isochoric processes. I have developed a new low-cost apparatus for the isothermal process which has been tested in different teacher workshops. I would like to develop activity-based modules for different core concepts like heat transfer, pressure, heat engines, entropy and second law of thermodynamics with which an entire course on introducing thermodynamics through activity-based modules can be developed. Integrating such approaches with teaching-learning processes is important for undergraduate phase of physics education especially in Indian context, where conventional mode is still predominant.

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