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

A Thesis

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by

Shirish R. Pathare

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research
Mumbai

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Declaration

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

The work was done under the guidance of Professor Savita Ladage and Professor Hemchandra C. Pradhan, at the Tata Institute of Fundamental Research, Mumbai.

Shirish R. Pathare

In my capacity as supervisor of the candidate's thesis, I certify that the above statements are true to the best of my knowledge.

Savita Ladage
Thesis Supervisor
Date: 29 - 07 - 2021

Dedication

To

My Parents

My Wife and

My Daughter

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Abstract

The study of heat and thermodynamics is an integral part of undergraduate physics students' education. Many fundamental concepts in this subject are related to everyday experiences. Yet in the formal study of the subject, these concepts take a rigorous form that students find difficult to cope 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 the 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. Therefore, it is essential to introduce active learning strategies to deal with them. In the Indian curricula, the theoretical courses are not supported by the practical coursework 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 the first law of thermodynamics. The modules consist of many activities with experiments/demonstrations designed

with specific objectives and structured activity sheets. These modules were implemented using the predict-observe-explain approach (POE). The study indicates that the developed modules helped enhance students' conceptual understanding of the central concepts covered in the module and thus minimised their alternative conceptions. Therefore, I believe that this approach can be adapted as a part of the laboratory curricula in undergraduate physics in India.

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Chapter 1

Introduction

The thesis work is on investigating students' alternative conceptions in elementary thermodynamics and developing and testing activity-based modules to address them. In physics education research (PER) literature, one finds numerous studies on alternative conceptions as well as on activity-based instructional strategies. The 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 for the Indian context.

Thermodynamics is a complex and conceptually rich domain having numerous applications in everyday life. The PER work indicates that learners have several alternative conceptions in thermodynamics. In the Indian context, it occupies a central position in the curricula, especially at the undergraduate level. Thus, it is still a fertile area of research in Physics education.

One of the probable reasons regarding students' difficulties with respect to concepts in thermodynamics is its inaccessibility through concrete experiences. Thus it is essential to present such experiences through experiments or demonstrations wherever possible.

1.1 Motivation

During my pre-university and undergraduate days, I found concepts in thermodynamics familiar to me from daily life, yet they were only seemingly simple. During my graduate coursework, I attended a course on Chemical Thermodynamics by a distinguished teacher, which helped me realize that my understanding of the subject was inadequate. The concepts, which earlier seemed deceptively simple, were introduced with a different perspective during this course, revealing their deeper meaning. This was the time when I was struck by the complexity of the subject. I felt that I should investigate students' difficulties in this subject and prepare material to help them develop a deeper understanding. In my exploratory work with undergraduate students from different colleges in Maharashtra, I found that several alternative conceptions prevailed with respect to the concepts related to thermodynamics. These observations further reinforced my idea to work in elementary thermodynamics. I also felt that my work should not be limited only to probing alternative conceptions but should be extended to addressing them.

In India, hardly any experiments on thermodynamics are included in the curriculum at the undergraduate level. Thus, I thought of adopting an activity-based approach for addressing the alternative conceptions as it will make the concepts more visual, concrete and accessible to the students.

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 of undergraduate physics students in India in elementary thermodynamics?

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 the investigation systematically, the research questions are further subdivided into multiple specific steps, which are summed by the following research objectives:

1. To study 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 based on the study, 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 analyze 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 arrive at the set of alternative conceptions by analyzing students' responses.

4. To design and develop activity-based modules to address the alternative conceptions in a few typical areas and 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 the University of Mumbai. From this review, I came up with a set of 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 finalize 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, the third research objective, was conducted with the first-year and/or second-year undergraduate students in different colleges with physics as one of the subjects. These questionnaires were given to the first and second year of undergraduate students ($N \sim 50$ to 300). 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 concept to the students and, in the process address their alternative conceptions that I found in my study. Given 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 standardized 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 reflect upon their alternative conceptions. The outcome of the work 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. In addition, 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 the literature review related to term alternative conceptions and the work done in physics education research with emphasis on elementary thermodynamics. First, it briefly discusses some of the most used instructional strategies aimed at challenging the alternative conceptions. It then describes the pedagogies to address alternative conceptions.

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, Leboutet and Barrell 1976, Stead and R. Osborne 1980) and formally through school science education. Since its inception, students' ideas related to concepts in physics has been an important research area in physics education research. These ideas have been labelled (Gurel, Erylmaz, and McDermott 2015) by a range of different terms (Duit 2009) such as "naïve beliefs" (Caramazza, McCloskey, and Green 1980), , "misconceptions" (Clement, Brown, and Zietsman 1989, Driver and

Easley 1978), "children's ideas" (J. Osborne et al. 1993), "conceptual difficulties" (McDermott 1993), "phenomenological primitives" (diSessa 1993), "alternative conceptions" (Wandersee, Mintzes, and Novak 1994). Even though these terms differ, they all focus on differences between the ideas (concepts) that students bring to the classroom and the scientifically accepted concepts. All these studies are aimed at understanding students' variant conceptions that impedes learning. Another focus of such studies has been the identification of productive components of these flawed conceptions that can be harnessed for learning in the formal setting (Gurel, Erylmaz, and McDermott 2015). In the present work, the term "alternative conception" is being used.

Some of the common sources responsible for alternative conceptions in physics listed in the literature (NRC 1997, Suprapto 2020) are as follows:

1. Preconceived notions:

   Due to daily experiences, students often have preconceived notions even before they are introduced to an established scientific concept as a part of formal science instruction. These affect students' understanding of different concepts like heat, energy, force and gravity (Brown and Clement 1991), among others. e.g., force is needed to keep the object in motion (Pathare and Pradhan 2010).

2. Vernacular alternative conceptions:

   Daily conversations give rise to many alternative conceptions. Often a word from formal physics is used in everyday life with different meanings, e.g., weight lifters have a lot of "power" in their arms (Pathare and Pradhan 2010).

3. Conceptual misunderstandings:

   When students are taught scientific concepts without provoking them to confront paradoxes and conflicts resulting from their preconceived notions and non-scientific beliefs, they construct faulty models. Moreover, these models are usually weak and have limited applicability. Thus, students themselves are insecure about these models, and such situations lead to conceptual difficulties.

4. Teacher driven:

   Generally, in a classroom, the teacher is viewed as an ultimate authority. The student often accepts the explanation of a concept delivered by a teacher as it is. Teachers may fail to give students an overview of the topic necessary for understanding the same, which may lead to the formation of alternative models; e.g., any two equal and opposite forces make an action-reaction pair (Pathare and Pradhan 2010).

For students, the textbooks are one of the significant sources of information and, perhaps, also for alternative conceptions (Cho, Kahle, and Nordland 1985). If the books present the material incorrectly, then it is inevitable that this affects students' understanding (Iona 1987).

2.3 Cognitive conflict strategy and alternative conceptions

Wandersee et al. (Wandersee, Mintzes, and Novak 1994), from their extensive literature review on alternative conceptions, claim that the alternative conceptions cut across age, ability, gender, and cultural boundaries. These alternative conceptions are often rigid and, therefore, very difficult to dislodge using conventional teaching strategies. The authors (Wandersee, Mintzes, and Novak 1994) assert the need for a conceptual change approach to address students' alternative conceptions in order to develop a scientifically accepted conceptual understanding, for which students' conceptions and existing knowledge structures may need modification. Many researchers offer different views about the process of conceptual change (Chi and Roscoe 2002, diSessa 2002, Hewson and Hewson 1983, Hynd et al. 1994, Posner et al. 1982, Thagard 1992, Vosniadou 2012). Most of these models have emphasised the role of cognitive conflict as a starting point in the process of conceptual change (Limon 2001). Posner's model (Posner et al. 1982) based on cognitive conflict has been widely used by many later studies (Basili and Sanford 1991, Costu, Ayas, and Niaz

2010, Calık, Ayas, and Coll 2007, Calik et al. 2007, Jensen and Finley 1996, Ozmen 2009, Pınarbas et al. 2007, Stavy and Berkovitz 1980, Thorley and Treagust 1987, Limón and Carretero 1997, Mason and Boscolo 2000, Lee et al. 2003). For conceptual change to take place, Posner et al. (Posner et al. 1982) suggested four conditions:

1. Learner should be dissatisfied with their existing conceptions (dissatisfaction)
2. The new concept must be clear and understandable for students (intelligibility)
3. The current problem should be solved by using the new concept (plausibility)
4. Similar future problems can be solved by using the new concept (fruitfulness)

Dissatisfaction can be created if a discrepant event is first introduced to the learner, with a meaningful procedure to reveal his/her spontaneous strategy. A discrepant event, to induce cognitive conflict, is the physical experience that provides the learner with evidence useful in contradicting their existing conceptions (Kang, Scharmann, and Noh 2004). With the introduction of the discrepant event, the inadequacies in learner's strategies are exposed using carefully contrived counterexamples (Rowell and Dawson 1979). Once the student recognizes the limitations, he/she gets engaged in a cognitive reassessment of the situation to resolve the conflict (Lee et al. 2003), i.e. the learner may either develop a new strategy or would be ready to accept one whose adequacy is demonstrated (Rowell and Dawson 1979).

Posner et al. (Posner et al. 1982) suggest that the presentation of anomalies will produce dissatisfaction only if

1. Students understand why the experimental findings represent an anomaly
2. Students believe that it is necessary to reconcile the findings with their existing conceptions
3. Students are committed to the reduction of inconsistencies among the beliefs that they hold

4. Students realize that their attempts to assimilate their findings into their existing conceptions are not working.

In order to create a meaningful cognitive conflict, students should be motivated and interested in the topic (Limón and Carretero 1997). The topic introduced to the students have to be relevant for them and should also be based on their prior knowledge. Different studies (Posner et al. 1982, Limon 2001) state that conceptual change is a gradual process. A dramatically radical change cannot be expected just after introducing discrepant events in a short instructional intervention. Studies suggest an appreciable statistical correspondence between cognitive conflict and conceptual change, which means that cognitive conflict is one of the important factors for the process of concept learning (Kang, Scharmann, and Noh 2004).

Limon suggests the introduction of analogies/metaphors can help a student to a meaningful cognitive conflict (Limón and Carretero 1997). In science education research, analogies are often perceived as one of the efficient ways to explain abstract ideas in familiar terms (Aubusson, Treagust, and Harrison 2009). Analogies promote conceptual learning as they encourage building links between past familiar knowledge, experiences and new contexts (Harrison and Treagust 2006). The areas/concepts, which students are generally well versed with or are at least familiar with, form the base domain, and the lesser-known area/concept forms the target domain. The analogy can be treated as a mapping from a base domain to a target domain. If the target domain is already structured in student's mind and if this structure needs to be changed, analogy helps the student to restructure by assisting them in constructing a new explanatory model which enriches the target domain (Brown and Clement 1989).

2.4 Instructional strategies for addressing alternative conceptions

Various instructional approaches/tools have been used to carry out the process of conceptual change. Some of the most widely used approaches are Investigative Science Learning Environment (ISLE), Interactive Video Vignettes (IVV), Predict-Observe-Explain (POE), the Interactive Lecture Demonstrations (ILD). These instructional approaches help in creating an active learning environment that promotes independent, creative and critical thinking as they demand students to analyze and reflect upon the given situations (Silberman 2006). These instructional approaches use activities/videos, which can challenge students' pre-existing ideas and hence create cognitive conflict, potentially bringing about a conceptual change.

In ISLE (Etkina and Van Heuvelen 2007), students observe phenomenon/activity, look for patterns and then develop explanations for these patterns. Based on these explanations, they make predictions about the outcomes of the experiments. Then they decide if the outcomes of the testing experiments are consistent with the predictions. If necessary, they revise explanations. Thus in this approach, students are expected to observe, explain and predict. ISLE can create an environment that helps the learner to discover and learn concepts in physics in ways similar to how physicists work and that too within the stipulated time (Etkina, Brookes, and Planinsic 2019). Using ISLE, multiple resources have been developed which can be used by teachers to teach different topics in physics (Etkina 2019).

Interactive Video Vignettes (Wright et al. 2016) are designed as ungraded web-based assignments for introductory physics students. Each online vignette addresses a learning difficulty identified by the physics education research. IVV elicits predictions from a student, confronts the student with experimental results and helps the student resolve any differences between the prediction and observations (*Interactive Video Vignettes* 2021). Thus IVV makes use of the predict-observe-explain approach. A collection of 9 IVVs on

mechanics and electrostatics are available (*Interactive Video Vignettes - examples* 2021).
Predict-observe-explain instructional approach places importance on students' reasoning (White and Gunstone 2014, Jasdilla, Fitria, and Sopandi 2019, Fitriani et al. 2020). The explanations 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).

Interactive lecture demonstrations (Sokoloff and Thornton 2004) engage students in activities that confront their prior understanding of a core concept. ILD is aimed at creating an active learning environment for large (or small) lecture classes using discovery-based laboratory curricula supported by real-time microcomputer-based laboratory tools. PER lists multiple studies of ILD in the classroom to improve students' conceptual understanding (Zimrot and Ashkenazi 2007, Wattanakasiwich, Khamcharean, et al. 2012, Georgiou and Sharma 2014). The interactive lecture demonstrations incorporate predict-observe-explain as a part of a pattern combination to improve the effectiveness of lecture demonstrations (Alexander and Winne 2006).

Thus, POE is a necessary instructional approach that has been used for creating cognitive conflict to address alternative conceptions.

2.5 Predict-observe-explain approach

The POE pattern involves introducing demonstration/experiment of a scientific phenomenon, eliciting predictions, running the demonstrations, and asking the students to reconcile contradictions (Shepardson, Moje, and Kennard-McClelland 1994, White and Gunstone 2014). First, students are given information about the activity (experiment/demonstration). They are asked to make some predictions about the outcome of the activity related to their prior knowledge and beliefs. The activity is then performed, and students are asked to note their observations. When observations contradict their prediction, cognitive conflict is generated, and students' attention is drawn towards the conflict. At this point, students are encouraged to get actively involved in reconstructing their explanation/view (Liew and Treagust 1998) and reconcile any discrepancies between their prediction and the outcome. POE, therefore, has the benefit when students use evidence to analyze their predictions (Alexander and Winne 2006). It helps students test and communicate their alternative ideas and offers evidence to the instructor about the progress in students' understanding at each step of the approach (Liew and Treagust 1998).

When students are asked to note the observations of the experiment, they may tend to observe and focus on the aspect of the experiment that supported their preconceived reason and knowledge. Students' prior knowledge is one of the significant factors that affect their own observations and interpretations of the new situation (Limón and Carretero 1997), which can result in students' varied responses to the POE activity. POE approach, therefore, is effective in identifying students' ability to reinterpret their observation and data that are contradictory to their prediction of the phenomenon (Liew and Treagust 1998). Due to this variation in students observation, it is difficult to assume the uniform observation outcome of a well-designed POE. Thus it is important to design POEs to produce "on-the-spot", "obvious" and "clear" observation outcomes to maintain the uniformity in students' observations (Liew and Treagust 1998).

POE-based activities, which always give unexpected results, should not be used often; otherwise, students might think POE as a trick, and they may try to predict outcomes that are unexpected rather than based on their actual reasoning of what would happen (Chin 2001). Some activities should also be chosen, which does not give surprising results and where the observations support the predictions.

In a classroom setting, teachers can use POE tasks to creatively design learning activities and strategies, which are based on students' viewpoint rather than the teacher's or scientists' viewpoint (Liew and Treagust 1998).

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 and Kolari 2003, Costu 2008, Costu, Ayas, and Niaz 2010). Cinici and Dimir (Cinici and Demir 2013) adopted a cooperative conceptual change model (CCCM) in which they incorporated discussions within the student groups to provide cognitive conflict. Eryilmaz (Eryilmaz 2002) stated the following guidelines for conceptual change based activity sessions:

1. Use the conceptual question that helps students to reveal their conceptions about a specific concept.

2. Let students predict, verbally and pictorially. Even if their prediction is incorrect, ask them to provide the justification.

3. Generate a discrepant event, creating conflict between exposed preconceptions and the observed phenomenon that students cannot explain with their preconceived knowledge.

4. Make students aware of this conflict.

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

6. Make students explicitly aware of oversimplification, exemplification, association, and multiple representations have happened, if any. If not, give exemplification, associations with other topics, and multiple representations for the topic.

I have used the POE approach with these guidelines in the current work to address alternative conceptions in elementary thermodynamics. The present study involves the development of activities (consisting of demonstrations/experiments) designed appropriately, which engages and helps students to establish relationships among various concepts in thermodynamics (Stepans 2008).

The PER literature includes a wide variety of physics topics (mechanics, optics, electricity and magnetism, thermodynamics) in which students' alternative conceptions have been investigated (Duit 2009). Since the work is related to alternative conceptions in elementary thermodynamics, it is equally important to look at the studies related to alternative conceptions in 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.
In the early 1980s, a group of technologists, classroom teachers and education researchers developed a computer as learning partner (CLP) integrated instructional unit to enhance students' understanding of the difference between heat and temperature (Linn 1997 and McKagan 2011). Thermal Concept Evaluation (TCE) was developed to gauge students' understanding and application of thermodynamics concepts which aimed at testing students' knowledge with respect to temperature, heat transfer, phase change, thermal properties of materials (Yeo and Zadnik 2001 and McKagan 2011). Heat and Temperature Concept Evaluation (HTCE) was developed to assess students' understanding of heat and temperature concepts (Thorton and Sokoloff 2001 and McKagan 2011). Thermal and transport concept inventory (TTCI) was developed to assess students' knowledge about the second law of thermodynamics, conversion of thermal energy to work, enthalpy, energy quality, internal energy, equilibrium processes, steady-state processes (Nelson et al. 2006, and McKagan 2011). Thermodynamic Conceptual Survey (TCS) was developed to understand students' conceptual understanding of heat and temperature, the ideal gas law, the first law of thermodynamics and processes (Wattanakasiwich, Taleab, et al. 2013, and McKagan 2011). A survey of thermodynamic processes and first and second laws (STPFaSL) was developed to measure the effectiveness of traditional and/or research-based techniques of teaching the first and second laws of thermodynamics and thermodynamic processes (Brown 2015, and McKagan 2011). When administered to students, these concept inventories bring out dif-

ferent alternative conceptions that students have in thermodynamics. Sreenivasulu B. and Subramaniam R. (Sreenivasulu and Subramaniam 2013) gives an extensive list of students' alternative conceptions in thermodynamics.

One of the most fundamental confusions arise due to the daily life experiences and scientific terminology for heat and temperature (Clough and Driver 1986, Kesidou, Duit, and Glynn 1995, Erickson 1979, Erickson 1985). Students use heat and temperature interchangeably in daily life and therefore use the same terminology to explain the scientific phenomenon. Many students hold conceptions very similar to the caloric theory of heat held by the scientists in 8^{th} century (Brush 1976). Many students confuse heat with an intensive quantity and temperature with the amount of heat (Kesidou and Duit 1993). Students do not accept that different objects attain the same temperature when left in the same environment for a sufficiently long duration (Thomaz et al. 1995, 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. Students' understanding of the first law of thermodynamics has been studied by many researchers (Barbera and Wieman 2009, Meltzer 2004, VanRoon, VanSprang, and Verdonk 1994). Many students confuse heat with internal energy (Granville 1985). Most studies focus on the compression and expansion of an ideal gas (Gonen 2014, Meltzer 2004, Kautz et al. 2005, Leinonen, Räsänen, et al. 2009, Loverude, Kautz, and Heron 2002). It was observed that in the case of adiabatic compression students used unsuitable explanations rather than the first law of thermodynamics. Meltzer (Meltzer 2004) reasons this for students' difficulty in recognizing the difference between different energy terms in the statement of the first law of thermodynamics and the change in these energy terms. Aspects of the basic ideas of the second law are investigated by many researchers (Shayer and Wylam 1981, Grimellini-Tomasini and Pecori Balanda 1987, Kesidou and Duit 1993, Cochran and Heron 2006) In response to the questions on heat engines and the second law, the students had few intuitive ideas but didn't have an adequate understanding of the topics (Cochran and Heron 2006).

2.7 Developing activities

The physics education literature indicates various methods to address the alternative conceptions regarding thermal equilibrium and the first law of thermodynamics. Clement (Clement 1977) emphasizes that representing content using multiple modes (e.g., verbal, mathematical, concrete-practical, pictorial) is necessary to help learners understand the science content comprehensively.

Discovery-based laboratory curricula using microcomputer-based laboratory tools (MBL) are good examples of active learning strategies for the introductory physics laboratory. Some of these efforts resulted in 'Tools for Scientific Thinking' (Thornton 1987), 'Computer as Learning Partner' (CLP) (Lewis, Stern, and Linn 1993) and 'Real-Time Physics (RTP)' Laboratories (Sokoloff, Thornton, and Laws 1998). The advantage of real-time data collection using sensors and computers saves considerable time involved in manual data collection. Further, it allows observing multiple quantities and the variations in them simultaneously and reduces the cognitive load with respect to data collection, graph plotting, and data analysis. Thus, it provides maximum time to learners for investigating the concept that they are expected to learn (Linn 1987).

The RTP module on thermodynamics (Sokoloff, Thornton, and Laws 1998) is focused on helping students attain an in-depth understanding of concepts related to heat and temperature, pressure, the ideal gas law, the laws of thermodynamics and heat engines. The learning cycle in the module consists of making a prediction, using MBL tools to collect and graph data, comparison of data with their predictions, and analysis and quantitative experimentation. In the activity on thermal equilibrium, temperature sensors are used to study the cooling curve of water and thermal equilibrium between two systems. By studying the variation in temperature of the water, students were expected to understand the rate of cooling at different instants of time and the process of heat transfer through conduction. The section on the first law of thermodynamics covers the topics like phase changes (change of internal energy due to heat), latent heat of fusion and vaporization, thermodynamic work performed while pushing the piston of syringe followed by the relation between heat, work and internal energy. In lab 6 of the module, students use a fire syringe to study what makes a process adiabatic and calculate the final temperature of the system using gas laws.

The CLP (computer as learning partner) curriculum involves an 11-week microcomputer-based study of thermodynamic variables and properties (Lewis, Stern, and Linn 1993) consisting of four main topics – (a) heat flow, (b) insulation and conduction, (c) heat energy and temperature and (d) thermal equilibrium (Clark and Linn 2003). It has been designed for 8^{th} grade students in which students worked in pairs on activities involving microcomputer-based labs (MBL) and simulations using computers, electronic laboratory notebook and internet software (Clark 2006). For instance, in the activity on thermal equilibrium, students measure and compare the temperature of objects in the classroom using probeware connected to their computers. In the 'equilibrium lab', an activity in which a test tube of hot water was brought in thermal contact with a beaker containing water at room temperature, students were expected to comment about the nature of heat flow in the process by studying the temperature variations of the two systems.

P. Brown (Brown 2011), using Predict-Share-Observe-Explain (PSOE), demonstrates activity on thermal equilibrium in which two half-full beakers of water at different temperatures are mixed. Before the water from these two beakers is combined, students predict the temperature of the mixture of water and share their predictions with their partners by justifying their predictions. Later the students take the data to enable themselves to confirm, refute or refine their scientific ideas. In the last "explain" stage, students provide an explanation for their observations.

Arnold and Millar (Arnold and Millar 1996) explained the concept of dynamic thermal equilibrium through the liquid flow analogy. They used a glass container with a water inflow at the top and outflow from the bottom with valves controlling the inflow and outflow. Students were asked to comment on the possibilities of changing the water level in the container by adjusting the rates of water inflow and outflow. In the next activity, students measured the variation in water temperature in a metal can, being heated by a small candle. The distance between the metal can and candle was adjusted so that the temperature of water in the container initially increased then remained constant. A discussion was carried out with students explaining the links between the base concept of water analogy (water input, water output, and water level) and the target concept of equilibrium (heat input, heat output, and temperature).

In a recent work by diSessa (diSessa 2017) on thermal equilibration, activity on Newton's law of cooling was used. Students participated in an open class discussion on what happens when a glass of water or milk is removed from a refrigerator and placed on a kitchen table. Later they were asked to sketch the graphs of how warming/cooling happens and justify the graphs. Students were asked to experiment with heating and cooling of water. They were provided with cold or hot water baths, test tubes containing hot or cold water, a thermal probe, and a computer data collection program for plotting graphs. Later, students' experimental results were discussed in the classroom, followed by teachers' scaffolding of constructing a computer model that could fit in the experiment results. Through this work, students could replace their understanding of the source/recipient model that 'hot objects emit heat to make the objects in surroundings hot' with learning that 'it is the temperature difference between two objects which is the main factor in deciding the rate of change of temperature'. They also learnt that two objects initially at different temperatures would eventually arrive at the same temperature. The conditions of thermal equilibration are conveyed through this work without involving the concept of heat flow (Amin 2017). Later the concept of thermal equilibration was extended to different daily life experiences which students can observe.

The current work uses the activity-based approach to address students' alternative conceptions related to thermal equilibrium and the first law of thermodynamics. In the Indian context, the teaching of thermodynamics often does not use demonstrations or experimental modules focused on students' conceptions. Hence, adapting an activity-based approach to teach concepts in thermodynamics becomes meaningful and crucial. Therefore building a set of activities involving a combination of real-time data collection and concept based demonstrations would be meaningful in addressing students' alternative conceptions. Additionally, this was also a natural choice for the researcher who has expertise in developing experiments for the international physics olympiad programme.

The development of activity-based modules is informed by the PER literature, and chapters 5 and 6 present necessary details about the same. The development went through several iterative stages of modifications with feedback obtained through their field trials which led to its final version. Overall, each iterative cycle of development involved stages of design, evaluation, analysis and revision.

Chapter 3

Research Methodology

3.1 Introduction

This chapter discusses the research methodology adopted for the current study, which has two major parts. The first part of the study is about how I arrived at the topics of investigation and students' alternative conceptions related to these topics. The second part of the study is related to the development of activity-based modules and their implementation to address the alternative conceptions. In both parts, the sample of the first-year and the second-year undergraduate students was from different state colleges located in different cities in India. The sample was not chosen randomly, but it was a convenient sample.

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 the selection of these broad topics/concepts. Students are introduced to some of the concepts of thermodynamics from their high-school level science courses.

Std.	Topics
7	**Transmission of heat** Definition of heat, heat transfer mechanism, thermos flask, role of heat conductivity, effects of heat, melting point, boiling point, expansion and contraction, bimetallic strip, expansion of liquids and gases, thermometer and its construction, measurement of heat, unit of heat, specific heat, calorimeter
8	Atmospheric pressure
9	**Change of state** Freezing, melting, evaporation, condensation, sublimation, cooling by evaporation, absorption of heat
11	**Thermal properties of matter** Temperature and heat, measurement of temperature, ideal gas equation and absolute temperature, thermal expansion, specific heat capacity, calorimetry, change of state, latent heat, heat transfer
12	**Kinetic theory of gases and radiation** Concept of an ideal gas, assumptions of kinetic theory, mean free path, derivation for pressure of a gas, degrees of freedom, derivation of Boyle's law **Thermodynamics** Thermal equilibrium and definition of temperature, first law of thermodynamics, second law of thermodynamics, heat engines and refrigerators, qualitative idea of black body radiation, Wien's displacement law, Green house effect, Stefan's law, Maxwell distribution, Law of equipartition of energy, and application to specific heat of gases

Table 3.1: Syllabus of class VII to XII for Maharashtra state board (2007)

So they are exposed to these concepts multiple times till they reach their undergraduate level. Therefore they are expected to be aware of them while studying more advanced topics. To understand the areas related to thermodynamics that the students study prior to their undergraduate phase of physics education, I critically looked at the syllabus at the secondary level (science textbooks) and at the higher secondary level (physics textbooks). The textbooks both at the state (Maharashtra state board where the researcher is located) and national level (Central Board of Secondary Education) were looked at for the same. Table 3.1 (*Syllabus of the Maharashtra state board* 2007) and 3.2 (*NCERT Syllabus* 2006) lists the topics from these textbooks.

Std.	Topics
8	Concept of hot and cold, measurement of temperature (laboratory thermometer), heat transfer mechanisms
11	**Thermal properties of matter** Temperature and heat, measurement of temperature, ideal gas equation and absolute temperature, thermal expansion, specific heat capacity, calorimetry, change of state **Thermodynamics** Thermal equilibrium, zeroth law of thermodynamics, heat, internal energy, work, first law of thermodynamics, specific heat capacity, thermodynamic state variables and equation of state, thermodynamic processes, heat engines, refrigerators and heat pumps, second law of thermodynamics, reversible and irreversible processes, Carnot engine **Kinetic theory of gases** Molecular nature of matter, the behaviour of gases, kinetic theory of an ideal gas, the law of equipartition of energy, specific heat capacity, mean free path

Table 3.2: Syllabus of class VIII to XI for CBSE (2006)

Std.	Topics
F.Y.	Concept of heat, the first law, non-adiabatic process and heat is a path function, internal energy, application of first law to simple processes, heat capacity and specific heat, general relations from the first law: enthalpy, the case of an ideal gas, dependence of atmospheric temperature on height above sea level
S. Y.	Reversible and irreversible processes, heat engines and definition of efficiency, Carnot's ideal heat engine, Carnot's cycle, effective way to increase efficiency, Carnot's engine and refrigerator, coefficient of performance, the second law of thermodynamics, Carnot's theorem, Claperyon's latent heat equation using Carnot's cycle and its applications, steam engines, Otto engine, petrol engine, diesel engine, the concept of entropy, change in entropy in an adiabatic process, change in entropy in a reversible cycle, the principle of increase of entropy, change in entropy in an irreversible process, T-S diagram, the physical significance of entropy, the entropy of a perfect gas, Kelvin's thermodynamic scale of temperature, the size of a degree, zero of absolute scale, the identity of a perfect gas scale and absolute scale, the third law of thermodynamics, the zero point energy, negative temperatures, the heat death of the universe

Table 3.3: Syllabus of heat and thermodynamics at the first-year and the second-year undergraduate studies in University of Mumbai (2007)

For the undergraduate level, I looked at the syllabi of the University of Mumbai, as substantial work, particularly the intervention study would be with students enrolled for bachelor courses in colleges affiliated with the University of Mumbai. Table 3.3 (*Syllabus of the University of Mumbai* 2007) gives the topics that are studied at the physics undergraduate level (first-and second-year) in the syllabus of the University of Mumbai. The undergraduate physics course of thermodynamics begins with the revision of basic concepts of heat taught in secondary schools. It then progresses to the laws of thermodynamics and their applications.

Following the syllabus an exhaustive list of 70 core concepts (appendix A) in thermodynamics was prepared. An open-ended study, in which students were asked to present their explanations of these concepts along with examples (if applicable), was conducted with 100 first and second-year undergraduate students from different colleges in Mumbai, Delhi, Kolkata and Bangalore. The purpose of this study was to understand the level of awareness about these core concepts.

Students' responses were categorized as "correct", "incorrect/inadequate," and "not attempted". I have summarized below the typical responses of the students obtained from this survey about the major broad concepts in elementary thermodynamics. I looked at how many students presented the explanation and also the correctness of the explanation. Such analysis helped to understand the concepts that are easy and difficult for the students. Some of the prototypical responses obtained from the students are presented below. These responses also indicated some of the alternative conceptions that students have.

1. Heat:

   "Heat is a form of energy" – was the most common response from the students. According to them, it is the energy that is 'stored' inside a body. Also, another common notion was that transfer of heat would always result in an increase/decrease in the temperature of some object.

2. Temperature:

   Some students consider temperature to be interchangeable with heat. They term temperature as the physical quantity that describes the 'degree of hotness or coldness of a body', with hotness (heat) as some energy contained in the body.

3. Internal Energy:

   The students did not have any clear concept of what internal energy is. Intuitively, for them, heat and internal energy were the same. They could not relate the internal energy of a body to its temperature.

4. Ideal gas:

   Students described ideal gas not through its properties but by using the gas equation, $PV = nRT$.

5. Laws of thermodynamics:

   For students, the first law is often not more than a qualitative statement of the law of conservation of energy. In the case of zeroth law, they realized that this law is about some kind of comparison between thermal states of systems but cannot explain it clearly. They have certainly heard of the terms second law of thermodynamics and entropy but cannot say what they mean.

6. Thermodynamic Equilibrium:

   Most students (43%) equate thermodynamic equilibrium to thermal equilibrium.

7. Heat transfer mechanisms:

   The students take conduction and convection to be identical. Some students feel that gravity is essential for convection to take place. For most students (56%), all radiation is thermal radiation.

It was observed that some of the concepts, e.g. second law of thermodynamics and related concepts, were not attempted by most of the students (78%). Thus it was rather difficult to understand the level of awareness of such concepts.

Based on the analysis of students' responses, a list of 44 most difficult concepts was arrived at. The broad topics that covered these concepts were also listed down. This list was shared with four physics teachers experienced in teaching thermodynamics at the undergraduate level. Detailed discussion sessions were conducted with these teachers where they reflected on the list and their own students' understanding of these concepts. There was a consensus opinion that the list covers most of the concepts that are difficult for undergraduate students. I also consulted the book, Heat and Thermodynamics by Zemansky and Dittman (Zemansky and Dittman 2008), which is a standard reference for undergraduate physics education in India. With inputs from analysis of students' responses, discussion with experienced teachers and the reference book (Zemansky and Dittman 2008), the topics that are difficult for students were narrowed down and are listed below:

1. Heat and temperature
2. Heat transfer mechanism
3. Thermal equilibrium
4. First law of thermodynamics
5. Pressure, elementary kinetic theory of gases
6. Second law of thermodynamics and related concepts

The fifth topic is not directly related to other topics and thus is an independent topic. The sixth topic, the second law of thermodynamics and related concepts, is a more advanced topic as compared to other topics and thus deserves a separate detailed study. Further in the survey, it was observed that very few students presented explanations about the concepts related to the second law of thermodynamics (Cochran and Heron 2006). Thus, it was difficult to have any perceptions about students' understanding regarding this topic.

I, therefore, decided not to investigate these topics and restricted my study to the first four topics given below.

1. Heat and temperature
2. Heat transfer mechanism
3. Thermal equilibrium
4. First law of thermodynamics

3.3 Development of questionnaires to identify alternative conceptions

For these topics, questionnaires (appendix B) consisting of situation-based and short answer types were developed to get more ideas about students' alternative conceptions. The pilot phase involved administering these questionnaires to different groups of students over time (group size ~ 30). These pilot studies' results helped me to modify the questionnaires with respect to content, language and flow. These modified versions of the questionnaires were then shown to senior experienced teachers from different colleges in Mumbai and Bangalore and also to subject experts within the institute. Their critical inputs and careful introspection on the researcher's part led to further standardization 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 the first law of thermodynamics. The first law of thermodynamics does cover concepts related to heat and temperature (topic 1). The topic of heat transfer mechanisms 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 they provided an opportunity to analyze the performance of each test item quickly 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 I analyzed from the short answer type questions in the preliminary studies.

3.4 The 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 the following criterion:

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 easy to tackle when 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. Generally, this topic is presented theoretically without any experimental/laboratory activity. The physics laboratory syllabus of standard XI and XII and the first year and second year of undergraduate physics of the University of Mumbai lists only the following experiments related to thermal physics.

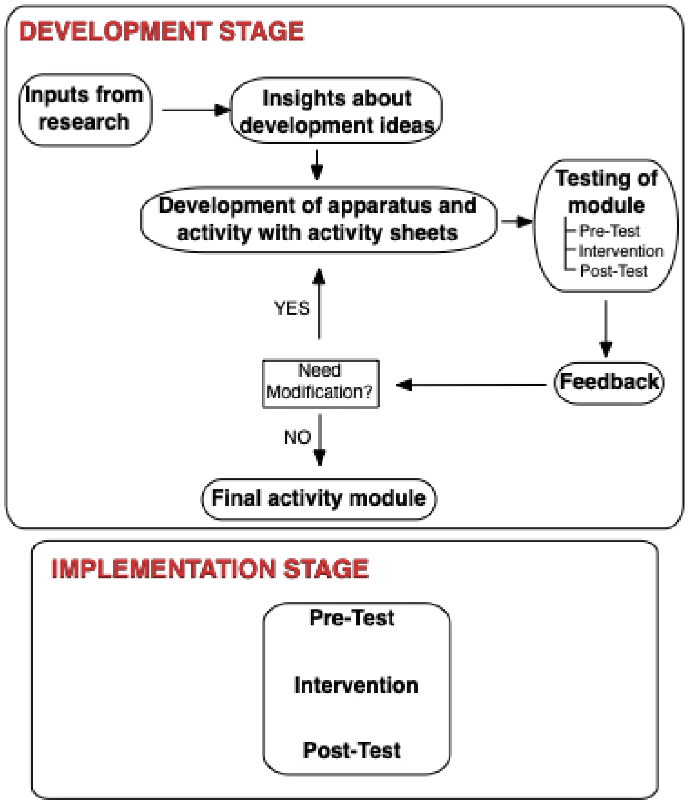


Figure 3.1: Activity-based module – development and implementation stages

- Boyle's Law
- Newton's law of cooling
- Specific heat capacity using the method of mixtures
- J by electrical method
- Constant volume air thermometer
- Constant pressure air thermometer
- Verification of Stefan's law (electrical method)
- Thermal conductivity by Lee's method

The experiments are presented in a typical manner in which the students follow the given procedure to collect the data and analyse it using graphs or equivalent data analysis methods. These experiments do not provide any conceptual questions or discussions on which students can reflect to help them develop a better understanding of the concept. Hence students do not get experiences that can be harnessed to understand the concepts in thermodynamics. Thus, the central thrust of the activity-based modules was to make the concepts observable to students. Further, the emphasis in the activity development process was to generate conflicting situations for students and critically studying their responses to these situations as cognitive conflict is evident from these responses. For both, development and implementation stage, the activities were administered using the POE approach as per the guidelines for conceptual change based activity sessions (Eryilmaz 2002). Students were reminded that their views for these activities are requested at each stage, and these views would not have any bearing on their college academic performance. To the best of my knowledge, this is one of the first such studies that aimed to develop activities for concepts in thermodynamics in the Indian context.

For developing these activity-based modules, I adopted the iterative cycle approach (figure 3.1). The module development process began with a design of the preliminary apparatus, along with activity sheet, needed to address a particular conceptual problem faced by the students about the given thermodynamic concept in the pre-test. The entire development process consisted of multiple cycles of design, testing and modification through feedback received from students' responses from pre-test, post-test and activity sheets. These modified activity modules were tested every time to check students' responses and how they affected students' reasoning. I adopted a quasi-experimental design where a pre-test – intervention – post-test was administered to the students for understanding the effectiveness of the activity module. The pre-test and post-test underwent multiple revisions for language, sequence of questions and content during the development stage. The responses were collected from the individual student as I was keen on studying the reasoning and understanding of each 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 content validity of the final activity module was checked by subject experts.

In the case of thermal equilibrium, I started with an idea to develop an activity-based module around alternative conceptions. However, I felt that it was not adequate in terms of developing a unit. Thus, I decided to include some activities on interlinked basic concepts (prerequisites) so as to approach alternative concepts more effectively. The specific details related to the development of the module which went through 3 iterative cycles are presented in chapter 5.

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 specific details related to the development of the module which went through 3 iterative cycles are presented in chapter 6.

In both the modules, the tests, activities and activity sheets were designed in such a way that the students' understanding could be probed at intermediate stages through their observations for the activities, through graphical representation, through relevant mathematical calculations and through informal interviews conducted to understand their written responses.

3.4.1 Module on thermal equilibrium

1. The pre-and post–tests:

   In thermal equilibrium, the pre-test consisted of two questions aimed at probing students' understanding of thermal equilibrium with respect to material dependence and size dependence, respectively (appendix C).

In the case of material dependence, two cylinders were made up of Brass (metal) and Delrin (insulator). In the case of size dependence, two cylinders were made of small Delrin and large Delrin. In each of the questions, the cylinders were initially at room temperatures. Later they were placed in a water bath maintained at a higher constant temperature. The students were asked to predict the final temperatures of these cylinders.

Each of the questions above had three sub-questions. First sub-question probed their understanding of the final temperatures of the two cylinders. Depending on their option selection second sub-question was presented, which probed their understanding of the final temperatures attained by the cylinders with respect to the temperature of the water bath. The third sub-question probed their understanding of the rate of increase of temperatures of the cylinders while attaining thermal equilibrium. In all the questions, students were asked to justify their choice selection. The post-test was similar to the pre-test. Additionally, students were administered an activity on the method of mixtures. This activity intended to check their understanding by both,

(a) calculating the final temperature of mixture and

(b) by drawing the nature of graph of temperature variation of both substances.

2. Activities

The activity module consists of 4 activities. The researcher carried out the activities, and the students were asked to observe and note the outcome of the activities.

The first activity replicated the situation given in pre-test questions. The three subsequent activities in the module aimed at explaining the process of thermal equilibrium to the students. Students were shown the liquid flow model and heat flow model of thermal equilibrium. In order to understand the analogy between the two models, students were asked to relate the terms in each model through matching the columns. The last activity was the liquid flow analogy of the first activity. This activity attempted to check how different parameters in both models affect the process of attaining equilibrium.

3. Activity sheets

   The five activity sheets corresponding to five activities (4 activities + 1 post-test activity on the method of mixtures) are given in appendix D. Each activity sheet was designed to elicit prediction from students, note down the corresponding observations from the activity shown and explain the discrepancy (if any). These activity sheets evolved in terms of the description related to the apparatus of the activity and the questions related to the activity. These activity sheets were finalized after receiving input from each of the iteration cycles.

   The activity sheets consisted of two parts - one that describes the apparatus/activity. The other part was to present questions that students were supposed to answer before and after the activity. The questions were designed to encourage the students to explore discrepancies between their responses and observations. In addition, space was provided for writing down the justification for the discrepancy (if any) between their prediction and observations and for drawing sketches of the graphs.

4. Implementation of the module

   I selected students from the first-and second-year of the bachelors' programme of science colleges in Mumbai. The study was entirely voluntary for both the control as well as the experimental group.

   The control group was administered only the tests, and the activities were not given to it. The experimental group was administered the complete module. The students worked on activities for 3 hours immediately after the pre-test. The post-test was given to both the control and the experimental groups one week after the pre-test. During this 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 at the laboratory in HBCSE for the complete module, whereas 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.

3.4.2 Module on the first law of thermodynamics

1. Pre and post-tests (appendix E)

   In the module on the first law of thermodynamics, the pre-test consisted of two processes: 1. Adiabatic compression and 2. Isothermal compression. Students were asked to predict the change in pressure, temperature and internal energy of the system. They were also asked to comment on the work done and net heat flow during the process. Students were asked to justify their choice selection.

   The post-test was similar to the pre-test but with additional questions on the expansion process. During the activity module, students were shown both adiabatic and isothermal compression processes through different tasks. They were expected to extend their understanding of applying the first law in the compression process to the expansion process in the post-test.

   In the end, students were given a table completion task. In this task, students were asked to categorize the quantities (like $Q = 0$, $\Delta T = 0$ etc.) under adiabatic and isothermal processes. This task was aimed at gauging their overall understanding developed through the activity module.

2. Activities

   The activity module consisted of 4 activities. The first activity aimed at familiarising students with the temperature sensor and heat flow indicator. The second activity consisted of an equivalent Joule's apparatus which showed the work done as an energy transfer mechanism. In the third activity on adiabatic compression, students were given three tasks. The first task was to familiarise them with the adiabatic process in practice, which consisted of a plastic syringe and a thermocouple. In the second task, students were introduced to the fire syringe, and a discussion session was conducted with the students using Fourier's equation of conduction on what it takes to make a process adiabatic. In the third task, students were shown a video of the fire syringe with zero net heat flow reading. Then they were also shown the calculations of different energy terms in the first law of thermodynamics related to adiabatic compression.

In the fourth activity on isothermal compression, students were given two tasks. In the first task, students were asked to carry out isothermal compression using a plastic syringe connected to a copper container with a thermocouple. The second task was a video on isothermal compression in which they were shown the values of pressure, temperature and heat flow during the process.

In this module, students were asked to perform some of the activities so as to get a feel of the adiabatic and isothermal processes in practice. The apparatus of the activities were easy to handle and did not require any additional skill on students' part.

3. Activity sheets (appendix F)

   The four activity sheets corresponding to four activities along with the information sheet are given in appendix F (F.1 - F.5). Though the activity sheets were self-explanatory, an initial demonstration for each activity was provided by the researcher. An information sheet was provided to the students explaining to them the sign convention for heat flow and work done. Students were provided space to note down their observations and also to justify the observed values.

4. Implementation of the module

   I selected a sample of students from the second year of the bachelors' programme of science colleges in India. The control group was administered only the tests, and the activities were not given to it. The experimental group was administered the complete module. The students worked on activities for 5 hours immediately after the pre-test. The pre-test and the post-test lasted for one hour each. For this module, since it was possible to carry the apparatus, the sample was collected from different colleges in India. The post-test was given to both the groups a week after the pre-test and the administration of the activities. During this one week, the students from both control and experimental groups attended their regular academic physics courses, which had almost the same content. These courses, however, did not include thermodynamics.

3.4.3 Data analysis for both 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-and post-tests of each (control and experimental) group to check the improvement in students' understanding due to the activity-based module. Students' qualitative responses from pre-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. The first law of thermodynamics, 4. Heat transfer mechanisms.

4.1 Heat and temperature

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, Alwan 2011, Suliyanah, Putri, and Rohmawati 2018). The literature provides a list of alternative conceptions arising from 1. daily life experiences, e.g., water always boils at the same temperature, (Luera, Otto, and Zitzewitz 2005), 2. cultural metaphoric reasoning, e.g., a cruel person is really cold, because such people are called cold-hearted dragons (Lubben, Netshisuaulu, and Campell 1999), 3. language related to heat and temperature, e.g., metals attract, hold, or absorb cold (Lewis and Linn 1994) and 4. textbooks, e.g., The majority of the textbooks (eight) use the conception of heat interchangeably as transit energy (Leite 1999). Therefore, it will not be surprising that alternative conceptions in heat and temperature are commonly found among students entering a thermal physics class.

The pilot study was conducted with 31 second-year undergraduate students from a college in Mumbai. A questionnaire consisting of 7 short answer questions was administered to this sample. The questions were based on probing 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 the standardization 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 a college in Mumbai. After preliminary analysis of students' responses, nine students were interviewed to gain greater insight into their reasoning and thinking.

Students' prototypical responses

When asked to explain, what heat is, many students did not go beyond the statement "Heat is a form of energy" (Sözbilir 2003). As observed in the study, 65% of students could not differentiate between "heat" and "temperature", and they used these terms interchangeably (A. Harrison 1996, Jara-Guerrero 1993, Kesidou and Duit 1993, Erickson 1985).

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 that heat might also lead to external work.

Some students stated that temperature measures '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 of students' responses confirmed that thermal equilibrium is an area where students had conceptual difficulties (Erickson 1985). I asked students, in the questionnaire, about the temperature attained by a body kept in a hot enclosure for a sufficiently long time. According to many students, the temperature attained depends on the material or the size of the body.

When probed about the nature of temperature, some students answered that if a gas container is partitioned into two unequal compartments, their temperatures will be different. They seemed to consider temperature to be an extensive quantity proportional to volume (Kartal, Öztürk, and Yalvaç 2011).

4.2 Thermal equilibrium

In my study on heat and temperature, I 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 of thermal equilibrium. I was also keen to understand whether students appreciate that when a system is in mechanical, chemical and thermal equilibrium, it is said to be in thermodynamic equilibrium. I developed the questionnaire consisting of 11 multiple-choice questions in the following 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 pilot study was conducted with 22 second-year undergraduate physics students from a college in Mumbai. The distractors were developed, and the questionnaire was modified based on the students' responses in the pilot study. This modified questionnaire was administered to a sample of 291 (first and second year) undergraduate students, 251 from Bangalore and 40 from Mumbai. Next, I discuss students' responses to questions in the above categories.

1. Understanding thermodynamic variables and thermodynamic equilibrium

   Students were given a situation where 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 out of the four alternatives given. About half (52%) 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 the average velocity per molecule. Some students (25%) also considered the position of the centre of mass of the system as a thermodynamic variable.

   Another question asked the students explicitly what a thermodynamic variable meant to them. It was somewhat surprising to note that a good 36% of 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 21% of students which might have even come through a random choice.

   From the responses to another question, it seemed that for students (39%), 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.

2. Confusion between adiabatic and diathermic walls

   In thermodynamics, an adiabatic wall corresponds to a wall, which does not allow the exchange of heat through it, and a diathermic wall allows the exchange of heat through it. In one of the questions, the students were asked to categorize materials according to their suitability as 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 categorizing the materials. Many students considered glass, paper and concrete as diathermic.

   Response 1: "... coffee feels hot through glass..."

   Response 2: "... paper burns..."

   Response 3: "... in summer concrete roof becomes hot... (which) makes us feel hot..."

   In these examples, students should have considered the thermal conductivities of glass, paper and concrete, which are very low. It is necessary to understand that for an adiabatic wall, these low thermal conductivity materials will take a 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.

3. 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 (43%) 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 would attain a higher temperature than the bigger cube. They reasoned that both the bodies receive the "same amount of heat" and the same amount of heat will increase the temperature for the smaller body. The interviews of the students confirmed this fact.

Response 1: "... smaller cube will acquire greater temperature as it will require less heat to do so..."

Some students argued that out of two bodies with the same material but different sizes, the larger body would have a larger temperature. For these students, a larger body necessarily has a larger surface area, and the larger surface area will absorb more heat and hence lead to a greater temperature.

4. 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. 64% 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, whereas 11% of students replied that the temperature of the wooden cube would be greater than the temperature of the copper cube. Only a small minority (10%) opted for the correct alternative that both the cubes will attain the same temperature as that of the enclosure. The 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. An interesting statement made by a student was

   "...Wood (being a bad conductor of heat) will resist the change in temperature".

5. Effective temperature of the mixture

   For a question, on the final temperature of the mixture of two identical samples of liquid initially at different temperatures (34°C and 96°C), 38% of students gave the correct answer (65°C). Surprisingly, almost an equal number of students (32%) gave the difference of two initial temperatures (62°C) as the answer.

4.3 First law of thermodynamics

I observed in the open-ended study (appendix A) 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.

In the case of the first law of thermodynamics, in general, all three quantities Q, dU and W need to be non-zero. I found that, especially in the context of students' background, such a general case was rather difficult to comprehend. Therefore, I decided to limit myself to the cases of adiabatic ($Q = 0$) and isothermal ($dU = 0$) processes leading to simple situation where only two energy terms becoming non-zero. Further, both the adiabatic and isothermal processes are important processes by themselves in elementary thermodynamics. I designed tests to probe students' understanding of the first law of thermodynamics as applied to adiabatic and isothermal processes, particularly adiabatic and isothermal compression of an ideal gas. 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

For an adiabatic process, since there is no transfer of heat, students stated that there should not be any change in temperature (Barbera and Wieman 2009, Kautz et al. 2005, Leinonen, Räsänen, et al. 2009, Loverude, Kautz, and Heron 2002). Similarly, since the word isothermal means that the temperature remains constant, many students thought that there would not be any heat transfer from/to the system. Thus, they seemed to know that heat and temperature are not identical, but both these terms were inseparable for them at an intuitive level. 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). For questions related to compression of a gas, isothermally or adiabatically, students could correctly state the increase in pressure. However, while explaining the increase in pressure, they used the ideal gas equation and interpreted that there also will be an increase in temperature in the compression process.

Internal energy

According to the students, in isothermal compression, the work done on the system would increase the 'heat content' of the system. For students, the energy pumped into the system due to work done has to increase the system's energy content, which they accounted for as the increase in the heat content of the system. However, they ignored the fact that the change in internal energy is zero in an isothermal process. They seemed to consider 'heat content' equivalent to internal energy (Zemansky 1970, Meltzer 2004, VanRoon, VanSprang, and Verdonk 1994, Loverude, Kautz, and Heron 2002). For questions related to adiabatic compression, students stated that the change in the internal energy would be zero as there was no heat transfer (Meltzer 2004, Loverude, Kautz, and Heron 2002). I observed that, for some students, the internal energy of the system decreased due to some kind of 'natural' dissipation of internal energy over time, and since there was no heat transfer, the internal energy did not get replenished. I found that students seemed to be unaware that the internal energy could be changed due to heat transfer as well as external work done.

In the case of isothermal compression, many students predicted that the system's internal energy 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' (Zemansky 1970, Meltzer 2004, VanRoon, VanSprang, and Verdonk 1994, Loverude, Kautz, and Heron 2002). Students seemed to be unaware of the fact that the change in the internal energy can be brought about not only by processes due to heating but also by the external work done on the system (Barbera and Wieman 2009, Kautz et al. 2005, Loverude, Kautz, and Heron 2002). Many students showed a lack of awareness about how internal energy and temperature were related (Barbera and Wieman 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. While responding to questions related to both the processes, students seemed to ignore the dependence of internal energy on temperature for an ideal gas. They often correlated temperature only with the term heat rather than to internal energy.

Sign convention

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

4.4 Heat transfer mechanisms

Students often encounter different heat transfer mechanisms, namely, conduction, convection and radiation, in their daily life. I conducted a pilot study with 22 undergraduate students. They were given open-ended short answer type questions on conduction, convection (natural and forced) and radiation. Students' responses indicated that they were quite familiar with conduction but not with convection and radiation. Based on this input, a short answer question test was prepared and then administered to a sample of 57 undergraduate students in which the students were supposed to label as conduction, convection or radiation and justify their choice. Further, I interviewed 12 students to gain greater insight into the justification provided. I describe, below, students' prototypical explanations in each case (conduction, convection and radiation). These explanations revealed multiple alternative conception/s (Pathare and Pradhan 2010).

Students' prototypical responses:

Conduction

In conduction, I give below two situations involving conduction which the students were asked to comment on.

Situation 1. *When a metal rod is heated at one end, the other end becomes hot*

In metals, at normal temperatures, the contribution to thermal conductivity by free electrons is much more dominant than the contribution of lattice vibrations. Some students felt that electrons are released at the heated end and travel to the other end, transferring, in the process, their energy. Some of them also regarded heat as a fluid. According to them, the conduction corresponds to the expansion of the fluid from the hot end.

A response by a student: "...if we heat the metal at one end, the hotness of one end of the metal expands as there is space on the other side of the rod... ".

Situation 2. *Two rods, one steel and one wooden, are kept in an air-conditioned room for a long time. When touched, the steel rod feels colder than the wooden rod*

70% of students responded to this situation by saying that steel radiated heat more than wood and was therefore at a lower temperature than wood. Some also said that steel "absorbs" more cold than wood.

Convection

In convection, students were presented with two situations corresponding to natural convection and forced convection.

Situation 1. *A beaker containing water is put on a burner. After some time, water at the top also becomes hot*

This is an example of natural convection. The density difference between the hotter water at the bottom and the cooler water at the top sets up convection currents in the water.

Some students considered water as a good conductor of heat like metals. Some felt that the water carries electrons, which transfer heat from the lower end to the upper end. 44% of students said that ‘cooler water molecules’ are heated by ‘warmer water molecules’, and thereby attributed hotness to a single molecule.

Situation 2. *Drying hands by a hot air blower*

The hot air blower is an example of forced convection in which air blown from the blower passes over a heater coil, thereby giving rise to hot air. For the students, however, the hot air is an intrinsic property of the air blower. They seemed to be unaware of the actual process of hot air production. They considered the heat to be conducted from the blower to the hand through an air column, disregarding the presence of the heating coil.

Some other students related this phenomenon to radiation emanating from the blower. They seemed to disregard the movement of air due to the blower.

Radiation

I asked students to comment on one situation with respect to radiation.

Situation: *We receive from the Sun not only light but also heat*

Some students felt that heat attributed to the Sun originates terrestrially due to the interaction between the electromagnetic waves coming from the Sun and the matter on the surface of the Earth. Some students thought that heat energy arises due to “friction” between air molecules and the electromagnetic radiation from the Sun. Some students said that there is some medium between the Earth and the Sun, and the molecules of this medium from the Sun to the Earth conduct heat.

4.5 Conclusion

From the study, what I found with respect to students' understanding in these four topics 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 external work as a mechanism by which internal energy can be changed.

5. Students have difficulty 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 the size and material of the objects.

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

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

9. In the 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 pertaining to the fourth topic, "heat transfer mechanisms" are rather disjoint from those in the first six enumerated earlier. The statements 1 to 6 form a unit pertaining to elementary thermodynamics. Therefore, from the point of view of further work, I felt that I should consider the first three topics: heat and temperature, thermal equilibrium, and the first law of thermodynamics more than the fourth one.

4.6 Publications from the part of this chapter

1. Pathare, S. R., Pradhan, H. C. (2007). Students' Alternative Conceptions on Heat and Thermodynamics. A poster presented at a conference on National Initiative in Science Education.

2. Pathare, S. R. and Pradhan, H. C. (2004). Students' Alternative Conceptions in Pressure, Heat and Temperature. Proceedings of episteme-1, International Conference to Review Research on Science Technology and Mathematics Education, Mumbai, India. 38 – 41.

3. Pathare, S. R., Pradhan, H. C. (2005). Students Alternative Conception in Pressure, Heat and Temperature. Physics Education, 21, No.3 - 4, p 213 - 218.

4. Pathare, S. R., Pradhan, H. C. (2005). Students' Misconceptions about heat transfer mechanisms and elementary kinetic theory. Presented at International Conference on Physics Education, New Delhi.

5. Pathare, S. R., Pradhan, H. C. (2010). Students' misconceptions about heat transfer mechanisms and elementary kinetic theory. Physics Education, Institute of Physics, UK, 45, 629.

6. Pathare, S. R. and Pradhan, H. C. (2011). Students' understanding of thermal equilibrium. Proceedings of episteme - 4, International Conference to Review Research on Science Technology and Mathematics Education, Mumbai, India. 169 –172.

7. Pathare, S. R., Huli, S. S., Ladage, S., Pradhan, H. C. (2014). Students' understanding of first law of thermodynamics. Conference booklet of GIREP-MPTL International Conference, Palermo, Italy 330 - 331.

8. Pathare, S. R., Huli, S. H., Ladage, S. A., Pradhan, H. C. (2018). Understanding First Law of Thermodynamics through Activities. Physics Education, Institute of Physics, UK, (53)2, 1 - 18.

9. Pradhan, H. and Pathare, S. R. (2016). Students' conceptions in heat and elementary thermodynamics. Physics News, 46(3 - 4), 53- 62.

Chapter 5

Module on Thermal Equilibrium

The current chapter discusses the activity module on thermal equilibrium, its development and implementation study. The chapter also presents the development of instrumentation related to the measurement of different parameters integral to the module on thermal equilibrium and the module on the first law of thermodynamics.

5.1 Development of instrumentation for activity modules

One of the important aspects of activities was the development of instrumentation related to measuring the parameters such as temperature, pressure, heat flow and liquid flow. The typical sensors needed are temperature sensors, pressure sensors, heat flow sensors and liquid flow sensors. Temperature sensors like mercury thermometers, thermistors, thermocouples are used quite regularly at the undergraduate level. However, the latter two are not very commonly known. During the developmental work, I spent a considerable amount of time developing some of these sensors in the laboratory. I also worked on choosing appropriate materials for developing containers whose walls can allow heat transfer (diathermic) and can resist the heat transfer (adiabatic) as per the situation required in the activity. For the measurement of these individual parameters, a dedicated apparatus and software interface was developed. The following section presents a discussion of the development of instrumentation related to each of the above parameters.

Temperature

For the range of temperatures that were required to be measured, a chromel-alumel thermocouple (figure 5.1) already available in my laboratory was quite suitable.

Figure 5.1: Chromel Alumel thermocouple

As the increase in temperature in one of the activities was rather quick, it necessitated a development of a data acquisition system (figure 5.2).

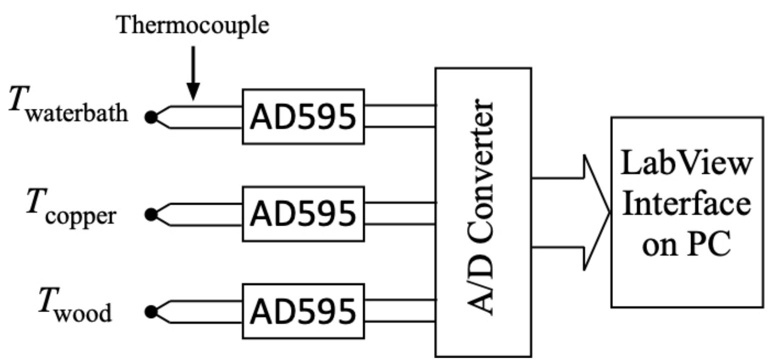
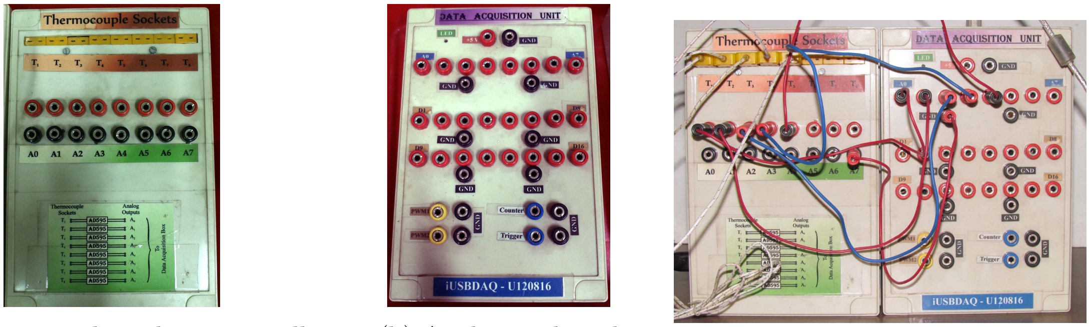


Figure 5.2: Block diagram of data interfacing unit

The data received from the thermocouple was amplified and then fed to this system (figure 5.3).



(a) Thermocouple sockets internally connected to AD595 amplifier (b) Analog to digital converter (c) With connections

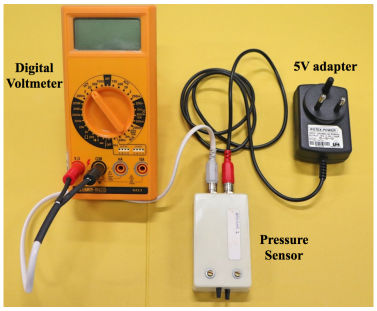
Figure 5.3: Data interfacing unit for temperature measurement

The LabView software was used to process and display the data. In the activities where the data-acquisition of temperature variation was not required, the chromel alumel thermocouple was connected to the handheld digital thermometer (figure 5.4).

Figure 5.4: Chromel Alumel thermocouple with digital thermometer

Pressure

The range of pressures to be measured, varied with activities. For the activity involving isothermal compression, the expected range was 0-10 kPa whereas for the activity involving adiabatic compression it was 0-200 kPa. The corresponding four pin Motorola sensors were procured, assembled (figure 5.5a) and then calibrated with a pressure sensor bought from PASCO (figure 5.5b).



(a) Pressure sensor using Motorolla IC

(b) PASCO pressure sensor for calibration

Figure 5.5: Pressure measurement

Heat flow indicator

For the heat flow measurement, the sensors available in the market were rather expensive. I devoted a considerable amount of time to develop the required heat flow sensors in the laboratory initially using thermistors and later using pairs of thermocouples. This, however, turned out to be technically unsatisfactory in design. Finally, I thought of using 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 (figure 5.6). I confirmed from literature in industrial electronics (McKinnon et al. 2010) that this device could indeed be used as a heat flow indicator.

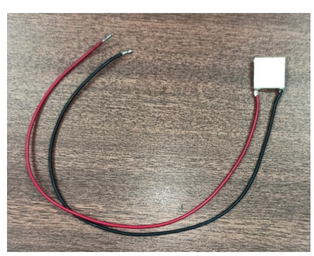


Figure 5.6: Peltier module

Liquid flow indicator

In one of the modules on thermal equilibrium, where an analogy between thermal equilibrium and hydrostatic equilibrium was used, a liquid flow sensor was needed. Just like heat flow sensors, liquid flow sensors available in the market are relatively expensive. I consulted the experts for this purpose from the Institute of Chemical Technology, Mumbai, but the options suggested by them were costly. Hence, I developed an in-house low-cost liquid flow indicator using commonly available materials like plastic tubes and ball pen refill springs. A small piece of refill was emptied and sealed at both its ends using Araldite adhesive. Two small sections of ballpen-springs were attached to both the sealed ends (figure 5.7).

Figure 5.7: Floater

This floater was positioned in an acrylic pipe. The acrylic pipe was held upright and was connected to two cylinders using silicon pipes and a three-way valve (figure 5.8).

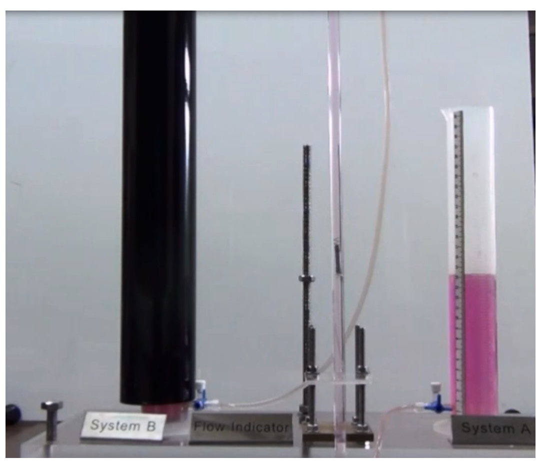


Figure 5.8: Floater in the acrylic tube

When the valve was opened, the water flow started between the cylinders and the floater was pushed up due to the flow. As the flow decreased the floater slowly moved down and finally settled at the bottom as the liquid flow became zero.

5.2 Development of the module

The apparatus and software developed for this module are as follows:

1. Constant temperature water bath with stirrer (figure 5.9b)
2. Data interfacing unit for recording temperature variation (figure 5.3)
3. LabView interface for observing comparative temperature variation
4. A container with two compartments separated by a graphite (diathermic) wall and fitted with two thermocouples and a heat flow indicator (figure 5.18b).

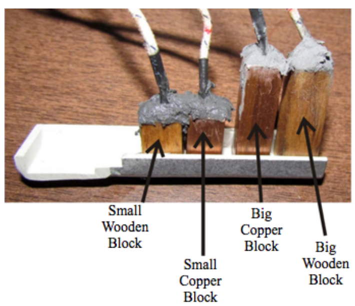
My work (section 4.2) indicated that students had difficulties in predicting the final temperatures of different material/size blocks immersed in the hot water bath. To address this difficulty, I decided to design an activity to show the real-time variation of temperature of the blocks from their initial 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 the same size and ii. when they are of different sizes but of the same material. The real-time temperature variation of these cylinders, as seen on the graphical interface, would be contradictory to their prediction, and therefore it has the potential to generate cognitive conflict.

The activity module development went through 3 cycles. In Cycle 1, the apparatus required for this activity (5.2.1) along with the activity sheets was developed, and the activity was tested with a sample of students. Based on students' responses in cycle 1, appropriate modifications were done in this activity in cycle 2. It was also realized from the testing in cycle 2 that along with this modified activity, additional activities were necessary for a comprehensive understanding of thermal equilibrium. The modified activity (5.2.2) along with the additionally developed three activities were finalized as a module in cycle 3 (5.2.3). In each cycle, the module was administered to a different sample of students. I modified the design as well as the activity sheets in each cycle.

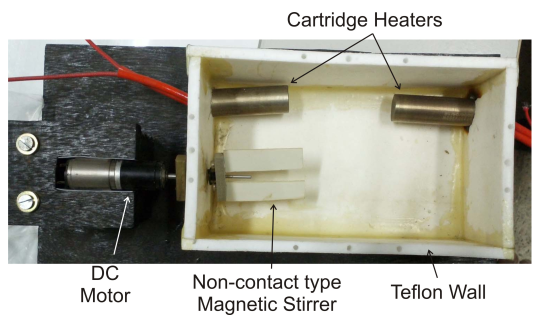
5.2.1 Cycle 1

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 (figure 5.9a) and a constant temperature water bath (figure 5.9b).



(a) Copper and wooden blocks



(b) Constant temperature water bath with stirrer

Figure 5.9: The apparatus

For the constant temperature bath, a cartridge heater was used and a non-contact type stirrer was developed. I used chromel alumel thermocouples to monitor the temperatures of blocks and the water bath. The outputs of these thermocouples were fed to a desktop computer through a data-interfacing unit (figure 5.2 and 5.3) with the LabView interface (figure 5.10).

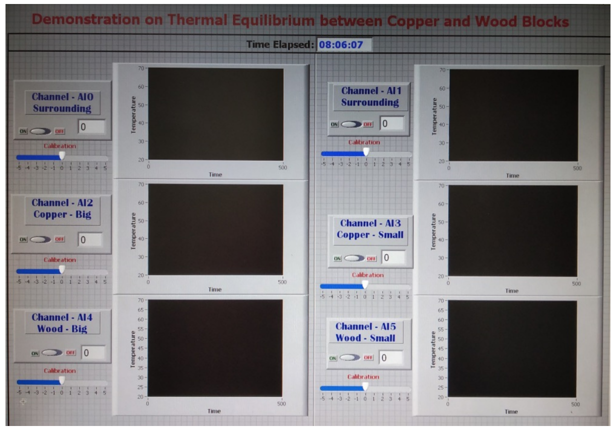


Figure 5.10: LabView interface for observing the temperature variation

The temperature variations of the blocks and the water bath was monitored with the assembly (figure 5.11).

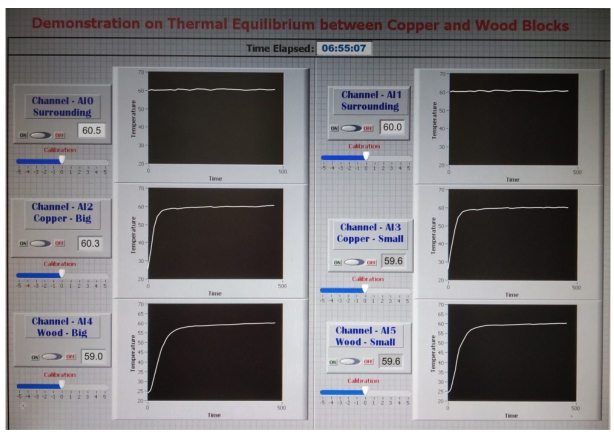


Figure 5.11: Temperature variations

This activity was administered to the group of 25 undergraduate students using POE approach. Each student was asked to predict the final temperature of these blocks. They were also asked to draw the graphs of the temperature variation of blocks. Later the activity was demonstrated to the students. Then they were asked to comment about the discrepancy (if any) between their prediction and the observation. Informal interviews

were conducted with six students to probe and understand their written responses.
The post-test and activity sheet responses indicated that 13 (out of 25) students were still of the opinion that the copper block would be at a higher temperature than the wooden block. Despite observing the real-time temperature variation, these students could not appreciate the attainment of thermal equilibrium and therefore did not find any discrepancy in their prediction and observation. Analysis of justification and responses in the interviews (presented in appendix G.1.1) helped me to identify the possible reasons for these incorrect responses, which were as follows.

1. Six separate windows for showing the temperature variation (figure 5.11) compelled students to pay attention to six different windows simultaneously. It did not generate an "obvious" clear comparison of temperature variations of two cylinders under study (appendix G.1.1).

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. These students used this observation to conclude that the two blocks would be at different temperatures at all times to be consistent with their prior understanding (appendix G.1.1).

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

On the basis of observed difficulties in cycle 1, I modified the activity as follows:

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. Brass

was chosen as it is a softer material than copper and allowed ease in shaping the cylinders of required size (figure 5.12a and 5.12b).

(a) Brass and Delrin cylinders

(b) Delrin cylinders of different sizes

Figure 5.12: Brass and Delrin cylinders

2. The plots of temperature variation were combined in pairs in one window as:

    (a) Big brass cylinder and big delrin cylinder (different materials)

    (b) Big delrin cylinder and small delrin cylinder (different Sizes)

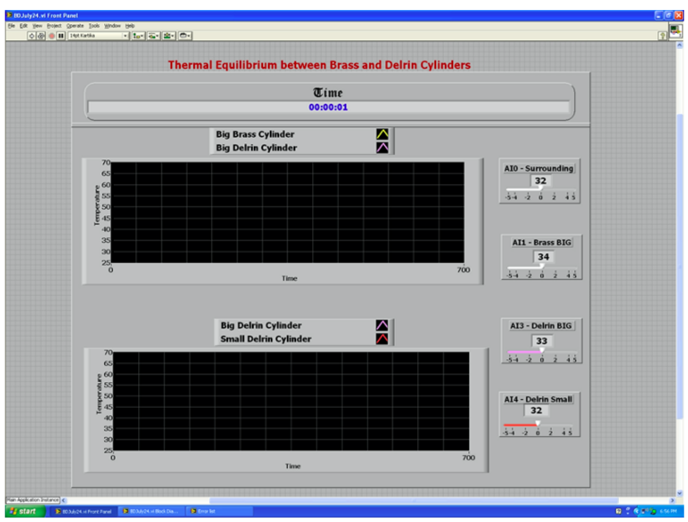


Figure 5.13: The modified interface

Modifying the interface in this manner (figure 5.13) limited students' attention to only two windows. This made it convenient for the students to not only observe the individual temperature change of cylinders, but also observe an "on the spot" generated comparison of temperatures.

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.

In the activity sheets (appendix D.1), students were asked to observe the final temperatures attained by the cylinders and the temperature rise in case of each cylinders in all the combinations. They were also asked to draw the sketch of the graphs observed in the space provided in different colours i.e. red and green in each case (figures 5.14 and 5.15).

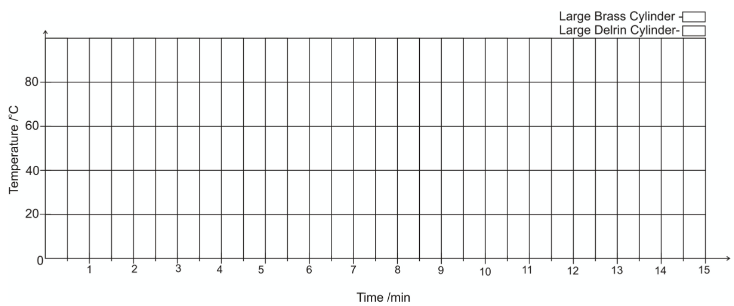


Figure 5.14: Graphical representation of temperature profiles - material dependence

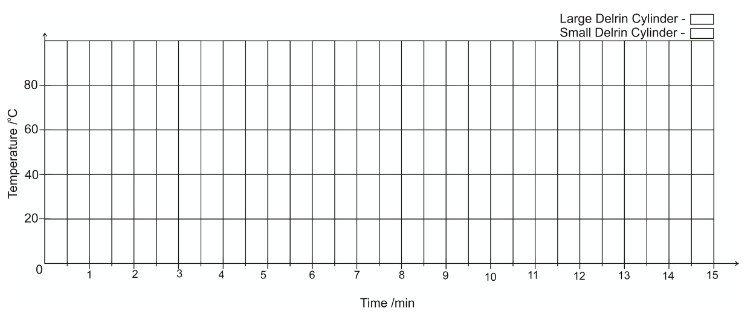


Figure 5.15: Graphical representation of temperature profiles - size dependence

After the observations space was provided to comment on the difference (if any) in their predictions and observations with a justification for the difference.

This modified version of activity was administered to another group of 25 undergraduate students. In this modified version of the activity, the real-time attainment of thermal equilibrium was clearly evident thus making the conflict explicitly visible to the students (figure 5.16).

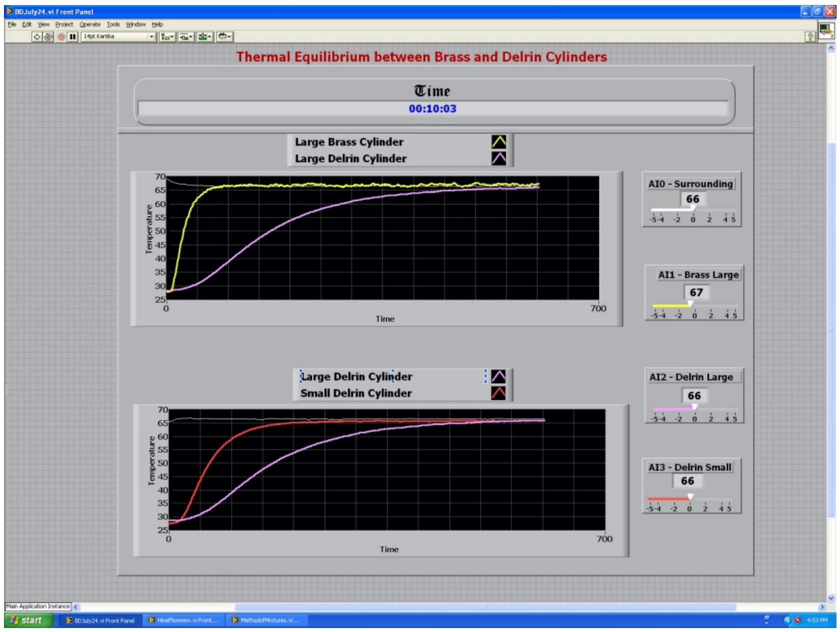


Figure 5.16: Screenshot of the activity 5.1

The responses of the students in post-test indicated that 76% of students were convinced that the final temperature attained for both the cylinders should finally attain the temperature of the water bath. During their prediction, 84% of the students attributed the final temperatures of the cylinders to their thermal conductivities/specific heats. In their explanations after the activity, students admitted that these properties would decide only the rate at which the temperatures of these cylinders will rise and not their final temperatures. They stated that the final temperature of these cylinders would be equal to the temperature of the surroundings (i.e. water bath) they are in contact with. In the interviews with ten students, they clarified that each cylinder finally attained the same temperature equal to that of surroundings (appendix G.1.2). Moreover, the students were asked to go beyond this activity in the interview sessions and explain what they meant by thermal equilibrium. During the interviews, all the students said that two bodies would be at thermal equilibrium if their temperatures were equal. They did not seem to be aware of the role of heat flow (appendix G.1.2). Further probing indicated that the students were clueless about the nature of heat flow during thermal equilibrium. Some of them mentioned that since there is no instrument to measure heat flow, it would be difficult to comment on the role of heat flow with respect to thermal equilibrium.

Thus to address this problem, a new set of activities, which would introduce students to the relationship between heat flow and thermal equilibrium, were developed.

5.2.3 Cycle 3

From cycle 2, I observed that it was important for students to understand the fundamental idea underlying thermal equilibrium that two objects in thermal contact are said to be in thermal equilibrium when the net transfer of heat between them is zero. In order to help students appreciate this idea, I decided to use an analogy between hydrostatic equilibrium and thermal equilibrium.

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.

The reason for choosing the liquid flow analogy is that the students are familiar with the concepts of liquid flow and hydrostatic equilibrium (base domain) from their school days and everyday experience. Students know the concept of thermal equilibrium (target domain), but their understanding is non-normative (Brown and Clement 1989). I felt that this analogy would help students restructure their understanding and help them understand the role of net heat flow in attaining thermal equilibrium.

The analogy was introduced in the form of two activities – the liquid flow model and the heat flow model. For simplicity, in the liquid flow model, I took two liquid containers, as hydrostatic systems, 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. I, then, developed a heat flow model of thermal equilibrium in which two compartments were separated by a diathermic wall, and a Peltier device attached to the wall, was used as heat flow indicator. These activities were implemented using the POE approach. Students were then presented with an activity to match the concepts undergoing similar changes from both domains.

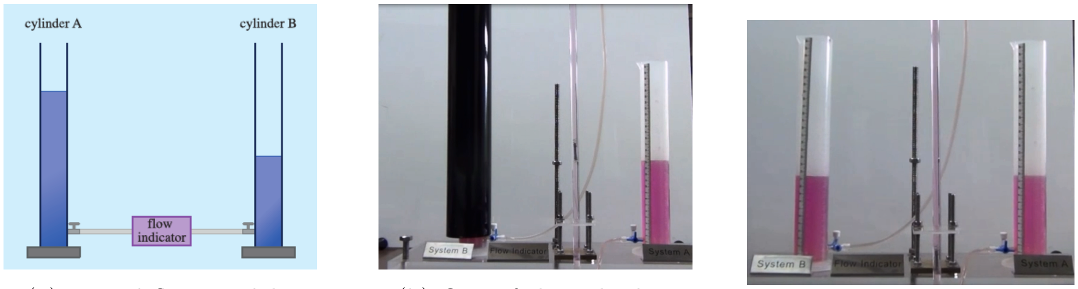
Finally, I thought of extending the liquid flow analogy to Activity 5.1. In this activity, students were demonstrated the dependence of attaining hydrostatic equilibrium on different parameters like the diameter of the connecting pipes and the base area of the receiving cylinders.

In order to check students' ability to apply their understanding gained (through Activity 5.1 and activities added in the present cycle) to a new situation, an activity on the method of mixtures was developed.

In cycle 3, during the development, 41 students (first-and second-year undergraduate students) from 3 different colleges in Mumbai participated.

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 5.17). Next, 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. This sequence of steps was explained to the students in the activity sheet (appendix D.2).



(a) Liquid flow model - schematic

(b) One of the cylinders covered

(c) Hydrostatic equilibrium

Figure 5.17: Liquid flow model

Before cylinder B was uncovered, the students were asked to predict the level of the water columns in cylinders A and B, when the liquid flow becomes zero. Then the cylinder B was uncovered and students were asked to observe the outcome of the activity. Space was provided for justification, if there was any difference between their observations and prediction.

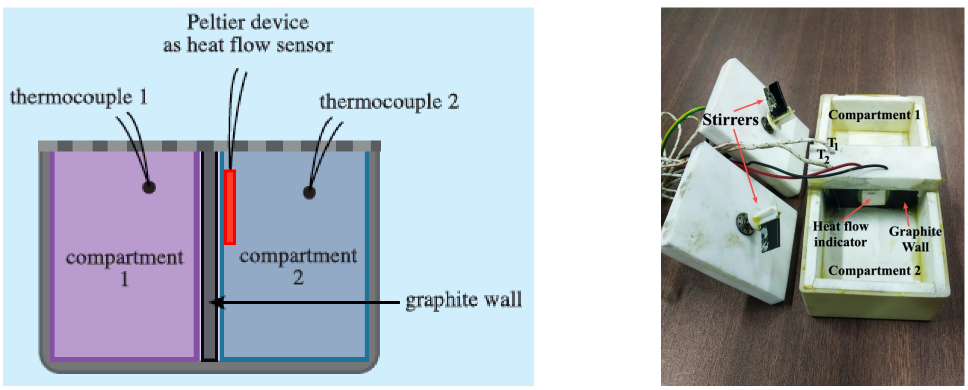
Students' proto-typical responses

All the students predicted rightly that the water column heights in the cylinders would be equal. When cylinder B was uncovered, the students observed that both water columns had the same height as they had predicted. One of the students stated that "...liquid flows from a region of high pressure to low pressure until the pressure becomes equal...so water will flow from cylinder A to B till the levels match.."

Activity 5.3 Heat Flow Model of thermal equilibrium

The aim of this activity was to demonstrate that when two systems with different temperatures are brought in thermal contact with each other, heat exchange takes place between the systems on account of their temperature difference. I wanted the students to appreciate the fact that when the net heat flow between the systems becomes zero, thermal equilibrium is attained. This attainment of thermal equilibrium can be seen in the form of the final temperatures of the systems becoming equal.

In this activity a container made up of insulating (Teflon) walls was used. This container had two compartments separated by an air gap. This air gap acted as an adiabatic wall (figure 5.18a). When a diathermic wall in the form of a graphite sheet was fixed in this gap the two compartments exchanged heat (figure 5.18b). The heat exchange was monitored using the Peltier device used as a heat flow indicator. The output terminals of thermocouple 1, thermocouple 2 and the heat flow indicator were connected to a data acquisition system.



(a) Heat flow model (b) The heat flow model apparatus

Figure 5.18: Heat flow model

The activity sheet (appendix D.3) began with the explanation of the apparatus. Separately, students were also explained the apparatus in person. Before the activity was performed, the students were asked to draw rough sketches of the output of the heat flow indicator, thermocouple 1 and thermocouple 2.

From the liquid flow model activity, the students had observed:

1. the movement of the floater in the liquid flow indicator when the flow started
2. the changes in the heights of liquid columns
3. when the liquid flow becomes zero, the heights of liquid columns become equal.

I expected that the students would recall this observation and use it for predicting the nature of graphs in the heat flow model.

Then they were shown the activity. In this activity, compartment 2 was filled with water at room temperature and compartment 1 with water at 60°C. The compartments were closed with the lids, which were fitted with a stirrer assembly.

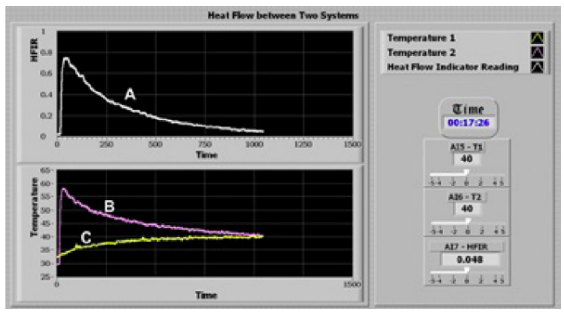


Figure 5.19: LabView interface - heat flow model

This screenshot of the graphs (with three regions marked A, B and C) 5.19 was given to the students after the activity. Students were asked to explain these regions with justification. 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.

Students' proto-typical responses

The nature of the graphs predicted by them in the activity sheets were correct (figure 5.20). From the analysis of students' prediction graphs, I found that,

1. Initial temperatures of water in both the compartments were correctly indicated

2. The heat flow indicator reading graph started from initial high value and gradually decreased to zero

3. As the heat flow indicator reading became zero, the temperatures of water in both the compartments reached an equal and intermediate value.

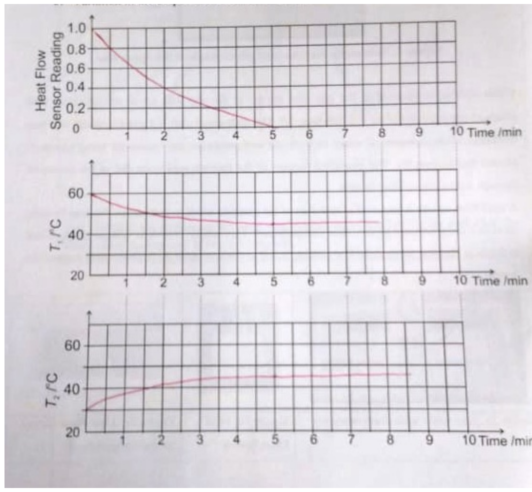


Figure 5.20: Students' typical prediction of the graph

As the activity was performed, students realized that their prediction matched with their observation. From the analysis of their explanations of the three regions A, B and C in the screenshot (figure 5.19), I found that students were able to use the idea of heat flow in the thermal equilibrium process. For region A in the output of heat flow indicator reading, students commented that as the wall between the compartments was diathermic, the heat transfer took place from the initial high value and gradually decreased to zero. For the region B and C, the students stated that the heat transfer was from water at high temperature to water at room temperature. The temperatures of the water in both the compartments became equal when net heat flow became zero.

Response 1: "as the wall separating the compartments was conducting, the heat lost by one compartment was gained by other compartment......leading to equal temperatures"

Finally, they collated all these responses and were able to construct an understanding of the role of heat flow in attaining thermal equilibrium.

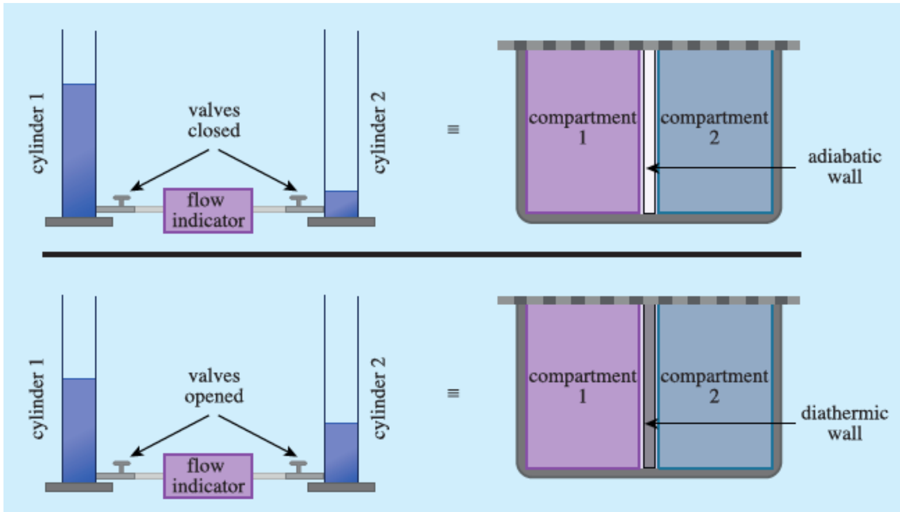


Figure 5.21: Analogy between liquid flow model and heat flow model

Since the students were exposed to both the liquid and the heat flow models, in the activity sheet, they were asked to match the concepts from the two models (Table 5.1). 90% of the students could relate the concepts from one model to the other (figure 5.21).

Response 2: "...when liquid flow becomes zero, water levels become equal, similarly when the heat flow becomes zero, the temperatures become equal...".

These students could see the correspondence of the heat flow in this activity to the liquid flow in activity 5.2.

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

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 the 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 the size of the object. In this activity, a measuring cylinder used as a reservoir had the water level in it maintained at a constant value (figure 5.22).

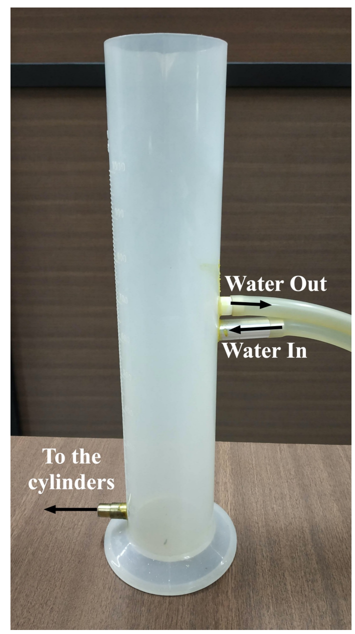
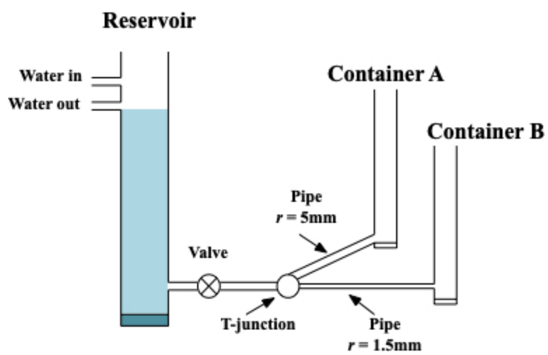


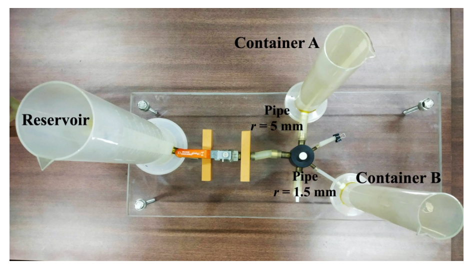
Figure 5.22: Measuring cylinder as reservoir

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). In the activity sheet (appendix D.4), detailed description of the apparatus was given and later it was explained to the students by calling them in small groups. Before the activity was performed, for both the parts of the activity, a space was provided in the activity sheet to sketch a schematic graph of the water level rise in both the cylinders. Then during the activity they were asked to observe the water levels in both the cylinders as the levels rose. They were asked to comment on their observation with respect to the rate at which the levels rose. With these observations, students were again asked to sketch the schematic graph of the water level rise in both the cylinders.

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



(a) Schematic diagram of the apparatus



(b) Effect of the radius of cross-section of the connecting pipes

Figure 5.23: Photograph of the apparatus

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 (figures 5.23a and 5.23b).

Students proto-typical responses

All the students could correctly predict that the water level in container A would rise faster than the water level in container B, and finally, the levels of water in both containers would be equal to the level of water in the reservoir (figure 5.24).

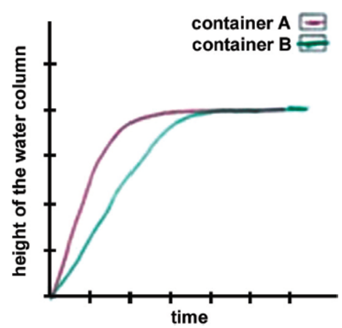
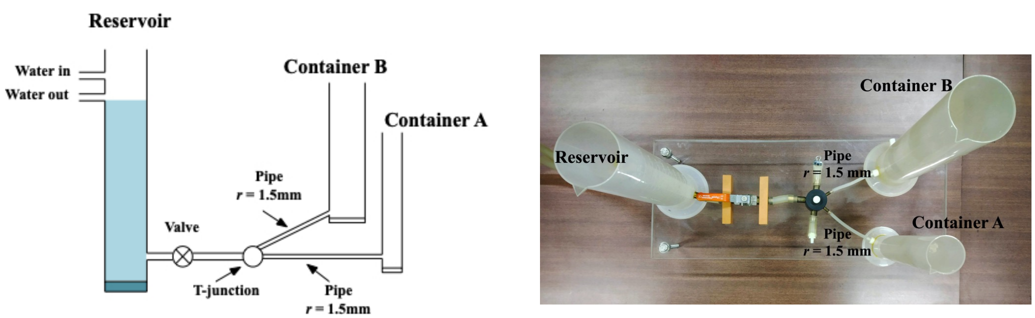


Figure 5.24: Student's drawing of height profile of water in containers

Response 1: "...cylinder A is connected to broader pipe...so more amount of water will be filled as compared to cylinder B...therefore graph of cylinder A will be steeper...”

Students observed in the activity that cylinder A and cylinder B both attained the same final level. But the rate at which cylinder A was filled was higher than the rate at which the cylinder B was filled. They could therefore verify their prediction with the observations. Students could explain that broader pipe would allow larger volume of water to flow in cylinder A, leading to faster attainment of equilibrium between the reservoir and the cylinder A. They further stated that the cylinder B would also eventually attain equilibrium with reservoir though at a slower rate.

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



(a) Schematic diagram of the apparatus

(b) Photograph of the apparatus

Figure 5.25: Different 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) (figures 5.25a and 5.25b).

Students proto-typical responses

As in the earlier case the students could predict the nature of the graphs, correctly justifying that the water level in container A would rise faster than the water level in container

B and finally the water levels in both containers would reach the same level as the water level in the reservoir (figure 5.26).

Response 1: "...cylinder B is of larger diameter...so more amount of water is needed to be filled in as compared to cylinder A...therefore graph of cylinder A will be steeper than that of cylinder B..."

When students observed the activity, they realized that even in this case, their predictions matched with their observations. They explained that as the cylinder B was of larger diameter, more amount of water was required to fill the cylinder. Therefore cylinder B will take more time to reach the final equilibrium level.

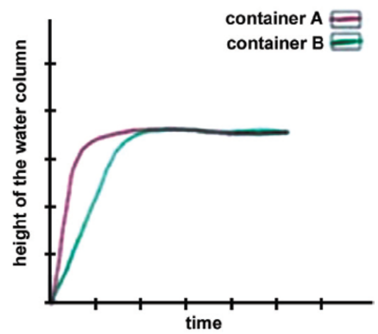
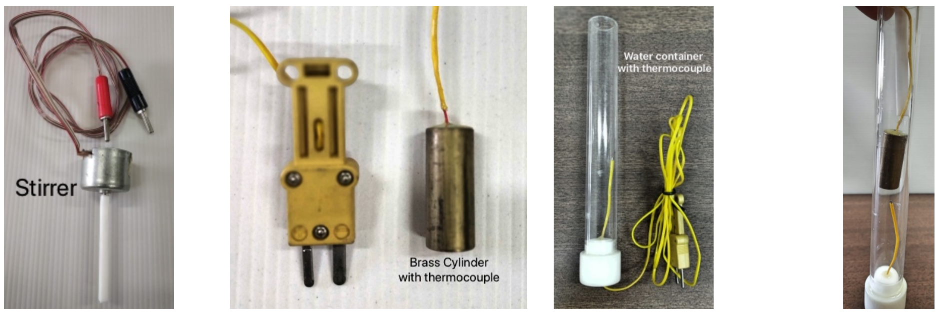


Figure 5.26: Student's drawing of height profile of water in containers

The students could correlate this activity to activity 5.1. They could infer from what they observed in this activity that the time to reach the equilibrium level would depend on the diameter of the connecting pipes and the base area of the cylinders, whereas the time taken to reach equilibrium temperature in activity 5.1 would depend on the material and the size of the object kept inside the enclosure. Interviews responses of students (n = 10) indicated the same (appendix G.1.3). Specifically, the situation in figures 5.23a and 5.24 would correspond to blocks of same size but of different thermal conductivities in Activity 5.1. Similarly, the situation in figures 5.25a and 5.26 would correspond to blocks of the same material but of different sizes in Activity 5.1.

5.2.4 Activity 5.5: Method of mixtures

In order to further test students' understanding about thermal equilibrium, an additional activity was developed. Students were presented with a situation (as in a method of comparing the specific heat of two substances, commonly known as method of mixtures) in which two substances with different specific heats and maintained at different temperatures are brought in contact with each other. A test tube with 20 ml of water (at room temperature) was mounted on a stand (figure 5.27).



(a) Stirrer attached to DC motor
(b) Brass cylinder with thermocouple
(c) Water container with thermocouple
(d) Complete assembly

Figure 5.27: Method of mixtures.

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 in the test tube. The water was continuously gently stirred.

In the activity sheet (appendix D.5), after the explanation of the apparatus, students were asked to predict the final temperature of both the brass cylinder and water with justification. By providing the values of specific heat of water and brass, they were asked to calculate the common final temperature. Then the students were shown the activity and the graph of variation of temperature of the brass cylinder and water (figure 5.28). The yellow graph represents the temperature variation of the brass cylinder, and the pink graph presents the temperature variation of water in the test tube.

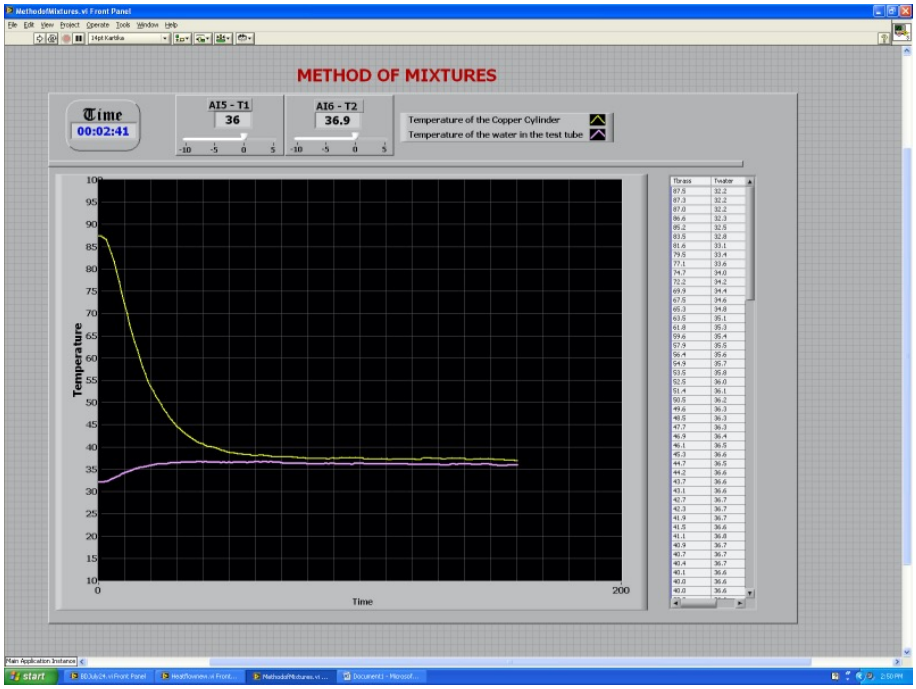


Figure 5.28: The temperature variation of brass cylinder and water

Students' proto-typical responses

88% 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 when the net heat flow between them is zero, and this final temperature would be intermediate between their initial temperatures. They also calculated this intermediate temperature.

The final module, thus, consisted of a set of 5 activities (Activities 5.1, 5.2, 5.3, 5.4 and 5.5).

5.3 Implementing the final module

Various components of the module were administered to the experimental group in the following order:

1. Pre-test (material and size dependence) (appendix C)

2. Activities

3. Post-test (material and size dependence) (appendix C)

4. Activity on method of mixtures

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

The final version of the module was administered to a sample of 112 students (experimental group) from different colleges in Mumbai. The students worked on activities for 3 hours immediately after the pre-test. The post-test was given to both the groups a week after the pre-test and the administration of the activities to avoid the direct effect of the activities on the students' performance. During this period, the students from both control and experimental groups attended their regular academic physics courses, and no additional thermodynamics content was taught. The effectiveness of the module was evaluated by comparing the responses on the post-test for both groups.

5.4 Results and discussion

Figure 5.29 summarize the students' pre- and post test responses for control and experimental groups for material dependence and figure 5.31 summarize the students' pre- and post responses for control and experimental groups for size dependence.

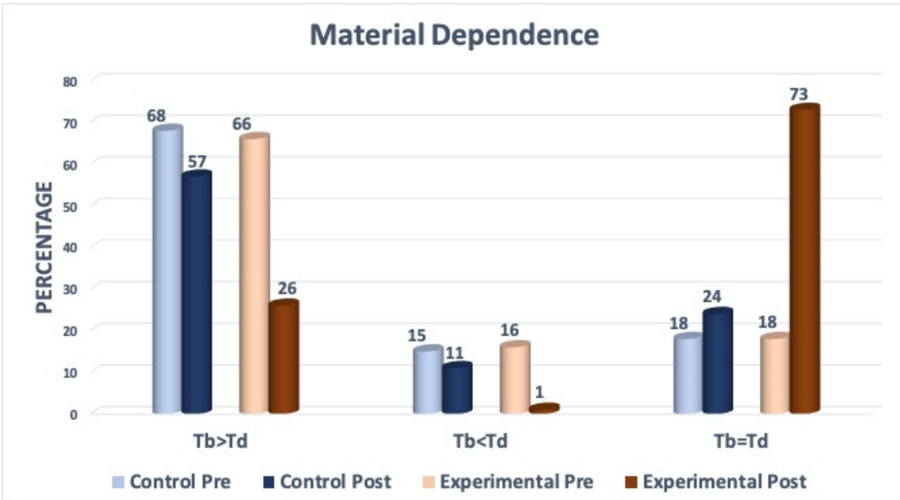


Figure 5.29: Percentage of students' responses in control and experimental group for material dependence

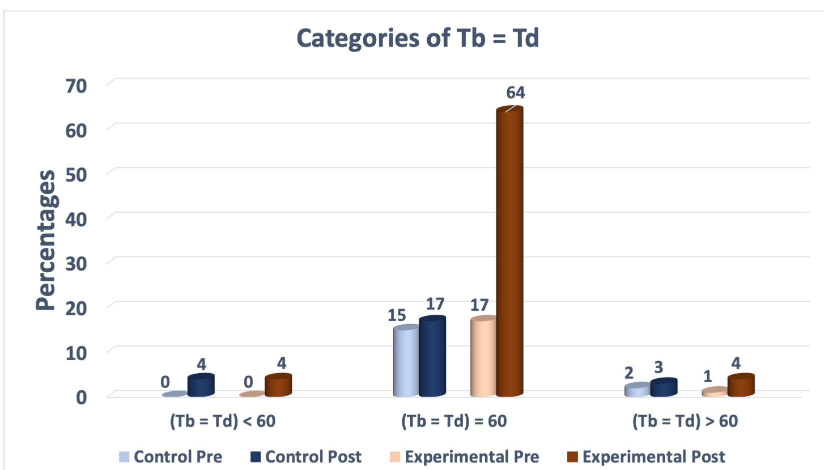


Figure 5.30: Categories in $T_b = T_d$

Out of 112 students, initially (in pre-test) only 17% of students (figure 5.30) could justify that both delrin and brass cylinders would attain the temperature of the water bath ($(T_b = T_d) = 60°C$). In the post-test, 73% of the total number of students (figure 5.29) answered that the temperatures of both the cylinders will be equal. But only 64% of the total number of students (figure 5.30) could satisfactorily justify that the temperature of these cylinders would be equal to the temperature of the water bath.

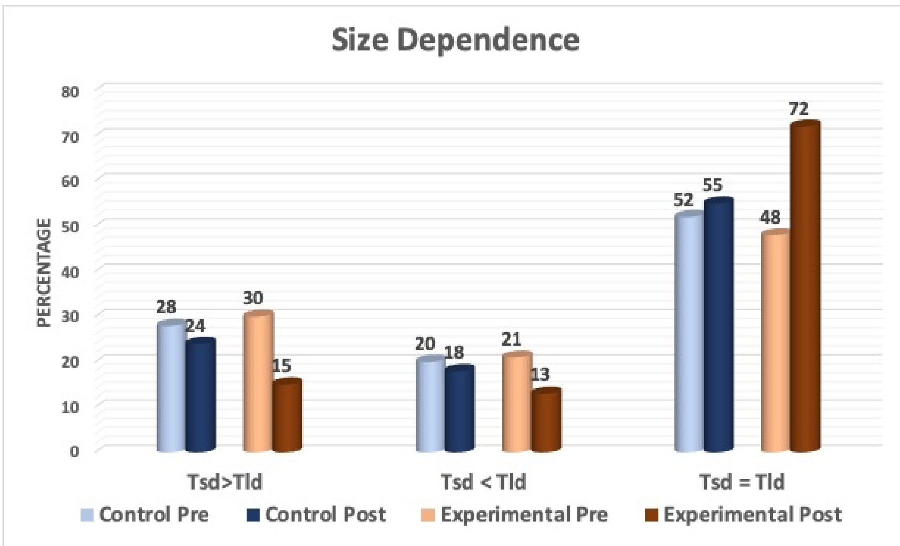


Figure 5.31: Percentage of students' responses in control and experimental group for size dependence

Similarly, 72% of the total number of students (figure 5.31) answered that the temperature of small and large Delrin cylinders would be equal. However, the percentage of students who could justify that both the small and large Delrin cylinders would attain the temperature of the water bath increased from an initial 30% to a final 64% (figure 5.32).

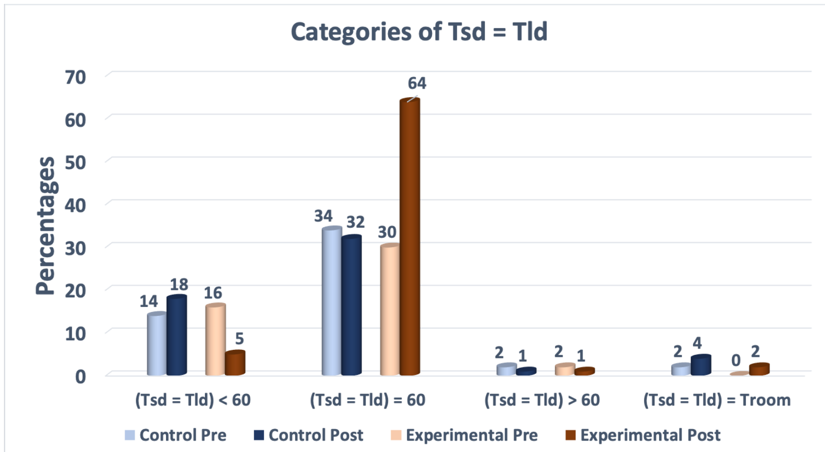


Figure 5.32: Categories in $T_{sd} = T_{ld}$

Activity 5.5 (method of mixtures) was conducted after the post-test. In this activity, 83% of the 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.

The written responses by students from the tests and activity sheets showed that the activities helped them to understand the concept of thermal equilibrium. 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. (tables 5.2 and 5.3).

Dependence	Group	Mean	n	S_{diff}	t_{MD}	Significance
Material	Control	0.176	131	0.049	0.061	Not significant at 5% level
	Experimental	0.179	112			

Table 5.2: t-test scores for material dependence for group equivalence

Dependence	Group	Mean	n	S_{diff}	t_{SD}	Significance
Size	Control	0.519	131	0.065	0.572	Not significant at 5% level
	Experimental	0.482	112			

Table 5.3: t-test scores for size dependence for group equivalence

I compared the pre- and post-test mean scores of the control group (tables 5.4 and 5.6) and the pre- and post-test mean scores of the experimental group using a correlated means t -test (Garrett, 1981) (tables 5.5 and 5.7).

Dependence	Test	Mean	n	r	S_{diff}	t_{MDC}	Significance
Material	Pre-test	0.176	131	0.310	0.042	1.467	Not significant at 5% level
	Post-Test	0.237	131				

Table 5.4: Control group - Material Dependence

Dependence	Test	Mean	n	r	S_{diff}	t_{MDE}	Significance
Material	Pre-test	0.179	112	0.282	0.047	11.73	Significant at 1% level
	Post-Test	0.732	112				

Table 5.5: Experimental group - Material Dependence

Dependence	Test	Mean	n	r	S_{diff}	t_{SDC}	Significance
Size	Pre-test	0.519	131	0.296	0.052	0.588	Not significant at 5% level
	Post-Test	0.550	131				

Table 5.6: Control group - Size Dependence

Dependence	Test	Mean	n	r	S_{diff}	t_{SDE}	Significance
Size	Pre-test	0.482	112	0.198	0.057	4.224	Significant at 1% level
	Post-Test	0.723	112				

Table 5.7: Experimental group - Size Dependence

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.

5.5 Concluding remarks

Activity 5.1 helped students to realise their own alternative conception and the later activities explained students the process of thermal equilibrium. Use of liquid flow analogy helped students to extend their understanding of the familiar situation of hydrostatic equilibrium to thermal equilibrium. In the activity on method of mixtures students correctly predicted the intermediate equilibrium temperature of cylinder and water. Therefore, from the t-test results and from the students' responses in post-test and activity sheets, I concluded that the module on thermal equilibrium helped students to improve their understanding of thermal equilibrium.

5.6 Publications from the part of this chapter

1. Pathare, S. 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.

2. 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.

3. Pathare, S. R., Huli, S. H., Nachane, M., Ladage, S., Pradhan, H. (2015). Understanding Thermal Equilibrium Through Activities. Physics Education, Institute of Physics, UK, 50(2), 146.

Chapter 6

Module on First Law of Thermodynamics

The current chapter discusses the activity module on the first law of thermodynamics, its development and implementation study. As discussed in chapter 4, I observed the following difficulties with respect to the understanding of the first law of thermodynamics:

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

2. Students do not distinguish between heat and temperature.

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

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

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

These difficulties formed the basis for the development of the module on the first law of thermodynamics. The primary purpose of the module was to present students with experiences of two basic thermodynamic processes, namely – adiabatic and isothermal and to demonstrate to them the application of the first law of thermodynamics in these processes. In these two processes, one of the energy terms in the statement of the first law of thermodynamics is zero. Thus, it would be easier for students to understand the inter-relations between only two energy terms.

6.1 Development of the module

The development of the module was based on the following rationale:

1. For the adiabatic process, students knew that $Q = 0$. Thus, providing visual evidence of $\Delta T \neq 0$ (when $Q = 0$) would contradict their alternative conception that heat transfer would always result in temperature change. Moreover, observing this temperature change of the system resulting from work done would make students realize that work is changing the system's temperature and, therefore, the internal energy of the system.

2. Similarly, in the isothermal process, where the temperature remains constant (and hence $\Delta U = 0$), demonstrating $Q \neq 0$, would contradict their alternative conceptions and help students to understand that heat transfer is not always accompanied by the temperature change and the work done results in heat flow.

The module on the first law of thermodynamics was standardized through 3 cycles of development. Like the previous module, the POE approach was used to administer the current module. The module included pre-and post-tests consisting of questions that will help to gauge students' understanding of the first law of thermodynamics. The pre-test consisted of questions related to the compression process (both adiabatic and isothermal). Students were asked to predict the changes in pressure, heat flow, temperature and internal energy of the system. They were also asked to predict the sign of work done and heat flow. In the observation stage, students performed the activities and noted their observations in the activity sheets. They were asked to explain the difference (if any) in their prediction and observation in the activity sheet.

In Cycle 1, I developed the apparatus to demonstrate adiabatic and isothermal processes, which replicated the pre-test situations. In cycle 2, these apparatus were modified, and a heat flow indicator was used to make the heat flow visible to the students. In cycle 3, to demonstrate and quantify the adiabatic process, the activity based on a fire syringe was developed as well as a steel cylinder of a larger dimension was used in the isothermal process.

6.1.1 Cycle 1

In Cycle 1, the activities developed on the adiabatic and isothermal processes were tested with 37 first and second-year undergraduate students from two colleges in Mumbai followed by the interviews with seven students.

Adiabatic process

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 air temperature inside the container. It was also fitted with a pressure dial gauge for pressure measurement (figure 6.1). In order to achieve adiabaticity, the piston of the syringe was pressed swiftly. Students were asked to record the pressure and temperature of the 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 with volume for the syringe obtained by the researcher was provided to the students so that they can calculate the work done by measuring the area under the curve. At this stage, I wanted the students to realize that a change in temperature is occurring due to work done by making them perform the compression process. Further, I expected that on observing this temperature change, they would qualitatively

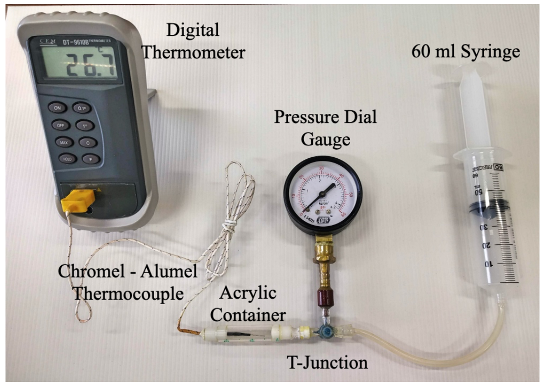


Figure 6.1: The set up with thermocouple and pressure dial gauge

understand that this work done is changing the internal energy of the system, according to the statement of the first law of thermodynamics.

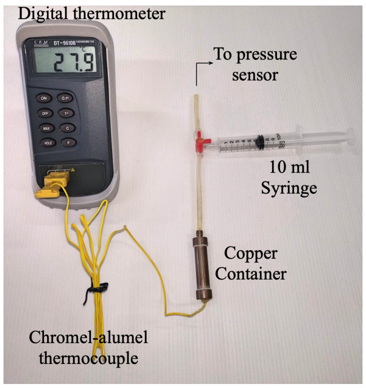
Students' proto-typical responses:

Students did not observe an appreciable change in the temperature of the system when the piston was pressed slowly. On pressing the piston swiftly, students observed a deflection in the pressure gauge and an increase in the temperature of the system. They stated that as the piston is being pushed, work is being done on the system. They were aware that for an adiabatic process, the heat flow is zero.

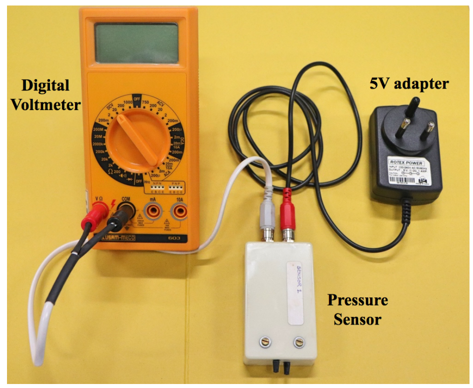
Students were convinced that work is being done on the system in the process, but they were unaware of the relation between temperature and internal energy. Hence they could not understand that work done leads to the change in the internal energy of the system. Only a few students who were aware of the relation between temperature and internal energy for a gas tried to match the work done on the system to the change in internal energy and calculated the expected change in temperature of air in the container. They, however, observed a much smaller change in temperature during the actual activity than the expected change based on their calculation. Later, on closer inspection, I identified an air leakage through the T-shaped silicon pipe, which connected syringe, acrylic tube and pressure gauge (figure 6.1).

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 to measure the air temperature inside the container (figure 6.2a).



(a) Assembly for isothermal process



(b) Pressure measurement assembly

Figure 6.2: Isothermal Process

A digital pressure sensor set up (Motorola IC, MPXM2010) was assembled for measurement of the air pressure in the container (figure 6.2b). The piston of the syringe was pressed very slowly in such a way that the air inside the container remained at a constant temperature. 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.

Students' proto-typical responses

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 could calculate the work done in the process by both the graph method and the formula provided. They noticed 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 (appendix G.2.1). 57% of them were confused about what happened to the heat flow.

The common problems encountered for both the processes were as follows. The corresponding interview responses are provided in appendix G.2.1 and G.2.1.

As seen from the written response, students seemed to be confused with respect to the sign convention of various energy terms both in the isothermal and adiabatic processes. They were also confused about the change in the internal energy of the system. One of the probable reasons for the same could be that the heat flow in/out of the system was not visible to the students. The activity was unable to explain the relationship between the change in internal energy and the change in temperature of the system in the processes. 57% of the students still equated the internal energy as *heat of the system*. Students' responses to questions related to heat flow and change in internal energy seemed rather random.

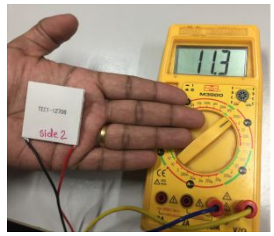
6.1.2 Cycle 2

With respect to the observed difficulties described above, in cycle 2, I felt the need to have an indicator of heat flow. A heat flow indicator was fabricated by us for this purpose using Peltier device available commercially. Further a separate instruction sheet explaining to the students (1) the relation between change in temperature and change in internal energy and (2) sign convention for work done and heat flow was provided. Air leakage problems were minimized. These modifications are described below:

1. Activity on familiarizing students with the heat flow indicator (appendix F.1):
   For many students, temperature measurement was a familiar task, but they had never come across heat flow measurement. In this cycle, I provided a Peltier device to the students to make the heat flow observable. The Peltier device generates a 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 6.3: Peltier device as heat flow indicator

The students were shown how a Peltier device (figure 6.3a) worked as a heat flow indicator. They were asked to touch a specimen device only on one side by their palm and note the voltage across the device in the activity sheet (figure 6.3b). They found that 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 6.3c). Thus, the voltage across the device was a measure of the net heat flow through it. A Peltier device was then used as an indicator of heat flow from the container to the surroundings, 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 (appendix F.2):

   In this cycle, an additional 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, diagrammatically.

3. Air leakage problems:

   For the adiabatic process, the acrylic container used in Cycle 1 was replaced by a thick-walled Delrin container and a Delrin piston (figure 6.4a).

(a) Modified piston-container (b) Screenshot of the video recording

Figure 6.4: Adiabatic Process

> This arrangement 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 to keep a track of the intermediate values of the pressure as it varied 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 hammered up to the red mark as shown in figure 6.4b. The process was video recorded with both the pressure sensor and thermocouple readings clearly visible in the video frame. The video was analyzed using a TRACKER software (https://physlets.org/tracker/) that allowed me to track the pressure, volume and temperature at any instant during the compression. The PV data was plotted on a graph paper and was given to the students for the calculation of the work done. Students were also asked to note the change of temperature of the air in the container in the activity sheet.

For carrying out the isothermal compression, the apparatus used for isothermal compression in Cycle 1 was not changed except for the addition of the heat flow indicator.

The activity module in Cycle 2 consisted of the following three activities.

Activity 1: Familiarizing with digital thermometer and heat flow indicator

Activity 2: Adiabatic compression with Delrin container–piston and heat flow indicator

Activity 3: Isothermal compression using heat flow indicator

These activities were given to 28 undergraduate students from a college in Mumbai. Informal interviews were conducted with six students.

The following observations were recorded specifically with respect to modifications, 1, 2 and 3.

Students' proto-typical responses

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.

In the adiabatic process, heat flow indicator played an important role in making students understand the absence of heat flow. Students could observe $Q = 0$ for the adiabatic process.

However, some students also mentioned that since $Q = 0$, the change in the internal energy should also be zero. They preferred to stick to their prior alternative conception that heat and internal energy are equivalent. When these students were reminded of the internal energy-temperature relationship during the interview, they misapplied this relation by stating that the change in the temperature of air should also be zero. However, 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 stating that no change in temperature could occur without heat flow. Additionally, they also commented that work done on the system by itself could not change the temperature of the system. They further argued that the observed change in temperature was some kind of experimental error (appendix G.2.2).

In isothermal compression, students could see that the temperature of the air inside the container remained constant. However, they could not observe any appreciable reading for the existence of heat flow (appendix G.2.2).

Following problems were observed during the implementation of the activity in cycle 2.

1. Even with the modified 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.

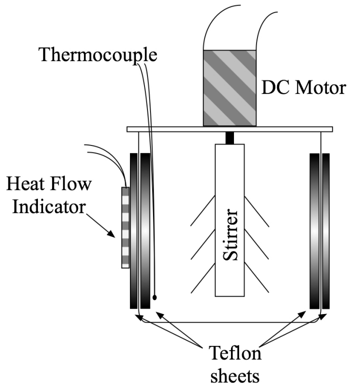
2. In the isothermal process, as mentioned above, the heat flow indicator did not show any noticeable change in its reading. One possible reason could be that the copper cylinder used as the air container was too small in size, and its cylindrical shape was not suitable for establishing good surface contact with the flat-shaped Peltier device-based heat flow indicator.

6.1.3 Cycle 3

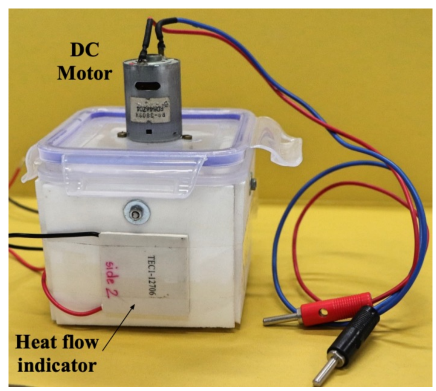
In cycle 3 the apparatus used in the activity was modified to avoid the problems described above and come up with a complete module on the topic. The activity for introducing the heat flow indicator described in cycle 2 was retained as the first activity. In this cycle, I added a new activity to follow the first activity. This activity was to convince the students that work done is an energy transfer mechanism. Secondly, two modifications were done in the apparatus; (1) a fire syringe was used to demonstrate adiabatic compression and (2) a steel cylinder was used with a larger base area so that the entire surface of the heat flow indicator was in contact with the cylinder. Each modified activity was administered to a typical group size of about 15 students. During cycle 3, the total number of students involved with the testing of the developed module was 66 the interviews were conducted with 12 students.

Understanding work done as energy transfer mechanism:

To address students' alternative conception, that in the adiabatic process, no transfer of heat corresponds to no change in temperature, I built an analogue of Joule's apparatus. Students were presented with a different context in this activity other than the piston-container assembly, wherein the first law of thermodynamics was applied. It also aimed to explain the difference between the terms - heat and internal energy by demonstrating that the system's internal energy can be changed even in the absence of heat transfer, which can be identified by the change in temperature of the system. This temperature change is brought about by the work done by the blades of the stirrer on the water (figure 6.5a).



(a) Schematic diagram of the apparatus



(b) The set up

Figure 6.5: Work done as energy transfer mechanism

In this apparatus a stirrer is rotated not by falling weights but by a DC motor. 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 (figure 6.5b). 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.

In the activity sheet (appendix F.3), students were asked to note down the reading of heat flow indicator, their observation regarding the temperature of the water. Based on these observations, they were asked to write down the first law of thermodynamics.

Students' proto-typical responses

The students observed that the temperature of the water increased gradually as it was stirred, but the heat flow indicator showed no heat transfer. Students observed a systematic change in the temperature of water over time as the water was stirred continuously. Thus, they realized that even if the net heat transfer between water and surrounding was zero, the temperature of the water could be changed. Students were asked to reflect on this situation. They 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 which made them realize that the work done is also an energy transfer mechanism responsible for changing the internal energy of the system. Students' interview responses are presented in appendix G.2.3.

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 that is frictionless and free of leakages. Therefore, I used a fire syringe (Jackson and P. Laws 2006) instead of a Delrin container-piston. But before the fire syringe activity, I introduced another activity for helping the students to appreciate the variation in temperature generated due to the varying speeds of the piston.

a. Introduction 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 the 25 ml mark. The thermocouple was inserted from the open end of the syringe. The open end was then closed tightly with the thumb (figure 6.6). The piston was pushed with varying speeds, and the corresponding temperature changes were to be observed.

Figure 6.6: Introduction to adiabatic process

In the activity sheet, students were asked to comment on different readings of temperatures with varying speeds. Followed by the activity, I introduced a discussion session to understand what can make a process adiabatic, in practice. The discussion was initiated with the equation of the Fourier law of heat transfer, namely,

$$\Delta Q = (kA\frac{dT}{dx})\Delta t \tag{6.1}$$

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 Δt is small, then ΔQ will be small too. As a result, by making Δt 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 6.7) is a thick-walled transparent acrylic cylinder with a snug–fit piston.

Figure 6.7: Fire syringe

A heat flow indicator was attached to the external walls of the fire syringe to check the presence/absence of heat flow. 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 at a sufficiently high speed, the temperature increase is sufficiently high to burn the small piece of cotton present inside the syringe. The low thermal conductivity of the acrylic cylinder walls allows practically no heat transfer for this time interval.

Students were shown a video demonstrating adiabatic compression using the fire syringe. The video explained the design and parts of the fire syringe and then demonstrated the process of generating the glow by swiftly pressing the piston. Multiple copies of the fire syringe were given to the students to try out the activity. They were asked to press the piston to generate the glow. Students performed the process multiple times before they could finally generate the glow (figure 6.8).

Figure 6.9: Modified fire syringe

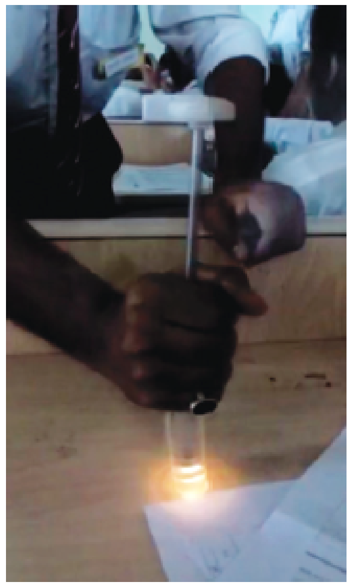


Figure 6.8: A student generating the glow

At this point, students were shown a video demonstration of the fire syringe activity with heat flow indicator attached to the external wall of the acrylic container. For this purpose, I modified the fire syringe apparatus. I fitted a spring over the piston (figure 6.9). 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 (figure 6.10). When the piston was released, a glow due to cotton-burning was observed.

At this stage, they were asked to note down their observations related to the temperature of the air inside the container and heat flow indicator reading in the activity sheet (appendix F.4). With the help of the information sheet, they were asked to comment on the sign of

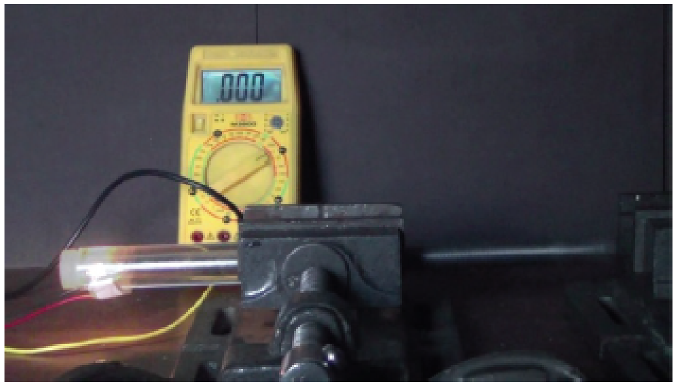


Figure 6.10: Adiabatic compression with heat flow reading displayed

the work done in the process. Based on these observations, they were asked to write down the first law of thermodynamics.

Students' proto-typical responses

Students stated 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. Due to the burning of the cotton piece, students could infer that there must be a considerable rise in temperature.

Students could experience the high speed with which they carried out the compression process to generate the glow. Additionally, the glow generated and the smell of the burnt cotton gave sensory evidence that the temperature generated was very high. From the information sheet, students, therefore, stated an increase in the system's internal energy. At the same time, students were convinced that there was no heat transfer. At this point, they were reminded of the first law $Q = \Delta U + W$. Q being zero $\Delta U = -W$. Students were asked to reflect on the source of energy associated with the temperature change. During the interviews, they said that the only source through which it could possibly come was the work done during compression (appendix G.2.3).

c. Quantification of fire syringe activity:

The video demonstration of the fire syringe gave visual evidence of the process of adiabatic compression to the students. At this stage, it would be important to emphasize the contribution of each energy term in the statement of the first law of thermodynamics as applied to the process of adiabatic compression.

To introduce this quantitative aspect of the fire syringe demonstration, I asked 15 students to do the calculations for estimating the temperature of the cotton plug when it catches fire in the video-demonstration activity of fire syringe. These students used the video analysis software – TRACKER to get the change in volume of the air during compression. The piston positions before the spring release and at the ignition of cotton were noted. The piston displacement thus measured, multiplied by the constant area, gave the change in volume during the compression process. From these measurements, these students calculated the work done by the piston by assuming the compression process to be both reversible and irreversible. This work done was equated with the change in the internal energy of the system, and the final temperature at which the cotton piece burnt was calculated. The relevant formulae were provided to these students.

I describe in detail these calculations associated with the adiabatic process (Guemez, C. Fiolhais, and M. Fiolhais 2007) carried out by students. I begin with the calculations assuming the process to be reversible. Later I present the calculations for this irreversible adiabatic process to show that the actual temperature reached is greater than the temperature considering the process to be reversible.

i] Reversible adiabatic compression:

The work done was calculated in the process using the formula for adiabatic work, W for an ideal gas,

$$W = \frac{K({V_f}^{1-\gamma} - {V_i}^{1-\gamma})}{1-\gamma} \tag{6.2}$$

where, V_i is the initial volume of the air before compression, V_f is the final volume after compression and γ is the ratio of specific heats (for air, $\gamma = 1.4$) and $K = P_i\ {V_i}^{\gamma}$.

Inner radius of the fire syringe = 0.55 cm

From the TRACKER analysis (figure 6.11), $h_1 = 11.0$ cm and $h_2 = 1.4$ cm

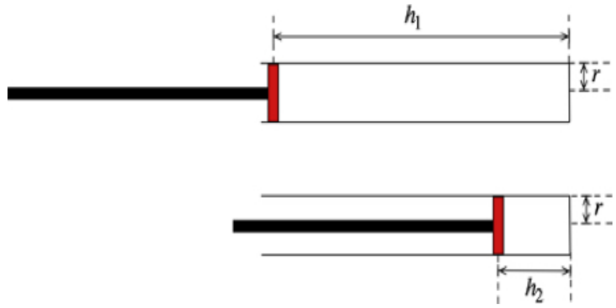


Figure 6.11: Parameters for volume calculations

Therefore,

The initial volume, V_i = 10.45×10^{-6} m^3 and

The final volume, V_f = 1.33×10^{-6} m^3 The atmospheric pressure P_i= 1.01325×10^5 Pa

Therefore, $K = P_i\ V_i^{\gamma} = 1.01325 \times 10^5 \times (10.45 \times 10^{-6})^{1.4} = 10.78 \times 10^{-3}$

$$W = \text{-3.392 J}$$

The work done was equated to the change in internal energy of an ideal gas using a formula.

$$\Delta U = mc_v \Delta T \tag{6.3}$$

Mass of the air:

Density of air, $\rho = 1.225$ kg/m^3

$$m = \rho \times V_i = 1.225 \times 10.45 \times 10^{-6} = 1.28 \times 10^{-5} kg$$

$$\Delta T = \frac{3.392}{1.28 \times 10^{-5} \times 718} = 369°C$$

Initial temperature, T_i = 30 °C

Final temperature of air inside the container, T_f = 399°C ii] Irreversible adiabatic compression:

The irreversible compression of the gas proceeds in one step against constant external pressure P_E (Mungan 2003, Guemez, C. Fiolhais, and M. Fiolhais 2007),

$$W = P_E \times \Delta V \tag{6.4}$$

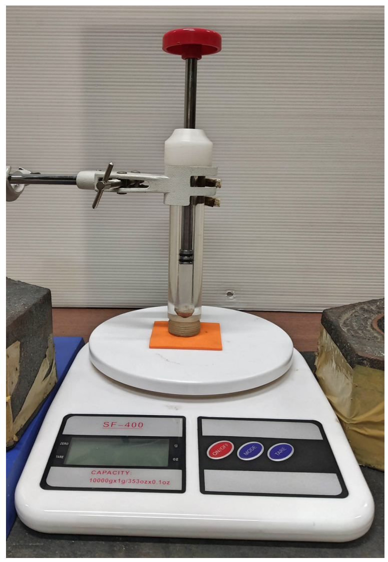


Figure 6.12: Arrangement for the pressure measurement during adiabatic compression

The external pressure applied on the piston during the compression process was $F_E = 58.8$ N as if a body of 6 kg was placed on the system (figure 6.12). This force was measured from the reading of the weighing pan when the piston was hit during the process.

$$P_E = \frac{58.8}{3.14 \times (0.55 \times 10^{-2})^2} = 6.19 \times 10^5 Pa$$

$$W = 6.19 \times 10^5 \times (1.33 - 10.45) \times 10^{-6} = -5.65J$$

$$\Delta T = \frac{5.65}{1.28 \times 10^{-5} \times 718} = 615°C$$

Final temperature of air inside the container, T_f = 645°C

The data available for the auto-ignition temperature of cotton gives a range between 360°C and 425°C (Lewin 2007). Thus, the estimate for the temperature of the burning of the cotton piece is consistent with the auto-ignition temperature data for cotton.

For the later batches of students, explaining to them the procedure used, I only showed and discussed these calculations.

The quantification of fire syringe activity gave concrete evidence regarding the contribution of each energy term in the process of adiabatic compression in terms of their magnitude and their inter-relation. Therefore, unlike the activity on adiabatic compression from Cycle 1 and Cycle 2, this activity seemed to convince students about the magnitude of work done in the process matching with the change in the internal energy of the system.

Isothermal compression

a. Introduction to isothermal compression:

Similar to the adiabatic compression process, an activity to make students understand the conditions for carrying out the isothermal compression process was developed. In this activity, another objective was to make the heat flow from the system to the surroundings observable to the students.

Figure 6.13: Introduction to isothermal compression

In this task, students were given a small, hollow, thin-walled copper cylinder with a thermocouple already inserted in it (figure 6.13). 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 observe the change in temperature of the air in the cylinder and check for the speed necessary to keep the temperature constant. They were asked to explain their observations in the activity sheet (appendix F).

b. Observing heat flow reading in the isothermal compression:

In this activity, I used the heat flow indicator to detect the heat flow in the isothermal process. I replaced the small copper container with a bigger steel cylinder with a snug-fit piston (figure 6.14). The heat flow indicator was attached to the base of the steel cylinder. The base area was sufficiently large to cover the entire surface of the heat flow indicator.

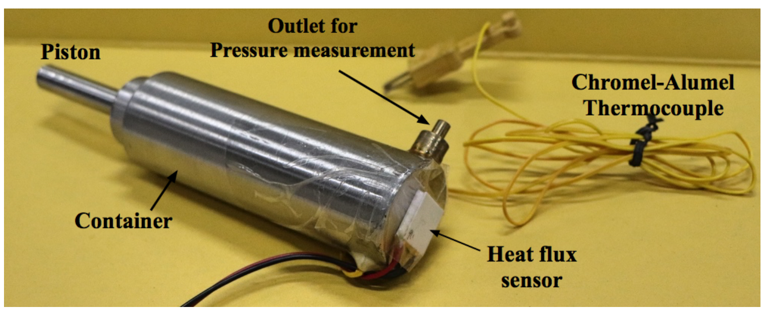


Figure 6.14: Modified piston-cylinder assembly

A thermocouple was inserted in the cylinder. A pressure sensor is also attached to measure the pressure of the air inside the cylinder during this process (figure 6.15). The piston of the cylinder was held in the bench-vice. The cylinder is then pushed slowly, such that the thermometer shows the constant reading, resulting in the compression of the air inside it. 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. In the activity sheet (appendix F.5), students were asked to note down their observations related to change in temperature and heat flow. Based on their observations, they were asked to comment about the change in internal energy and the sign of heat flow and work done and therefore, they were asked to write down the first law of thermodynamics for the isothermal process.

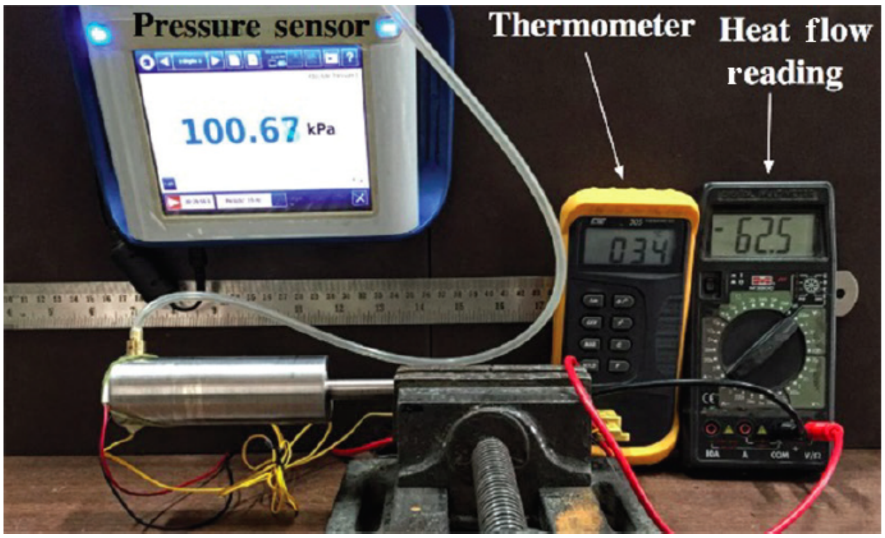


Figure 6.15: Complete set up for isothermal process

Students' proto-typical responses

In the activity on getting introduced to isothermal compression, considering the earlier discussion on heat conduction (equation 6.1) carried out during adiabatic compression, the students realized 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 from the system to the surrounding. Some of the responses obtained during the interviews are presented in appendix G.2.3.

In the video demonstration of the activity on isothermal compression (figure 6.15), students observed that the heat flow indicator showed a negative reading. At this point, they were reminded of the first law $Q = \Delta U + W$. ΔU being zero $W = Q$. They could infer that the heat is transferred from the system to the surrounding while work is done on it.

The students correlated the energy pumped into the system to work done on the system. They also stated that as the process was carried out slowly and the temperature remained constant, the container could dissipate this 'pumped in energy' in the form of heat, which was visible through the heat flow indicator reading. It was clear from their response in the activity sheets that they related no change in temperature to no change in internal energy. At the end of Cycle 3, I finalized the module with following activities:

Activity 6.1	Familiarizing with digital thermometer and heat flow indicator
Activity 6.2	Work done as energy transfer mechanism
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 process
Task 2	Isothermal compression – activity through video

Table 6.1: Final activity sequence in the module

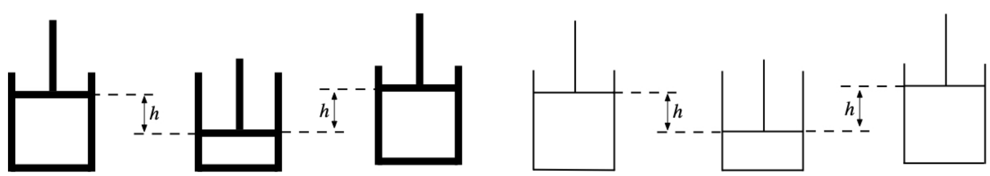
In summary, activity 6.1 introduced students to thermocouple and heat flow indicator. Activity 6.2 was to demonstrate to the students that the temperature and hence the internal energy of the system can also be changed due to work done in the absence of heat transfer. Activity 6.3 on adiabatic compression presented not only a hands-on experience of carrying out an adiabatic process but also gave them experience of zero net heat flow and finite temperature change. Activity 6.4 on isothermal compression demonstrated that even though the temperature remained constant, there was a heat transfer from the system to the surrounding.

6.1.4 The pre-and post-tests

The pre-test consisted of 10 multiple-choice questions. The first five questions were on adiabatic compression, whereas the next five questions were similar questions on isothermal compression. The situation presented for this question is represented in figure 6.16. For the adiabatic process, it was stated that the piston and the walls of the container do not allow heat transfer, whereas for the isothermal process, both piston and walls of the container freely allow heat transfer. Additionally, for the isothermal situation, it was stated that the temperature of the gas inside the container was constant, and the piston moved slowly during the compression process.

(a) Adiabatic process (b) Isothermal process

Figure 6.16: Pre-test questions



(a) Adiabatic process (b) Isothermal process

Figure 6.17: Post-test questions

The students were asked to predict the changes in temperature, pressure and internal energy during the processes and also the sign convention for heat transfer and work done. In the post-test, along with the compression process, a new situation of expansion was also given. Thus the post-test consisted of 20 questions: (i) 10 identical questions on compression as the pre-test, (ii) 10 similar questions on expansion, returning the system to the original state (figure 6.17). Additionally, a table-completion task was given to the students as part of the post-test, which has been described below.

This task presented various quantities related to the first law of thermodynamics along with the expansion and compression situations covered in the activity module (figure 6.18). For the given quantity in column 1, students had to tick the appropriate check-box by choosing the suitable process category. This task presents a summary about whether the students could understand the correlation between the quantities and processes.

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 6.18: Table completion task

6.2 Implementing the final module

The sequence for the implementation of the final module to the experimental group was done in following manner:

1. Pre-test on adiabatic and isothermal process (appendix E)
2. Activities
3. Post-test on adiabatic and isothermal process and Table-completion task (appendix E)

The study was conducted with 124 second-year undergraduate students enrolled for the bachelors' programme in science colleges. These students were from first and second-year undergraduate colleges from Mumbai, Ratnagiri, Nagpur, Belgaum and Tehri. The control group, consisting of 99 students, was administered only the tests, and the activities were not given to them.

For the experimental group, the module was administered immediately after the pre-test. These students worked on the module for 5 hours immediately after the pre-test. In the experimental group, out of the 124 students, who were available for tests on adiabatic components, 18 students dropped out for various reasons, and only 106 were available for tests on the isothermal component. The table completion task was given 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. The post-test was delayed so as to avoid the direct effect of the activities on the performance of the students. During this period of one week, the students from both control and experimental groups attended their regular academic physics courses and were taught almost the same content. No additional thermodynamics content was taught during this period. To evaluate the effectiveness of the module, the comparison of responses on the post-test for both groups was carried out.

6.3 Results and discussion

Each item on the MCQ test was scored one mark for the correct answer and zero for the incorrect answer. The total scores for adiabatic and isothermal compression were obtained separately for each student, independently for pre-test and post-test. 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). The t-test scores are presented in tables 6.2 and 6.3. Since there was no significant difference between the mean scores as indicated by the t-test, I infer that both the control and the experimental groups were equivalent in terms of performance.

Process	Group	Mean	n	S_{diff}	t_{Ad}	Significance
Adiabatic	Control	2.808	99	0.138	1.743	Not significant at 5% level
	Experimental	3.048	124			

Table 6.2: t-test scores for adiabatic process for group equivalence

Process	Group	Mean	n	S_{diff}	t_{Iso}	Significance
Isothermal	Control	2.364	99	0.166	0.538	Not significant at 5% level
	Experimental	2.453	106			

Table 6.3: t-test scores for isothermal process for group equivalence

I compared the pre and post-test mean scores for the control as well as for the experimental groups separately using a correlated means t -test (Garrett, 1981). The obtained results are presented in tables 6.4, 6.5, 6.6, 6.7.

Process	Test	Mean	n	r	S_{diff}	t_{Ad}	Significance
Adiabatic	Pre-test	2.808	99	0.170	0.114	1.155	Not significant at 5% level
	Post-Test	2.939	99				

Table 6.4: Control group - Adiabatic process

Process	Test	Mean	n	r	S_{diff}	t_{Ad}	Significance
Adiabatic	Pre-test	3.048	124	0.352	0.108	9.305	Significant at 1% level
	Post-Test	4.056	124				

Table 6.5: Experimental group - Adiabatic process

Process	Test	Mean	n	r	S_{diff}	t_{Iso}	Significance
Isothermal	Pre-test	2.364	99	0.442	0.142	1.567	Not significant at 5% level
	Post-Test	2.586	99				

Table 6.6: Control group - Isothermal process

Process	Test	Mean	n	r	S_{diff}	t_{Iso}	Significance
Isothermal	Pre-test	2.453	106	0.256	0.139	10.357	Significant at 1% level
	Post-Test	2.586	106				

Table 6.7: Experimental group - Isothermal process

The mean scores did not differ significantly (even at 5% level) for the control group whereas they differed significantly at 1% level for the experimental group. Thus, I can infer that the implementation of the activity module did impact the performance of students from the experimental group, in the post-test. In the following section, I discuss the performance of students from the experimental group for each test item given in tests.

Adiabatic process

For question related to temperature in the pre-test, the percentage of students giving correct response was 4% (figures 6.19). It was observed that this percentage increased to 76% in the post-test. For questions related to internal energy, the percentage of correct responses changed from 21% to 74% from pre- to post-test. Regarding the question related to work done on the system during the adiabatic compression, the observed increase in the percentage of correct responses was from 7% to 87%. All these changes in the percentage indicate significant improvement in students' understanding.

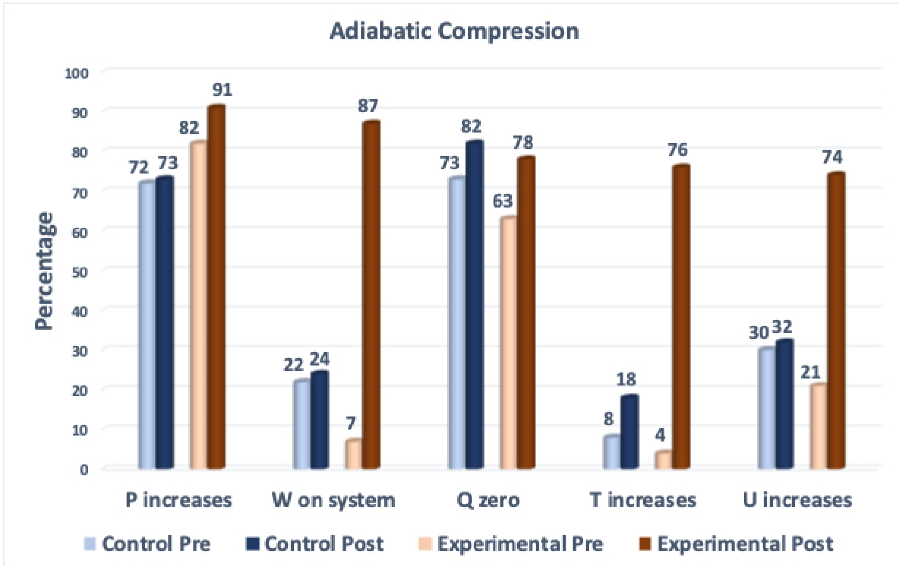


Figure 6.19: Students' correct responses about adiabatic compression process

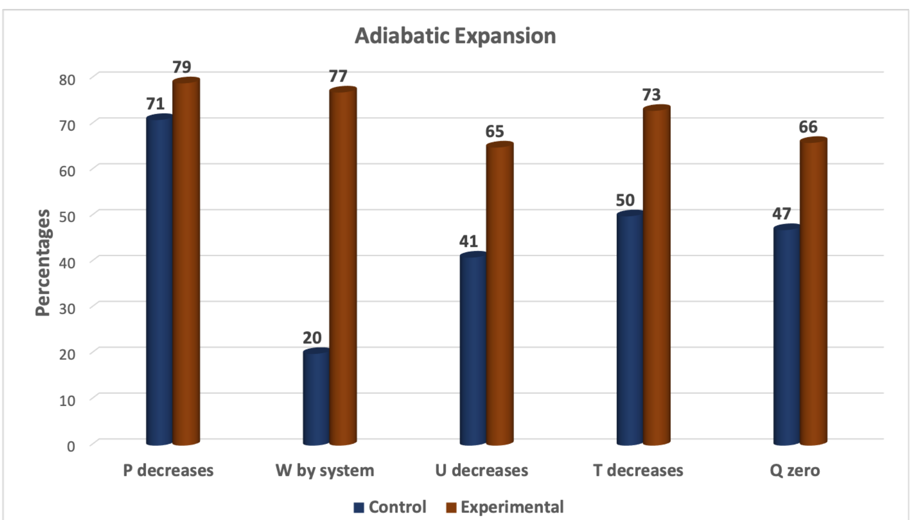


Figure 6.20: Students' correct responses about adiabatic expansion process (post-tests)

For questions related to adiabatic expansion, a new situation presented in the post-test, students' responses seemed to be consistent with those for adiabatic compression. However, the percentages of correct responses in expansion process in comparison with the compression process were consistently less. Such an observation indicates that less number of students could extrapolate learning from compression situation to the expansion situation. It indicates extrapolation of learning from one situation to another situation does not happen easily.

Isothermal process

For the question related to temperature remaining constant in isothermal compression in the pre-test (figure 6.21), the percentage of students giving correct response was 52% which increased to 72% in the post-test. For the question related to the internal energy remaining constant, the percentage of correct responses changed from 31% to 62%. The percentage of students for whom the heat transfer was negative during the isothermal compression increased from 33% to 80%, whereas for those for whom work was done on the system, the percentage increased from 14% to 85%. These changes indicated a significant improvement in students' understanding.

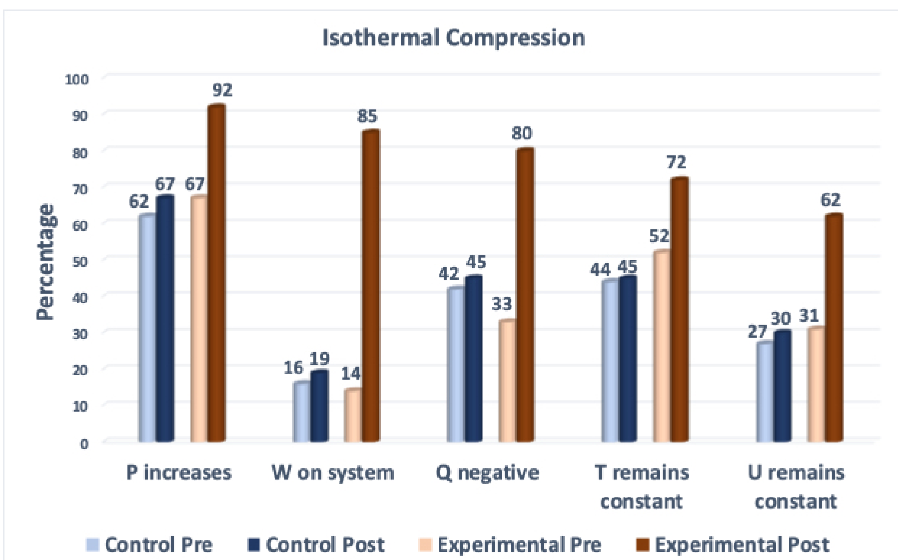


Figure 6.21: Students' correct responses about isothremal compression process

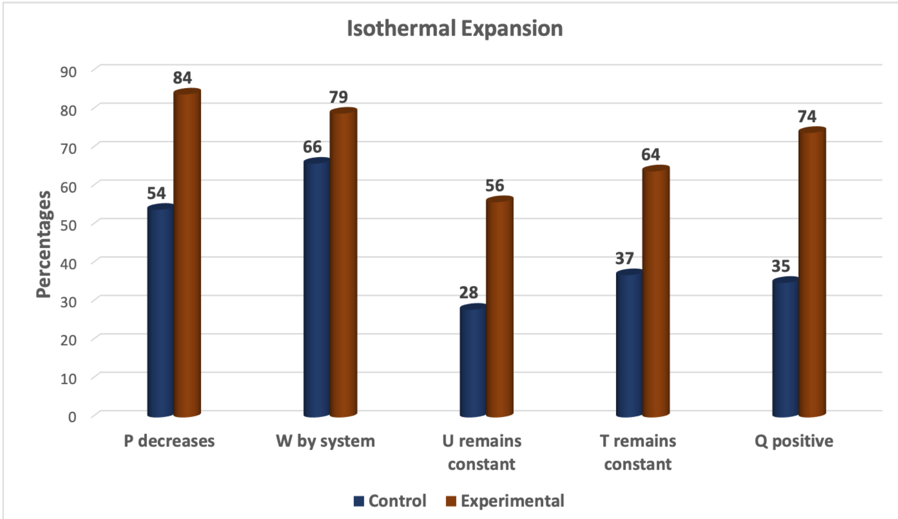


Figure 6.22: Students' correct responses about isothermal expansion process (post-tests)

For questions related to the isothermal expansion, the results seemed to be consistent with the results for isothermal compression. However, as in the adiabatic case, here too, the reduced percentages of the respective responses indicated that less number of students could extrapolate their understanding from compression to expansion (National Academies of Sciences, Medicine, et al. 2000).

Table-completion task results

Figures 6.23 to 6.26 summarize the results of the table-completion task for both control and experimental group. These figures discuss the percentage of students marking correct check-box. Some observations about the experimental group selecting correct options are discussed further.

Adiabatic process

Figures 6.23 and 6.24 indicate that most students confirmed zero heat transfer in case of adiabatic compression (89%) and expansion (85%) processes. Similar numbers were observed in the case of work done and $\Delta T \neq 0$.

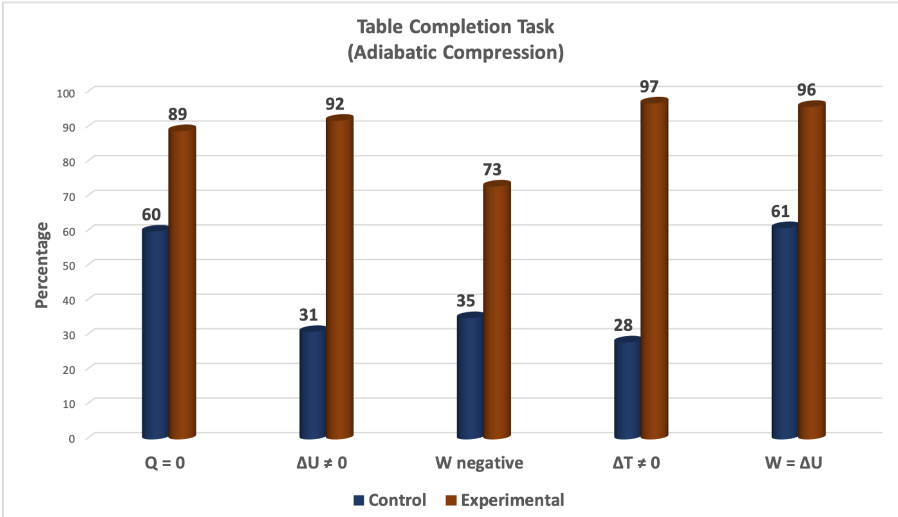


Figure 6.23: Table completion task - Percentage of students giving correct responses

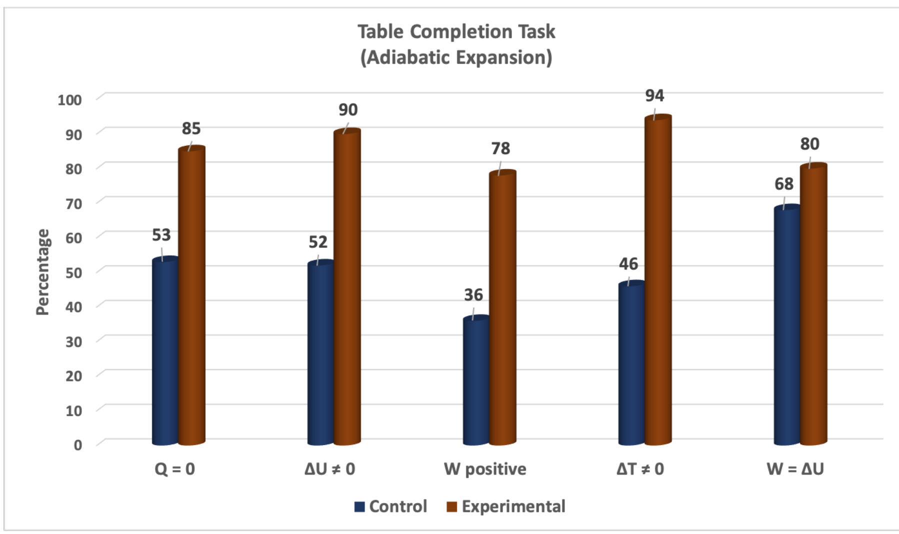


Figure 6.24: Table completion task - Percentage of students giving correct responses

Isothermal process

In the case of isothermal compression as well as expansion (figures 6.25 and 6.26), most students (95% and 91% respectively) confirmed that $\Delta T = 0$. In the 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 the case of other quantities/relations. It was found that those who responded could answer it correctly.

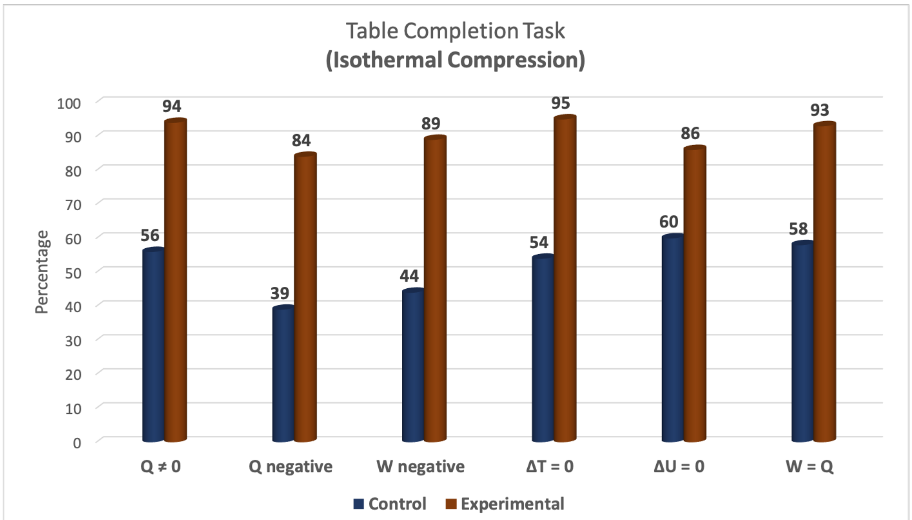


Figure 6.25: Table completion task - Percentage of students making correct marks

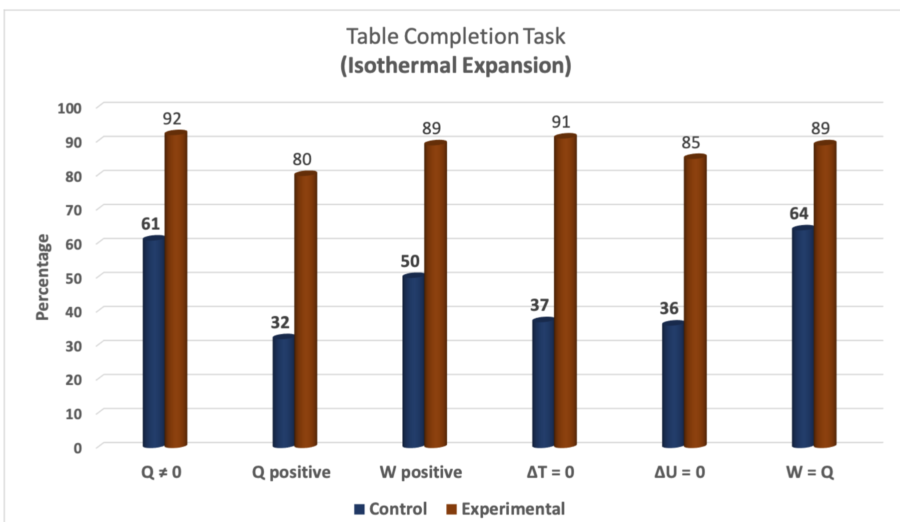


Figure 6.26: Table completion task - Percentage of students making correct marks

6.4 Concluding remarks

In order to understand the first law of thermodynamics, I felt that it is essential to make students understand the law in simpler situations, facilitating understanding of the individual energy terms. The simpler situations that I identified were the adiabatic and the isothermal processes. On the basis of my study of students' alternative conceptions about first law of thermodynamics, the primary points that were catered to while developing the module were as follows.

1. An adiabatic process means no heat transfer, and therefore adiabatic work will involve a change in internal energy with a resulting change in temperature.

2. An isothermal process, in the case of an ideal gas like system, corresponds to ΔU=0. Therefore, isothermal work on or by such a system will be accompanied by heat transfer.

The results showed that the experimental group's performance was significantly better on the post-test compared to the 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.

6.5 Publications from the part of this chapter

1. Pathare, S. R., Huli, S. S., Ladage, S., Pradhan, H. C. (2014). Students' understanding of first law of thermodynamics. Conference booklet of GIREP-MPTL International Conference, Palermo, Italy 330 - 331.

2. Pathare, S. R., Huli, S. H., Ladage, S. A., Pradhan, H. C. (2018). Understanding First Law of Thermodynamics through Activities. Physics Education, Institute of Physics, UK, (53)2, 1 - 18.

3. Pathare, S. R., Huli, S. H., Ladage, S., Pradhan, H. (2015). Students' understanding of the First Law of Thermodynamics. Presented at Indian Association of Physics Teachers, Hyderabad, India.

Chapter 7

Conclusion

This chapter presents conclusions of my work on the 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 and secondary school physics studies in India. Then, 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 the following six topics that were difficult to understand:

1. Heat and temperature

2. Thermal equilibrium

3. The first law of thermodynamics

4. Heat transfer mechanisms

5. Pressure and the elementary kinetic theory of gases

6. The second law of thermodynamics and related concepts

The second law of thermodynamics and related concepts like a 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. The first law of thermodynamics

4. Heat transfer mechanisms

I carried out the investigations into 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 the size and material of the objects.
7. Students consider heat as fluid while explaining the process of conduction.
8. In the case of natural convection, students attribute hotness to a single molecule.
9. In the 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, it was meaningful to consider the first three topics rather than the fourth one for designing the modules. Given 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. The first law of thermodynamics. I believed that the topic of "heat and temperature" is naturally covered under these two topics. The findings of students' alternative conceptions in the first three topics (statements 1 to 6) formed the basis for developing these activity-based modules.

7.1.2 Designing the modules

I observed that the alternative conceptions were related to understanding various prerequisite concepts related to the central concept. Thus, I realized 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 to build adequate conceptual understanding, which will help students 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 other aim was to develop 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 incremental in developing the understanding 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 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 with the guidelines for conceptual change based activity sessions (Eryilmaz 2002). The module began with a conceptual question describing a situation. Then, 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 the 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. In addition, the supporting sub-activities and discussions conducted by the researcher generated opportunities for students to engage with a 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 the surroundings. Therefore, the central activity (Activity 5.1) was designed to show students how the temperature of objects with different materials and sizes 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. They were clueless about the nature of heat flow during thermal equilibrium. Therefore, I looked for a possible analogy that could be demonstrated, and such an experience could be harnessed to enable students for developing an understanding of thermal equilibrium (Treagust and Duit 2009). The critical 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.

Arnold and Millar (Arnold and Millar 1996) used the liquid flow model to demonstrate the concept of dynamic equilibrium to the students and later used this model to check students' understanding of equilibrium in different situations. In the analogical model by Arnold and Millar, students are expected to apply the water analogy to the equilibrium model and, from this analogy, interpret the invisible movement of heat. In the present module, the assembly developed for hydrostatic equilibrium demonstrates two cylinders initially filled with water at different levels. Due to their familiarity with hydrostatic equilibrium, students can easily understand the role of liquid flow in attaining equilibrium. With this knowledge of the familiar liquid flow model, students drew correct prediction graphs of the heat flow indicator reading as thermal equilibrium is attained along with the variation in water temperature in the two compartments. The heat flow indicator made this heat flow visible to the students during the activity as the thermal equilibrium was attained and the temperatures became equal. Therefore, in the present study, the demonstration of the base domain (hydrostatic equilibrium) would make it easier to relate its sub-concepts to the target domain (thermal equilibrium) for students and hence, help them extend their understanding to the target domain.

The studies on thermal equilibrium in CLP (Lewis, Stern, and Linn 1993), RTP (Sokoloff, Thornton, and Laws 1998) or by diSessa (diSessa 2017), focus on predicting and observing the rate of change of temperature with time in a cooling process. Students are required to interpret this rate of change of temperature to the heat transfer to attain thermal equilibrium. In the present study, however, students directly observe the role of heat flow along with the temperature profiles of water in both the compartments.

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 emphasized that in one case, the quantity involved was the matter, whereas in the other case, it was energy.

Module on the 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 the quantitative representation of different energy terms. The information sheet explained students, the relationship 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 the 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 helpful in addressing students' difficulty of not distinguishing between heat and temperature. In addition, this change in temperature, that is, change in internal energy with $Q = 0$, would help students realize that heat flow and 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 the heat and internal energy to be equivalent. In adiabatic compression, the external work during the compression process in the fire syringe was equated to the change in internal energy. Real-time Physics laboratory module (Sokoloff, Thornton, and Laws 1998) used fire syringe to introduce to adiabatic compression and used the gas law to arrive at the final temperature of the ignited piece of paper. In the present study, to calculate the final temperature, I have used the statement of the first law of thermodynamics in both reversible and irreversible adiabatic compression processes. Such an approach provided students with a better explanation of individual energy terms in the first law. In another activity, work done in stirring the water changed the internal energy of water. These activities proved 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.
In both adiabatic and isothermal processes, indicating the absence/presence of heat flow using the heat flow indicator (Peltier Device) proved very useful to understand the term of heat flow and helped students provide an explanation of the other two energy terms in the first law.

7.1.3 Testing the effectiveness of the modules

One way to differentiate whether students' understanding has improved due to the intervention is to examine whether they are better prepared to continue learning once the intervention disappears (Bransford and Schwartz, 1999). Thus, the students have to learn to apply their knowledge in different contexts rather than just reciting the facts, as they need not come across the same exact problem that they were taught. It is very important for any good instructional strategy to know whether students are able to internalize their improved understanding and whether they can use it to tackle new problems.

In order to check the effectiveness of the final modules on thermal equilibrium and the first law of thermodynamics, a quasi-experimental design consisting of pre-test- intervention - post-test was used. The entire module was given to the experimental group, whereas the control group was given only the pre-test and post-test. Certain components of the post-test included questions pertaining to the new situation, like the activity on the method of mixtures in the case of the module on thermal equilibrium and the expansion process and table completion task in the module on the first law of thermodynamics. The students' responses in the pre-and post-tests as well as in the activity sheets were analyzed. There was a statistically significant change in the percentage of correct responses of the experimental group compared to the control group. The students' responses to these questions made it evident that their improved understanding enabled them to tackle new situations even after a week of implementing the intervention.

The changes that were observed in students' responses with respect to their difficulties are given below:

1. Students do not distinguish between heat and temperature

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

the presence of heat flow even if the temperature of the system remained constant.
In the case of adiabatic compression, the percentage of students saying an 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 an equal percentage of students agreed that both temperature (76%) and therefore the internal energy of the system (74%) increases. In the isothermal process, an equal percentage of students said that both temperature (72%) and internal energy of the system (62%) remains constant. This indicated that students could relate the 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 marked $Q = 0$ and 92% students agreed to $\Delta U \neq 0$. In case of isothermal compression 86% students marked $\Delta U = 0$ and 94% students marked $Q \neq 0$. For adiabatic compression (where the majority of students are aware of $Q = 0$), the percentage of students saying $\Delta U \neq 0$ increased. 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 evidence of their realization of external work as a mechanism by which internal energy can be changed.

5. Students have difficulty understanding energy terms in the 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 the size and material of the objects.

Students realized that thermal equilibrium is attained when net heat flow between two objects becomes zero, leading to an equal final temperature of the objects. Students were convinced that the time taken to attain thermal equilibrium depends on material and size. However, the final temperature reached is independent of these factors and equal to the surrounding temperature. Students could apply this understanding to the activity on the 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 from the state colleges affiliated with universities 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 the 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 for 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 in 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 the present college system. The sensors which have been chosen are low-cost and are readily available either in electronic shops or online websites. I also developed some activities with an alternate design enabling manual data collection, which otherwise uses data-logging instruments in the module. These alternate apparatus were later tested in different teacher workshops. The purpose of this 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. However, at certain places where it is very difficult to get the required sensors and material to develop the activities, one can use these videos. Moreover, such carefully designed activity modules present opportunities to revisit thinking and reflect on the same, which is crucial in advancing 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 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 generalizable. 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 a 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 to understand the improvement in students' understanding and retention. It is important to check whether students retain the improvement over time by administering similar tests over time. However, access to the same sample on a 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 consider those concepts that 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 they will affect the interlinkages among various concepts. Thus, reflection on the nature of concepts is crucial while adapting the suitable approach. For example, it is difficult to develop activities for the relationship between change in temperature and change in internal energy.

In the module on the first law of thermodynamics, the activities were related to the compression process. In the post-test, along with the questions on compression, questions on the expansion process were given to the students. It was observed that this extrapolation was attempted by many students; the percentage of correct responses for the expansion process was lower than that obtained for the 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 the 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 teachers implement the activity modules. The first law of thermodynamics unit 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 mechanism, pressure, heat engines, entropy and the 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 essential for the undergraduate phase of physics education, especially in the Indian context, where conventional mode is still predominant.

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Appendix A

70 core concepts in elementary thermodynamics

The 70 concepts were divided into following four groups. These groups were given to different batches of students. Following question was asked to the students:

What do the following concepts mean to you? Explain each with an example. Please put a cross mark in front of the concept which you are not familiar with.

GROUP A		**GROUP B**	
Thermodynamics		Thermal Equilibrium	
Kinetic Theory		Mechanical Equilibrium	
Statistical Mechanics		Chemical Equilibrium	
System		Thermodynamic Equilibrium	
Surrounding		State of a system	
Open system		Adiabatic Process	
Closed System		Diathermic	
Macroscopic Variable		Heat	
Microscopic Variable		Work	
Thermodynamic Coordinates		Internal Work	
Intensive Variables		External Work	
Extensive Variables		Positive Work	
Pressure		Negative Work	
Temperature		Isothermal Process	
Internal Energy		Thermometry	
Hydrostatic System		Boiling Point	
Isotherm		Freezing Point	
		Sublimation Point	
		Triple Point	

GROUP C		**GROUP D**	
Change of state		Ideal gas	
Change of phase		Real Gas	
Equation of state		Zeroth law of thermodynamics	
Quasistatic Process		First law of thermodynamics	
Heat Capacity		Second law of thermodynamics	
Internal Energy Capacity		Third law of thermodynamics	
Molar heat capacity		Heat Engine	
Mechanical equivalent of heat		Heat Pump	
Heat Reservoir		Reversible Process	
Heat Sink		Irreversible Process	
Heat Conduction		Carnot Cycle	
Heat Convection		Thermodynamic Temperature Scale	
Natural Convection		Absolute zero	
Forced Convection		Entropy	
Thermal Radiation		Helmholtz Free Energy	
Black Body Radiation		Gibbs Function	
Extensive Coordinate			
Intensive Coordinate			

Appendix B

Questionnaires for investigating students' alternative conceptions

B.1 Heat and Temperature

1. What is heat? Try to say where your ideas come from.
2. What is temperature? Try to say where your ideas come from.
3. Think of a container filled with hot air placed on a train moving with uniform velocity. Observer A is on the train and observer B is standing on the ground by the side of the track. According to observer A the internal energy of the gas is U. Will the internal energy be greater than, equal to or less than U for observer B? Explain your reasoning.
4. Suppose that you have two cubes of the same mass, one made of wood and the other made of copper. Both are at room temperature. They are then kept in a hot air enclosure at 70°C for a few hours.

   (a) How do you think the temperature of the two cubes will compare? Explain your answer.

(b) How do you think that the heat energy gained by the two cubes above will compare? Explain your answer.

5. I have two bricks made from the same kind of clay, but one is large and the other is small. Suppose I put them both in an oven at 120°C for a few hours. At the end of the few hours, how will the temperature of the two bricks compare?

6. Suppose I have a pot of boiling water on the stove. If I turn the knob of the gas stove to a higher flame, what will happen to the temperature of boiling water? Explain your answer.

7. Consider a box of volume V which is filled with air at room temperature (27°C). Let it stand for a few hours.

   (a) Suppose the box is partitioned in two equal compartments of volume $V/2$ each. What will be the temperature of the gas in each compartment?

   (b) Suppose the box is partitioned in two unequal compartments, one of volume $V/3$ and the other of volume $2V/3$. What will be the temperature of the gas in the two compartments?

B.2 Heat Transfer Mechanisms

1. Explain how heat is transferred from one place to another in following cases. We will appreciate your detailed answers.

    (a) A metal rod is heated at one end. We find that the other end of the rod becomes hot after some time.

    (b) A beaker containing water is put on a burner. After some time it is observed that even the water in the top layer is hot and if we wait for some more time the water starts boiling.

    (c) We receive from the sun not only light but also heat.

2. Identify which of the following processes (one or more) namely conduction, convection and radiation contribute in the following situations. Justify your answer.

    (a) A vessel containing hot water at 90°C is kept in a room. The room temperature is 30°C. The vessel and the water gradually cool down.

    (b) Often in rest rooms of restaurants, a hot air blower is provided. If we hold our wet hands in front of the blower, our hands get dry.

    (c) In winter on a chilly night, sitting next to a fire place makes us feel warm.

    (d) For joint pain relief, under medical advice

        i. we soak our feet in hot water

        ii. we take "infrared light" treatment

    (e) The mercury in the clinical thermometer rises when kept in the armpit of a person who has fever.

3. We know that the diamond is a very good electric insulator whereas silver is a very good electric conductor. Electrical conductivity of silver is much greater than that of diamond by many orders of magnitude (typically 1018 times greater). But the

thermal conductivity of diamond is 5 times greater than silver. How do you think this is possible?

4. Suppose that a room is maintained at 25°C. A steel rod and a wooden rod are placed in the room for a long time. If a person touches both the rods then he finds that steel rod is colder than the wooden rod. Explain why.

B.3 Thermal Equilibrium

1. 100 g water at 50°C is mixed with 50 g water at 80°C. The experiment is carried out on a platform moving with a uniform velocity v. (You may neglect loss of heat due to radiation and other causes). The final temperature of the mixture will be

   (a) no steady temperature will be reached as the platform is moving

   (b) 65°C

   (c) can't say as the temperature reached will depend on the velocity of the platform

   (d) 60°C

2. Consider a gas enclosed in a cylinder fitted with a movable piston. The cylinder is kept on a platform which is moving. Example of a thermodynamic variable for the gas in the cylinder taken as a system is

   (a) the velocity of the cylinder

   (b) the position of the centre of mass of the system

   (c) the velocity of any molecule of the gas enclosed

   (d) none of the above

3. If a system is in a state of thermodynamic equilibrium,

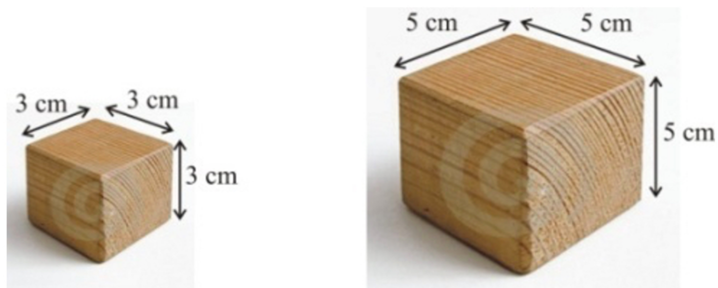
   (a) The macroscopic variables of the system and the surrounding do not change in time; the microscopic variables of the system and the surrounding may be changing in time.

   (b) Both macroscopic as well as microscopic variables of the system and the surrounding do not change in time.

   (c) The microscopic variables of the system and surrounding do not change in time, the macroscopic variables may be changing in time.

(d) Both macroscopic and microscopic variables of the system may be changing in time but those of the surrounding do not change in time.

4. Suppose that you have two cubes of wood say cube A and cube B. Cube A has volume of 27 cm^3 and cube B has a volume of 125 cm^3. Both are at room temperature. They are then kept in a hot air enclosure at 70°C for a few hours.



(a) Temperature of cube A will be greater than that of cube B

(b) Temperature of cube B will be greater than that of cube A

(c) Temperature of both the cubes will be the same

(d) Both cubes attain a steady temperature but the temperature attained by each one is different

5. If a system is in a state of mechanical equilibrium

(a) there is no change in time in any thermodynamic variable describing the system.

(b) there is no unbalanced force in the interior of the system, but there may be unbalanced forces between the system and its surrounding.

(c) there is no unbalanced force either in the interior of the system or between the system and the surrounding

(d) there is no unbalanced force between the system and the surrounding, the forces in the interior do not matter

6. Categorize the following materials as practically suitable for adiabatic (A) and diathermic (D) walls. (Mark 'A' or 'D' in the answersheet.)

	A or D		A or D
Plastic		Concrete	
Glass		Diamond	
Brass		Aluminum	
Paper		Gold	
Rubber		Teflon	

7. A system is described by two thermodynamic variables X and Y. Variables X and Y are said to be independent. This means

   (a) X and Y can take various values, but given a value of X, the value of Y is decided

   (b) X and Y can take various values, for any value of X, any value of Y can be taken

   (c) X and Y have fixed values

   (d) X and Y can take various values, but these values are decided by the value of a third variable

8. Two systems A and B are characterized by definite thermodynamic variables X_1, Y_1, and X_2, Y_2 respectively. These two systems are separated by a wall. They are not in equilibrium with each other at the instant when observed. After a while,

   (a) X_1, Y_1, and X_2, Y_2 will remain the same irrespective of whether the wall is adiabatic or diathermic

   (b) X_1, Y_1, and X_2, Y_2 will change irrespective of whether the wall is adiabatic or diathermic

(c) X_1, Y_1, and X_2, Y_2 will change if the wall is diathermic

(d) X_1, Y_1, and X_2, Y_2 will remain the same if the wall is diathermic

9. When two identical samples of a liquid at different temperatures 34°C and 96°C respectively, are mixed, the final temperature will be

   (a) 65°C

   (b) 130°C

   (c) 62°C

   (d) 34°C

10. Suppose that you have two cubes of the same mass, one made of wood and the other made of copper. Both are at room temperature. They are then kept in a hot air enclosure at 70°C for a few hours.

    (a) Temperature of the wooden cube will be greater than the temperature of the copper cube as the specific heat of wood is higher than that of copper.

    (b) Temperature of the copper cube will be greater than the temperature of the wooden cube as the thermal conductivity of copper is higher than that of the wood.

    (c) Both cubes will be at the same temperature, but the temperature reached will be some temperature less than 70°C.

    (d) Temperature of both the cubes will be 70°C

11. A thermodynamic variable is

    (a) any macroscopic quantity describing a system

    (b) any macroscopic quantity having a bearing on the internal state of a system

    (c) any macroscopic quantity having a bearing on the external state of a system

    (d) any microscopic quantity describing a system

B.4 First Law of Thermodynamics

Process 1

Consider a container fitted with a frictionless movable piston. The walls of the container and the piston do not allow any transfer of heat. The gas in the container (Fig. (a)) is at room temperature. Now, the piston is pushed down by distance h as shown in Fig.(b). The work done in this process is denoted by W and the net heat flow by Q.

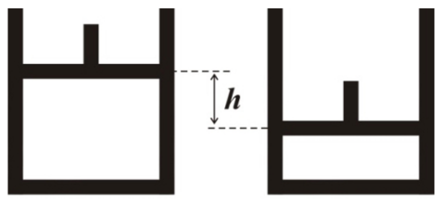


Fig.(a) Fig.(b)

Assume that the process of moving the piston down [fig.(a) to fig.(b)] is reversible. The system in the question refers to the gas in the container. The process refers to the piston moving from the position in fig.(a) to the position in fig.(b). From the statements given below tick the option which according to you hold true for the entire process. Also justify your choices in the space provided.

1. Pressure, P

   (a) Pressure of the system will remain constant during the process

   (b) Pressure of the system will increase in the process

   (c) Pressure of the system will decrease in the process

2. Work done, W

   (a) Work done on the system will be zero

   (b) Work is done on the system

   (c) Work is done by the system

3. Internal Energy, U

   (a) The internal energy of the system will increase in the process

   (b) The internal energy of the system will decrease in the process

   (c) The internal energy of the system will remain constant during the process

4. Temperature, T

   (a) The temperature of the system will remain constant during the process

   (b) The temperature of the system will increase in the process.

   (c) The temperature of the system will decrease in the process.

5. Net heat flow, Q

   (a) The net heat flow (Q) into the system during the process will be negative

   (b) The net heat flow (Q) into the system during the process will be positive

   (c) The net heat flow (Q) into the system during the process will be zero

Process 2

Consider a container fitted with a frictionless movable piston. The walls of the container and the piston freely allow transfer of heat. The gas in the container (Fig. (a)) is at room temperature. Now, the piston is pushed down slowly by distance h as shown in Fig.(b).

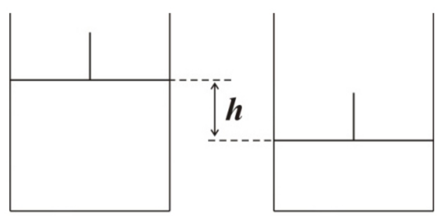


Fig.(a) Fig.(b)

The work done in this process is denoted by W and the net heat flow by Q. During this period the temperature of the gas in the container is maintained. Assume that the process of moving the piston down [fig.(a) to fig.(b)] is reversible. The system in the questions below refers to the gas in the container. The process refers to the piston moving from the position in fig.(a) to the position in fig.(b). From the statements given below tick the option which according to you hold true for the entire process. Also justify your choices in the space provided.

1. Pressure, P

    (a) Pressure of the system will remain constant during the process.

    (b) Pressure of the system will increase in the process.

    (c) Pressure of the system will decrease in the process

2. Work done, W

    (a) Work done on the system will be zero

    (b) Work is done on the system

    (c) Work is done by the system

3. Net heat flow, Q

    (a) The net heat flow (Q) into the system during the process will be negative.

    (b) The net heat flow (Q) into the system during the process will be positive

    (c) The net heat flow (Q) into the system during the process will be zero

4. Internal Energy, U

   (a) The internal energy of the system will increase in the process

   (b) The internal energy of the system will decrease in the process

   (c) The internal energy of the system will remain constant during the process

5. Temperature, T

   (a) The temperature of the system will remain constant during the process

   (b) The temperature of the system will increase in the process.

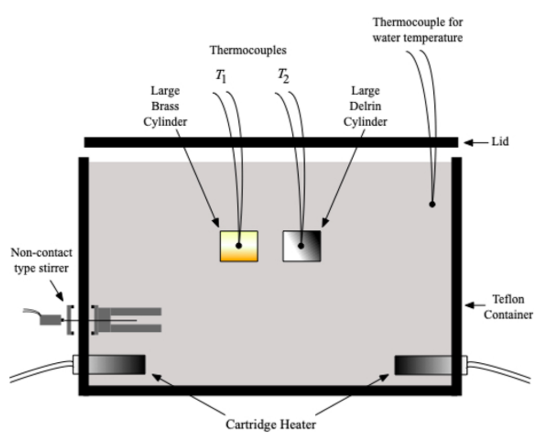
   (c) The temperature of the system will decrease in the process.

Appendix C

Pre and Post test - Module on Thermal equilibrium

C.1 Pre-Test

1. Two solid cylinders of the same size, one made up of an insulator (delrin) and another made up of a metal (brass), are initially at room temperature (T_{room}). These cylinders are then placed in a water bath maintained at 60°C ($= T_{waterbath}$). The cylinders are kept in the water bath for a long time.



(a) What will be the final temperature of these cylinders? Which of the following predictions do you support? Tick the option which you feel is correct.

i. $T_{brass} > T_{delrin}$

ii. $T_{brass} < T_{delrin}$

iii. $T_{brass} = T_{delrin}$

Provide an explanation for the choice.

(b) Depending on the option you selected in 1(a), answer the following question:

i. If you have selected Option 1 in 1(a), then tick the option which you feel is correct:

A. $T_{brass} = T_{waterbath}$ and $T_{delrin} < T_{waterbath}$

B. $T_{brass} > T_{waterbath}$ and $T_{delrin} = T_{waterbath}$

C. $T_{brass} = T_{waterbath}$ and $T_{delrin} = T_{room}$

ii. If you have selected Option 2 in 1(a), then tick the option which you feel is correct:

A. $T_{brass} < T_{waterbath}$ and $T_{delrin} = T_{waterbath}$

B. $T_{brass} = T_{waterbath}$ and $T_{delrin} > T_{waterbath}$

iii. If you have selected Option 3 in 1(a), then tick the option which you feel is correct:

A. $(T_{brass} = T_{delrin}) < T_{waterbath}$

B. $(T_{brass} = T_{delrin}) = T_{waterbath}$

C. $(T_{brass} = T_{delrin}) > T_{waterbath}$

Provide an explanation for the choice.

(c) Choose the correct choice:

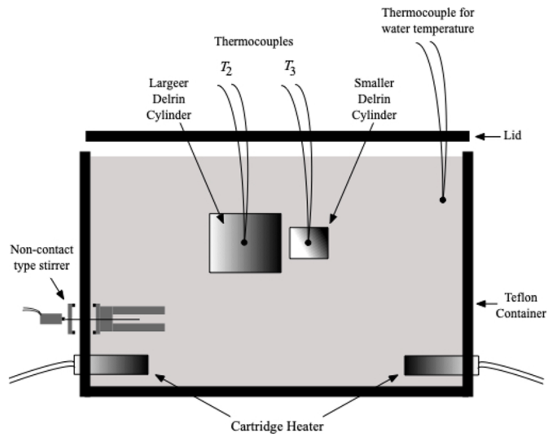
i. Temperature of the brass cylinder will rise faster than the temperature of the delrin cylinder

ii. Temperature of the delrin cylinder will rise faster than the temperature of the brass cylinder

iii. Temperatures of both the cylinders will rise at an equal rate.

Provide an explanation for the choice.

2. Two solid cylinders of delrin are provided. One cylinder has a smaller volume and the other cylinder has a larger volume, both are initially at room temperature (T_{room}). These cylinders are then kept in a water bath maintained at 60°C ($= T_{waterbath}$) for a long time.



(a) Predict the final temperature of these cylinders. Tick the option which you feel is correct.

i. $T_{smalldelrin} > T_{largedelrin}$

ii. $T_{smalldelrin} < T_{largedelrin}$

iii. $T_{smalldelrin} = T_{largedelrin}$

Provide an explanation for the choice.

(b) Depending on the option you selected in 2(a), answer the following question:

i. If you have selected Option 1 in 2(a), then tick the option which you feel is correct:

A. $(T_{smalldelrin} = T_{waterbath})$ and $(T_{largedelrin} < T_{waterbath})$

B. $(T_{smalldelrin} > T_{waterbath})$ and $(T_{largedelrin} = T_{waterbath})$

C. $(T_{smalldelrin} < T_{waterbath})$ and $(T_{largedelrin} = T_{room})$

ii. If you have selected Option 2 in 2(a), then tick the option which you feel is correct:

A. $(T_{smalldelrin} < T_{waterbath})$ and $(T_{largedelrin} = T_{waterbath})$

B. $(T_{smalldelrin} = T_{waterbath})$ and $(T_{largedelrin} > T_{waterbath})$

iii. If you have selected Option 3 in 2(a), then tick the option which you feel is correct

A. $(T_{smalldelrin} = T_{largedelrin}) < T_{waterbath}$

B. $(T_{smalldelrin} = T_{largedelrin}) = T_{waterbath}$

C. $(T_{smalldelrin} = T_{largedelrin}) < T_{room}$

Provide an explanation for the choice.

(c) Choose the correct choice:

i. Temperature of the smaller delrin cylinder will rise faster than the temperature of the larger delrin cylinder.

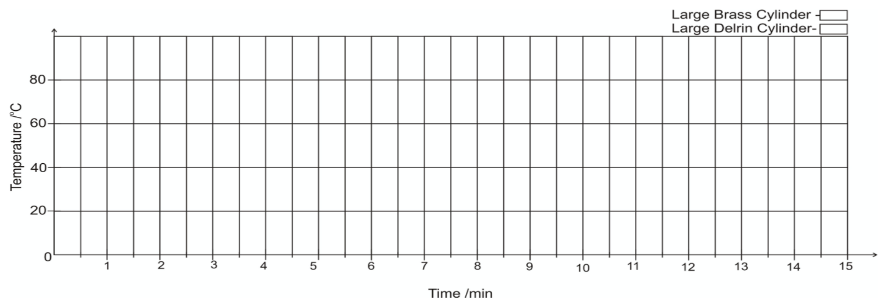
ii. Temperature of the larger delrin cylinder will rise faster than the temperature of the smaller delrin cylinder.

iii. Temperatures of both the cylinders will rise at an equal rate.

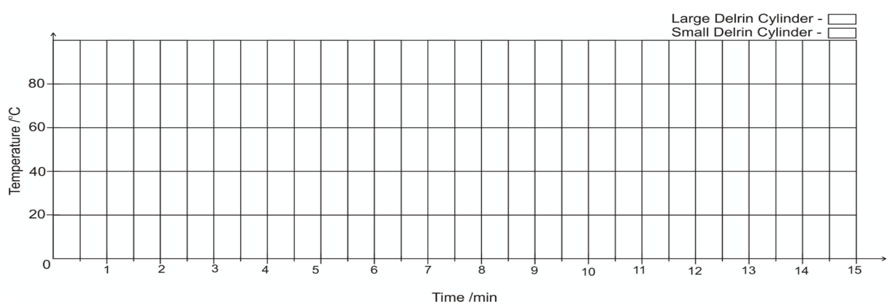
Provide an explanation for the choice.

Sketch the Temperature Profiles

1. Sketch the graphs below in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.

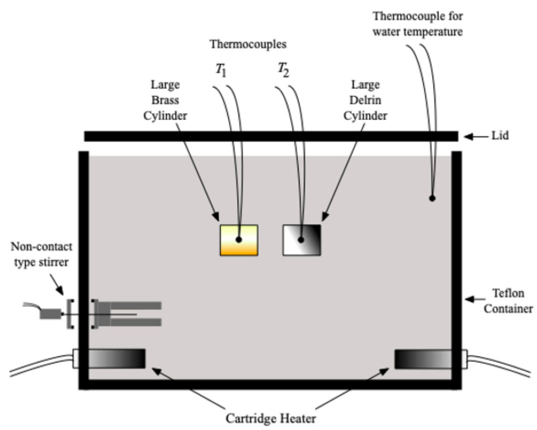


2. Sketch the graphs below in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.



C.2 Post-Test

1. Two solid cylinders of the same size, one made up of an insulator (delrin) and another made up of a metal (brass), are initially at room temperature (T_{room}). These cylinders are then placed in a water bath maintained at $T_{waterbath}$ (=   °C). The cylinders are kept in the water bath for a long time.



   (a) What will be the final temperature of these cylinders? Which of the following predictions do you support? Tick the option which you feel is correct.

      i. $T_{brass} > T_{delrin}$

      ii. $T_{brass} < T_{delrin}$

      iii. $T_{brass} = T_{delrin}$

   Provide an explanation for the choice.

   (b) Depending on the option you selected in 1(a), answer the following question:

i. If you have selected Option 1 in 1(a), then tick the option which you feel is correct:

A. $(T_{brass} = T_{waterbath})$ and $(T_{delrin} < T_{waterbath})$

B. $(T_{brass} > T_{waterbath})$ and $(T_{delrin} = T_{waterbath})$

C. $(T_{brass} = T_{waterbath})$ and $(T_{delrin} = T_{room})$

ii. If you have selected Option 2 in 1(a), then tick the option which you feel is correct:

A. $(T_{brass} < T_{waterbath})$ and $(T_{delrin} = T_{waterbath})$

B. $(T_{brass} = T_{waterbath})$ and $(T_{delrin} > T_{waterbath})$

iii. If you have selected Option 3 in 1(a), then tick the option which you feel is correct:

A. $(T_{brass} = T_{delrin}) < T_{waterbath}$

B. $(T_{brass} = T_{delrin}) = T_{waterbath}$

C. $(T_{brass} = T_{delrin}) > T_{waterbath}$

Provide an explanation for the choice.

(c) Choose the correct choice:

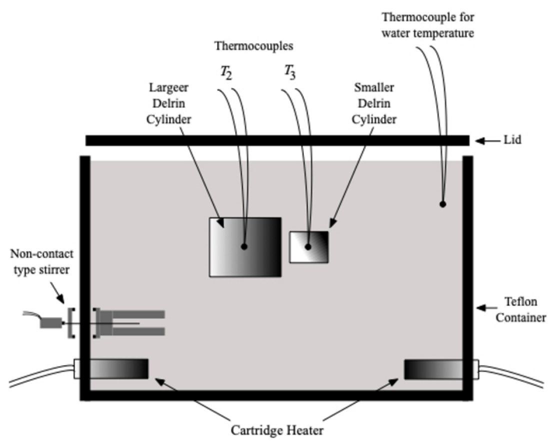
i. Temperature of the brass cylinder will rise faster than the temperature of the delrin cylinder

ii. Temperature of the delrin cylinder will rise faster than the temperature of the brass cylinder

iii. Temperatures of both the cylinders will rise at an equal rate.

Provide an explanation for the choice.

2. Two solid cylinders of delrin are provided. One cylinder has a smaller volume and the other cylinder has a larger volume, both are initially at room temperature (T_{room}). These cylinders are then kept in a water bath maintained at $T_{waterbath}$ (= °C) for a long time.



(a) Predict the final temperature of these cylinders. Tick the option which you feel is correct.

i. $T_{smalldelrin} > T_{largedelrin}$

ii. $T_{smalldelrin} < T_{largedelrin}$

iii. $T_{smalldelrin} = T_{largedelrin}$

Provide an explanation for the choice.

(b) Depending on the option you selected in 2(a), answer the following question:

i. If you have selected Option 1 in 2(a), then tick the option which you feel is correct:

A. $(T_{smalldelrin} = T_{waterbath})$ and $(T_{largedelrin} < T_{waterbath})$

B. $(T_{smalldelrin} > T_{waterbath})$ and $(T_{largedelrin} = T_{waterbath})$

C. $(T_{smalldelrin} < T_{waterbath})$ and $(T_{largedelrin} = T_{room})$

ii. If you have selected Option 2 in 2(a), then tick the option which you feel is correct:

A. $(T_{smalldelrin} < T_{waterbath})$ and $(T_{largedelrin} = T_{waterbath})$

B. $(T_{smalldelrin} = T_{waterbath})$ and $(T_{largedelrin} > T_{waterbath})$

iii. If you have selected Option 3 in 2(a), then tick the option which you feel is correct

A. $(T_{smalldelrin} = T_{largedelrin}) < T_{waterbath}$

B. $(T_{smalldelrin} = T_{largedelrin}) = T_{waterbath}$

C. $(T_{smalldelrin} = T_{largedelrin}) = T_{room}$

Provide an explanation for the choice.

(c) Choose the correct choice:

i. Temperature of the smaller delrin cylinder will rise faster than the temperature of the larger delrin cylinder.

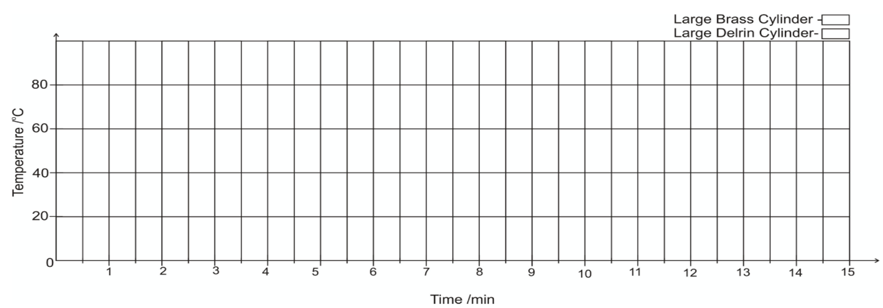
ii. Temperature of the larger delrin cylinder will rise faster than the temperature of the smaller delrin cylinder.

iii. Temperatures of both the cylinders will rise at an equal rate.

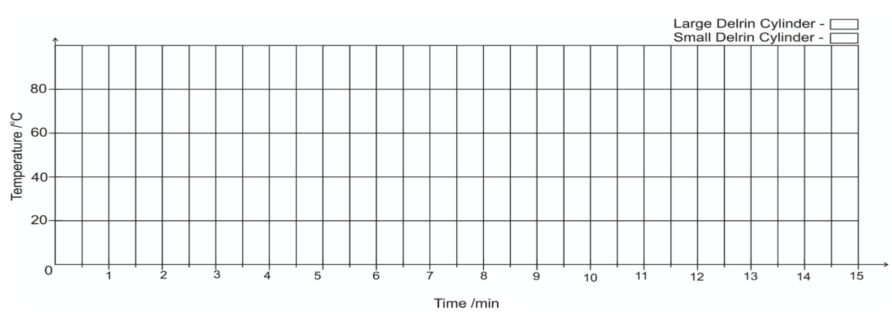
Provide an explanation for the choice.

Sketch the Temperature Profiles

1. Sketch the graphs below in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.



2. Sketch the graphs below in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.



Appendix D

Activity Sheets - Module on Thermal Equilibrium

D.1 Activity 1: Thermal Equilibrium between a metal cylinder and an insulator cylinder

This activity consists of:

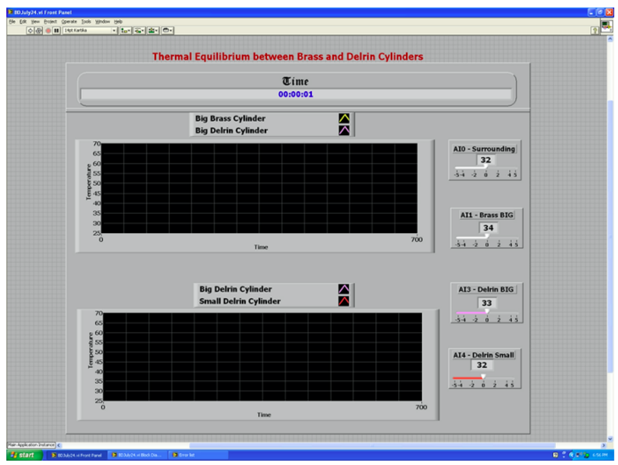
- One brass cylinder and one delrin cylinder of same volume and another delrin cylinder of smaller volume
- The temperature profile of these cylinders will be studied in the following combinations:
  - Material Dependence: Large Brass Cylinder and Large Delrin Cylinder
  - Size Dependence: Large Delrin Cylinder and Small Delrin Cylinder
- A water bath in a Teflon container with stirrer and heater.
- Data acquisition system connected to a laptop

Observe:

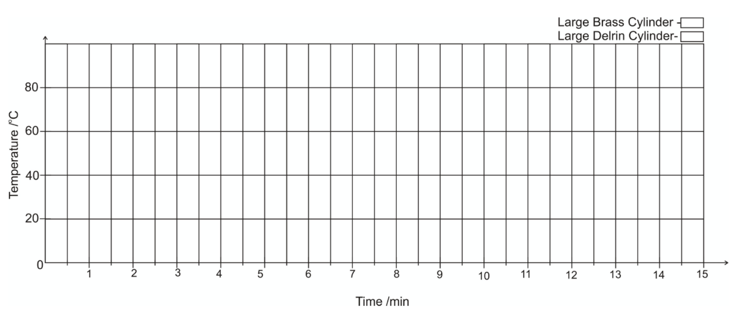
1. The water bath is maintained at a temperature =   ˚C.

2. All the three cylinders will be immersed simultaneously in the water bath.

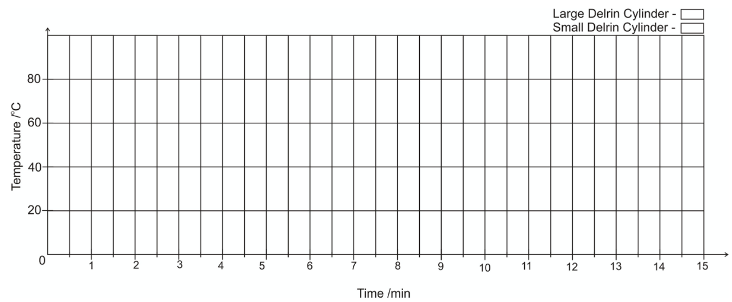
3. Observe the final temperatures attained by the cylinders and the temperature rise in case of each cylinders in all the combinations as shown in the screenshot below:



4. Draw the sketch of the graphs you observed in the space provided “only for the combinations mentioned” in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.[Large Brass Cylinder and Large Delrin Cylinder]



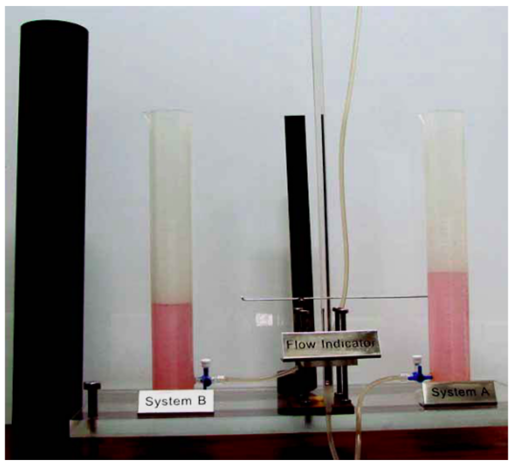
5. Draw the sketch of the graphs you observed in the space provided “only for the combinations mentioned” in different colours i.e. red and green in each case. Mark the respective colours next to the titles by drawing a line in the box.[Large Delrin Cylinder and Small Delrin Cylinder]



6. Is there any difference between the predictions that you made and the results that you observed? Explain the difference, if there is a difference.

D.2 Extension Activity 1: Thermal equilibrium using liquid flow analogy

Two plastic cylinders, of equal volume (each of 250 ml) are used as two (hydrostatic) systems. These cylinders are connected to each other through a flow indicator. The floater in the flow indicator goes up when there is a flow of liquid between the cylinders. In the absence of any liquid flow the floater remains at the bottom.



The cylinders (named as system A and system B) are filled with water at different levels. The water level in system A cylinder is greater than the water level in system B cylinder. The system B cylinder is covered with a black pipe. Valves are attached to the cylinders to control the flow.

Observe:

1. When the control knobs are opened, the liquid starts to flow from one cylinder to the other.

2. The floater in the flow indicator moves up when the liquid starts to flow.

3. Wait till the floater comes down to the bottom indicating the flow of water from one cylinder to the other has stopped.

4. What do you think will the levels of water in both the cylinders be? (Tick correct option.)

    (a) Water level in system A cylinder will be greater than that in system B cylinder.

    (b) Water level in system A cylinder will be less than that in system B cylinder.

    (c) Water level in both the cylinders will be equal.

5. If the system A shows 11.5 cm reading, then what so you think the reading in system B will be (Tick the correct option)? Explain.

    (a) System B reading will be equal to 11.5 cm.

    (b) System B reading will be greater than 11.5 cm.

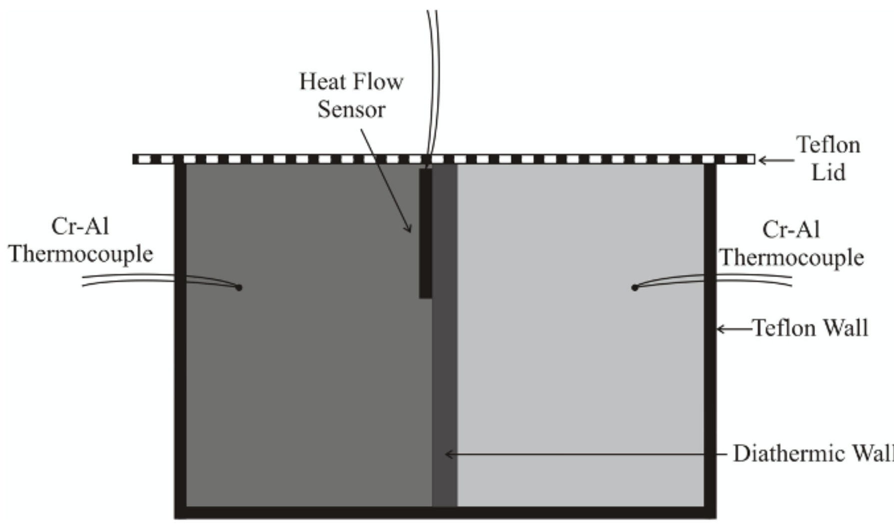
    (c) System B reading will be less than 11.5 cm.

6. Did you find any difference between your prediction of reading before and after the black cover was raised? If yes, then explain.

D.3 Extension Activity 2: Thermal Equilibrium between two systems

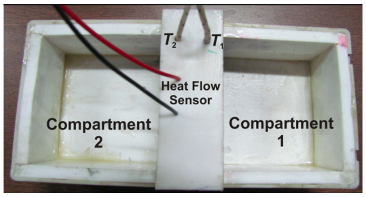
This activity will help you to understand the process of thermal equilibrium.

The apparatus consists of a chamber divided into two compartments as shown in the Fig.1 below. Both the compartments are separated by a gap in which either an adiabatic or a diathermic wall can be inserted. A diathermic wall will allow the heat flow between two compartments and the adiabatic wall will not allow such a flow.

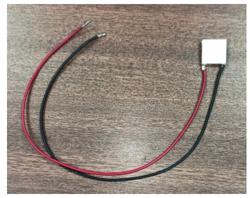


When nothing is inserted in the gap then the air in the gap will act as the adiabatic wall (thermal conductivity of air = 0.026 W/m·K). A graphite sheet (of 7 mm thickness) is fixed in the gap, it will act as a diathermic wall (thermal conductivity of graphite = 470 W/m·K). Temperatures of water in both the compartments are measured using chromel-alumel thermocouples. The amplified outputs of the thermocouples are fed to the computer through a data acquisition system.

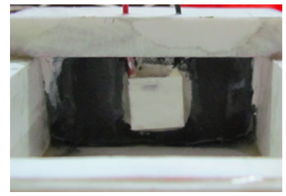
A heat flow indicator is attached to one side of the graphite sheet to note down the heat flowing from one compartment to the other compartment. This sensor produces voltage proportional to the heat flowing through it. The voltage is fed to the computer through the data acquisition system.



(a) Assembly with compartments



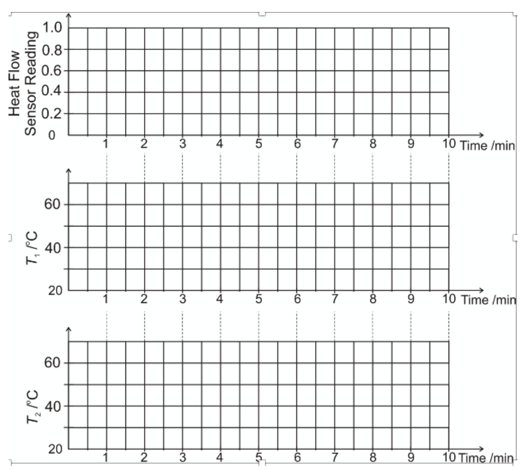
(b) Heat Flow Indicator



(c) Heat Flow Indicator attached to the graphite wall

Predict:

Compartment A (in which heat flow indicator is located) is filled with water at room temperature and compartment B is filled with hot water (with its temperature around 60°C).



Draw a rough sketch of

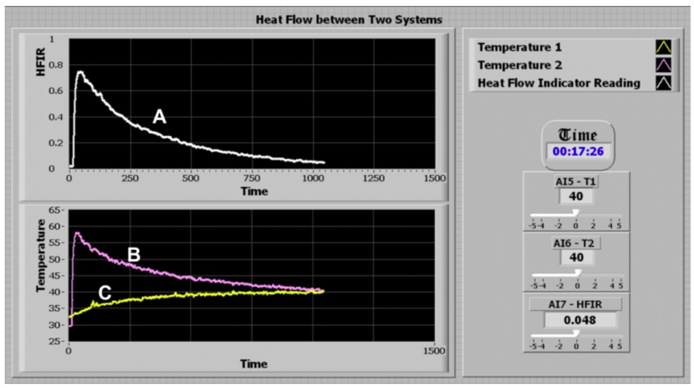
1. how the output of the heat flow indicator changes with time.

2. how the temperature of water in compartment A (T_A which is initially at 60°C) changes with time.

3. how the temperature of water in compartment B (T_B which is initially at room temperature say 30°C) changes with time.

Observe and Explain:

Observe the variation in Heat Flow Indicator Reading, T_1 and T_2. You are given a printout of all the three graphs. Regions are marked as A, B and C. Explain these regions with justifications.



A
B
C

Considering your responses in the Liquid flow model activity and Heat flow model activity, give your reflection about the process of thermal equilibrium?

Match the columns:

You are given a set of heat flow model concepts in the table below.

Heat Flow Model	**Liquid Flow Model**
Temperature	
Heat flow	
Adiabatic wall	
Diathermic wall	
Heat flow rate	

Choose and match from the following liquid flow concepts and write them next to the corresponding heat flow model concept:

Control valve in the open state

Height of the liquid column

Liquid flow rate

Control valve in the closed state

Liquid flow

D.4 Extension Activity 3: Liquid Flow Analogy for the Activity 1

In this activity you will do a liquid flow analogy of the main activity.

Three measuring cylinders are used in this activity. One cylinder will act as a reservoir whose water level will be maintained at a constant value. There are two openings near the open end of the reservoir cylinder. The upper opening (inlet) lets the water constantly enter the cylinder and the lower one allows the water to flow out. As a result a constant level of water is maintained in the cylinder as shown in the figure. Water from the reservoir is supplied to two cylinders (system A and system B) through pipe 1 and pipe 2 respectively as shown in figure D.2. The flow of water is controlled by a valve. The water flow here is analogous to heat flow.

Pipe 1 has inner diameter of 10 mm whereas the pipe 2 has inner diameter of 3 mm.

Case 1:

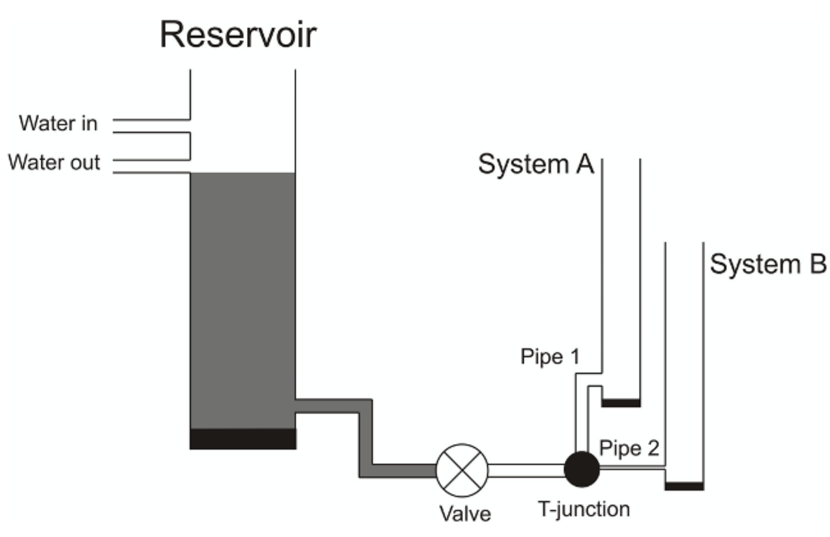


Figure D.2: Connecting pipes with diameters

Two cylinders with equal volumes are taken as two systems. The cylinder connected to the pipe with inner diameter 10 mm is called as system A and the cylinder connected to pipe with inner diameter 3 mm is called as system B.

Predict:

Sketch a schematic graph of the water level rise (figure D.3) in both the cylinders. Use Red pen for system A and green pen for system B.

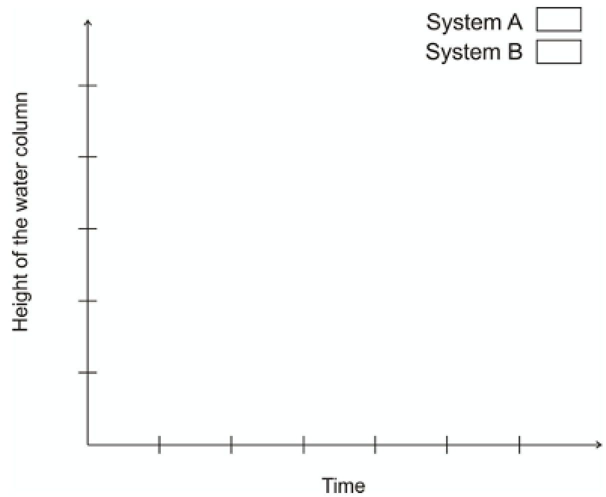


Figure D.3: schematic graph of the water level rise

Observations:

1. The reservoir cylinder is filled with water and a constant level is maintained in the cylinder.

2. The valve is shifted to ON position.

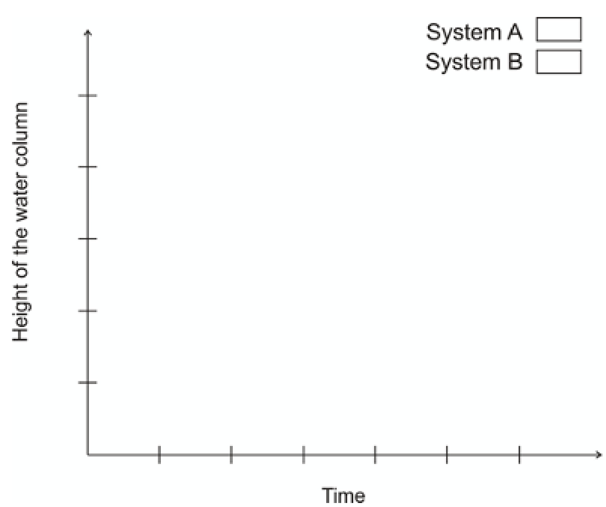
3. Observe the water levels in both the cylinders as the levels rise.

   (a) About the water level in system A (cylinder connected to a pipe of 10 mm diameter):

(b) About the water level in system B (cylinder connected to a pipe of 3 mm diameter):

(c) Do the levels rise at equal rate? If not which rises at a faster rate?

(d) With these observations, sketch the schematic graph of the water level rise in both the cylinders . Red pen for system A and green pen for system B.



Case 2:

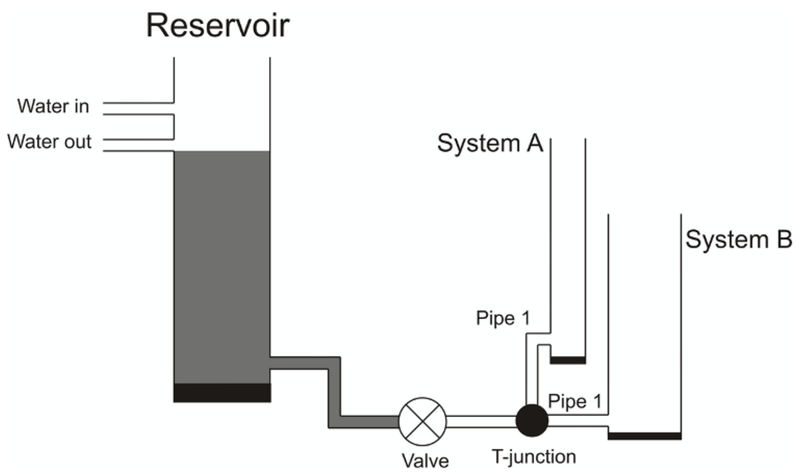
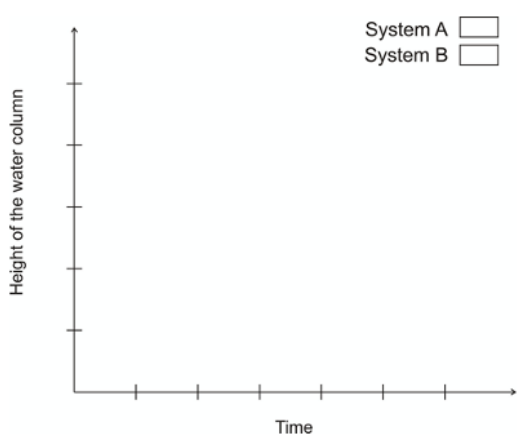


Figure D.4: Cylinders with different areas of cross-section

Two cylinders with different volumes are taken as two systems (figure D.4. Here both the cylinders are connected to the pipes with inner diameter 10 mm. The cylinder with smaller volume is called as system A and the cylinder with larger volume is called system B.

Predict:

Sketch a schematic graph of the water level rise in both the cylinders. Use Red pen for system A and green pen for system B.



Observations:

1. The reservoir cylinder is filled with water and a constant level is maintained in the cylinder.

2. The valve is shifted to ON position.

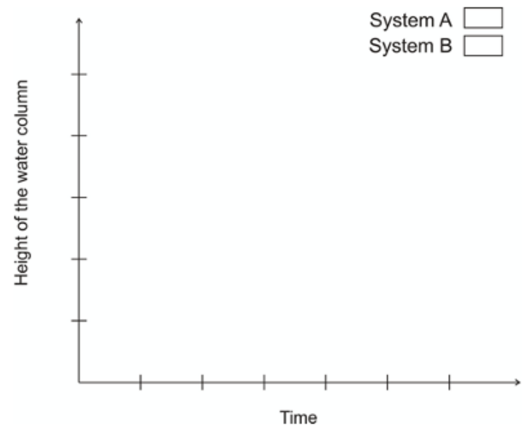
3. Observe the water levels in both the cylinders as the levels rise.

   (a) About the water level in system A (Smaller cylinder):

   (b) About the water level in system B (Larger cylinder):

   (c) Do the levels rise at equal rate? If not which rises at a faster rate?

(d) With these observations, sketch the schematic graph of the water level rise in both the cylinders . Use Red pen for system A and green pen for system B.



Considering your responses in the Liquid flow analogy of the Activity 1 and in the Activity 1, reflect on the parameters which decides the rate at which the equilibrium is attained.

D.5 Post – test activity on Method of mixtures

A test tube with 20 ml of water (at room temperature = 30°C) is mounted on a retort stand. A brass cylinder (mass = 19.7 g) is kept in a kettle in which the temperature of the contents (water and the cylinder) is maintained at 85°C. The brass cylinder is then taken out from the kettle and immersed into the water in the test tube. The water is stirred. How do you think the temperature of the brass cylinder and the water will change with time? Tick the option which you feel is correct.

1. The temperature of the brass cylinder will decrease and the temperature of the water will increase. Finally the temperature attained by the brass cylinder will be greater than the temperature attained by the water.

2. The temperature of the brass cylinder will decrease and the temperature of the water will increase. Finally, the temperature attained by the brass cylinder will be less than the temperature attained by the water.

3. The temperature of the brass cylinder will decrease and the temperature of the water will increase. Finally, the temperatures attained by both, the brass cylinder and the water, will be equal.

4. The temperature of the brass cylinder will decrease and will be equal to the room temperature where as the temperature of water will remain constant at room temperature.

Provide an explanation for your choice.

State how you will calculate the common temperature reached by both the brass cylinder and water.

Calculate the above common temperature. (Remember the specific heat of water = 4.18 J/gK and the specific heat of brass = 0.38 J/gK.)

Appendix E

Pre and Post test - Module on First Law of Thermodynamics

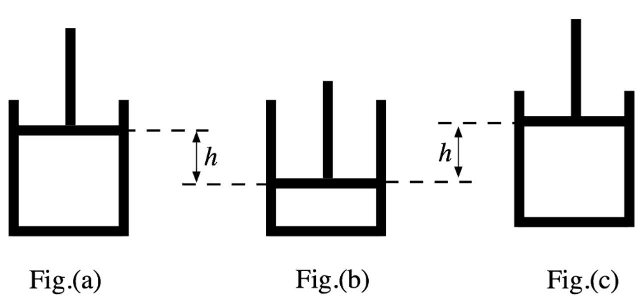
E.1 Adiabatic process

E.1.1 Pre-test

Same as given in Appendix A4

E.1.2 Post-test

Consider a container fitted with a frictionless movable piston. The walls of the container and the piston do not allow any transfer of heat.



The initial position of the piston is shown in fig.(a). The piston is then moved down by a distance h as shown in Fig. (b).

Then the piston is brought to its original position as shown in Fig. (c).

Assume that both the processes of moving the piston down [fig.(a)to fig.(b)] and up [fig.(b) and fig.(c)] are reversible.

Let the temperatures of the system be denoted by T_a, T_b and T_c corresponding to fig.(a), fig.(b) and fig.(c) respectively.

Let the work done in moving piston down be W_1 and the work done in moving piston up be W_2.

Let the change in internal energy when the piston is moved down be ΔU_1 and when the piston is moved up be ΔU_2.

From the statements given below tick the option which according to you hold true for the entire process. Also justify your choices in the space provided.

Case I	**Case II**
Fig.(a) to Fig.(b)	Fig.(b) to Fig.(c)

Case I

1. Pressure, P_1:

   (a) Pressure of the system will remain constant during the process.

   (b) Pressure of the system will increase in the process.

   (c) Pressure of the system will decrease in the process.

2. Work done W_1:

    (a) Work is done on the system.

    (b) Work is done by the system.

    (c) Work done on the system will be zero.

3. Change in the internal energy, ΔU_1:

    (a) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be negative.

    (b) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be positive.

    (c) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be zero.

4. Temperatures, T_a and T_b:

    (a) $T_a = T_b$

    (b) $T_a > T_b$

    (c) $T_a < T_b$

5. Heat Flow Q_1:
   (a) The heat flow (Q_1) into the system when the piston is moved down will be negative.
   (b) The heat flow (Q_1) into the system when the piston is moved down will be positive.
   (c) The heat flow (Q_1) into the system when the piston is moved down will be zero.

6. Taking into account the results from Q.1 to Q.5, rewrite the first law of thermodynamics depending on the status of ΔU_1, W_1, and Q_1 in this process.

Case II

7. Pressure, P_2:

   (a) Pressure of the system will remain constant during the process.

   (b) Pressure of the system will increase in the process.

   (c) Pressure of the system will decrease in the process.

8. Work done W_2:

   (a) Work is done on the system.

   (b) Work is done by the system.

   (c) Work done on the system will be zero.

9. Change in the internal energy, ΔU_2:

   (a) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be negative.

   (b) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be positive.

   (c) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be zero.

10. Temperatures, T_b and T_c:

    (a) $T_b = T_c$

    (b) $T_b > T_c$

    (c) $T_b < T_c$

11. Heat Flow Q_2:

    (a) The heat flow (Q_2) into the system when the piston is moved down will be negative.

    (b) The heat flow (Q_2) into the system when the piston is moved down will be positive.

    (c) The heat flow (Q_2) into the system when the piston is moved down will be zero.

12. Taking into account the results from Q.7 to Q.11, rewrite the first law of thermodynamics depending on the status of ΔU_2, W_2, and Q_2 in this process.

13. Is W_2 related to W_1? If yes, then state the relation between them. Also explain your answer.

14. Is ΔU_2 related to ΔU_1? If yes, then state the relation between them. Also explain your answer.

E.2 Isothermal Process

E.2.1 Pre-test

Same as given in Appendix A4

E.2.2 Post-test

Consider a container fitted with a frictionless movable piston. The walls of the container and the piston freely allow any transfer of heat.

The initial position of the piston is shown in fig.(a). The piston is then moved down slowly by a distance h as shown in Fig. (b).

Then the piston is slowly brought to its original position as shown in Fig. (c).

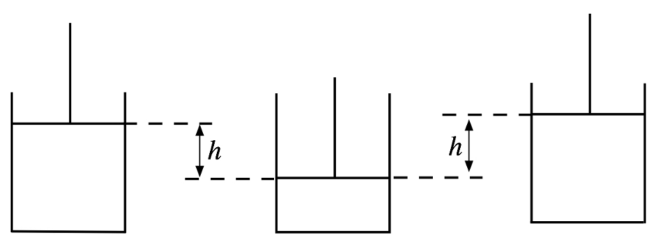


Fig.(a) Fig.(b) Fig.(c)

Assume that both the processes of moving the piston down [fig.(a)to fig.(b)] and up [fig.(b) and fig.(c)] are reversible and temperature of the gas is maintained during both the processes.

Let the temperatures of the system be denoted by T_a, T_b and T_c corresponding to fig.(a), fig.(b) and fig.(c) respectively.

Let the work done in moving piston down be W_1 and the work done in moving piston up be W_2.

Let the change in internal energy when the piston is moved down be ΔU_1 and when the piston is moved up be ΔU_2.

From the statements given below tick the option which according to you hold true for the entire process.
Also justify your choices in the space provided.

Case I	**Case II**
Fig.(a) to Fig.(b)	Fig.(b) to Fig.(c)

Case I

1. Pressure, P_1:

   (a) Pressure of the system will remain constant during the process.

   (b) Pressure of the system will increase in the process.

   (c) Pressure of the system will decrease in the process.

2. Work done W_1:

   (a) Work is done on the system.

   (b) Work is done by the system.

   (c) Work done on the system will be zero.

3. Heat Flow Q_1:

   (a) The heat flow (Q_1) into the system when the piston is moved down will be negative.

   (b) The heat flow (Q_1) into the system when the piston is moved down will be positive.

   (c) The heat flow (Q_1) into the system when the piston is moved down will be zero.

4. Change in the internal energy, ΔU_1:

   (a) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be negative.

   (b) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be positive.

   (c) The change in the internal energy of the system (ΔU_1) when the piston is moved down will be zero.

5. Temperatures, T_a and T_b:
   (a) $T_a = T_b$
   (b) $T_a > T_b$
   (c) $T_a < T_b$

6. Taking into account the results from Q.1 to Q.5, rewrite the first law of thermodynamics depending on the status of ΔU_1, W_1, and Q_1 in this process.

Case II

7. Pressure, P_2:

   (a) Pressure of the system will remain constant during the process.

   (b) Pressure of the system will increase in the process.

   (c) Pressure of the system will decrease in the process.

8. Work done W_2:

   (a) Work is done on the system.

   (b) Work is done by the system.

   (c) Work done on the system will be zero.

9. Heat Flow Q_2:

   (a) The heat flow (Q_2) into the system when the piston is moved down will be negative.

   (b) The heat flow (Q_2) into the system when the piston is moved down will be positive.

   (c) The heat flow (Q_2) into the system when the piston is moved down will be zero.

10. Change in the internal energy, ΔU_2:

    (a) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be negative.

    (b) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be positive.

    (c) The change in the internal energy of the system (ΔU_2) when the piston is moved down will be zero.

11. Temperatures, T_b and T_c:

    (a) $T_b = T_c$

    (b) $T_b > T_c$

    (c) $T_b < T_c$

12. Taking into account the results from Q.7 to Q.11, rewrite the first law of thermodynamics depending on the status of ΔU_2, W_2, and Q_2 in this process.

13. Is W_2 related to W_1? If yes, then state the relation between them. Also explain your answer.

14. Is Q_2 related to Q_1? If yes, then state the relation between them. Also explain your answer.

E.3 Table Completion Task

Make a tick-mark in the checkbox corresponding to the statement row and the process column.

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: $\Delta W = \Delta Q$	☐	☐	☐	☐

Appendix F

Activity Sheets - Module on First Law of Thermodynamics

F.1 Activity 1: How to use the heat flow indicator

You are given a heat flow indicator. It measures the heat flow from one side of the indicator to the other side.
Connect the red and black leads of the indicator to the multimeter (red lead to voltage socket and black lead to the COM socket). Select the dc voltage range of 2V.

- What is the reading in the heat flow indicator?

- Now place "side 1" of the heat flow indicator on your left palm. What did you observe in the heat flow indicator?

- Next place “side 2” of the heat flow indicator on your right palm. What did you observe in the heat flow indicator?

Now place left palm on “side 1” and right palm on “side 2” simultaneously. Wait for a few seconds. What did you observe in the heat flow indicator? Explain your answer.

F.2 Information sheet

Internal energy

For a gas the internal energy is the sum of the energies of all the molecules of a gas. In case of an ideal gas, the internal energy is the function of only the temperature.

Change in internal energy ΔU is proportional to the change in temperature ΔT and the relationship can be given as, $\Delta U = mc_v \Delta T$, [m is mass of the gas in the container and c_v is the specific heat at constant volume].

> In summary,
> Heat is the energy in transit (energy which flows) due to temperature difference and Internal Energy is the energy contained within the system.

First Law of thermodynamics

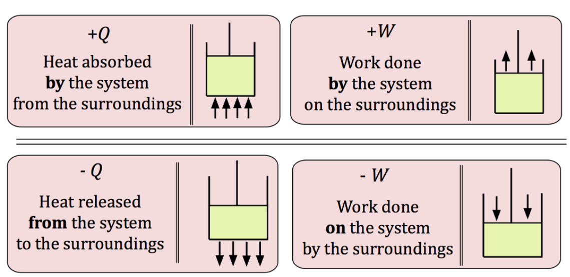
First law of thermodynamics tells us how change in internal energy comes about. It comes about by two ways:

- Mechanical work done
- Heat absorbed or released

The net change in the internal energy is indicated by,

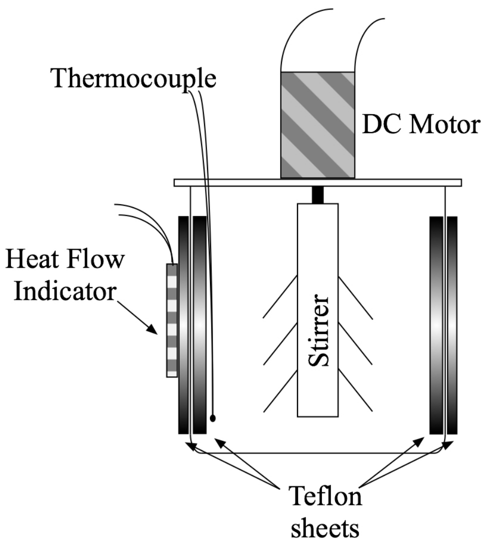
$$\Delta U = Q - W$$

Sign Conventions: (System = Gas inside the container, Surrounding = Everything other than the gas)

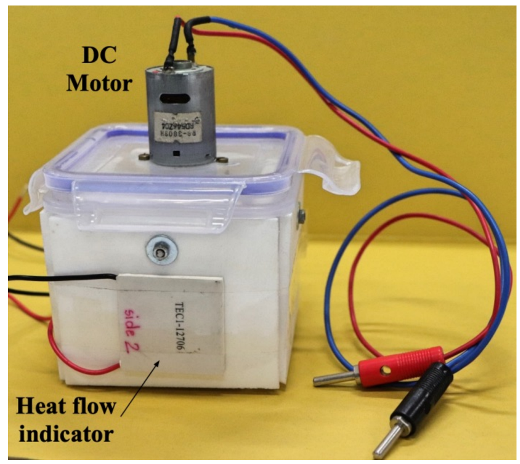


F.3 Activity 3: Work done as energy transfer mechanism

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 (figure F.1.



(a) Schematic diagram of the apparatus



(b) The set up

Figure F.1: Work done as energy transfer mechanism

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.

1. Watch the activity.
2. Observe the reading of the heat flow indicator and digital thermometer.
3. Answer the following questions.

1. Net heat flow, Q:

   What was the reading of the heat flow indicator?

2. What is your observation regarding the temperature of water? Explain.

3. Based on your answers in earlier questions, write down the first law of thermodynamics.

F.4 Activity 4: Adiabatic Process – COMPRESSION

You are given a 25 ml syringe and a thermocouple. Insert the thermocouple in the syringe from the open end. Keep the piston on 25 ml mark. Close the open end with your thumb.

- Press the piston slowly.
- Press the piston very fast.

Observe and note the temperature of air inside the syringe in both the cases. With the increase in the speed of the piston what happens to the temperature of air inside the syringe? Explain your observations.

- Watch the video on fire syringe and also perform the activity on fire syringe.
- Watch another video on fire syringe with heat flow measurements.
- Answer the following questions.

If you find any difference between the answers that you gave in the pre-test and the observations that you made in each of T,Q, P,W and ΔU, explain the difference, if there is a difference.

1. What happened to the cotton? Explain your observation.

2. What do you think happens to the temperature of the air inside the container during the process? Is your response different from your observation?

3. Net Heat Flow, Q:

   In the activity, observe and note the reading in the heat flow meter. Explain the reason behind the heat flow meter reading.

4. Is the work done in this process positive or negative? Why? (Use the information sheet)

5. What can you infer about the change in the internal energy of the system ($\Delta U = mc_v\Delta T$)? Which process resulted in the change – heat flow or work done? Justify your answer.

6. Write down the first law of thermodynamics with proper sign convention for this process.

7. You will be shown and explained the calculation for the work done in the process. This work done will be equated to the change in internal energy of the system. From these calculations the temperature of the air inside the container will be calculated.

F.5 Activity 5: Isothermal Process - COMPRESSION

You are given a copper cylinder fitted with a thermocouple. Adjust the piston of the syringe to 10 ml mark. Attach the syringe to the cylinder.

1. Push the piston with varying speeds and observe the temperature change.
2. Push the piston "very slowly" to maintain the temperature constant.

Why should you push the piston slowly to maintain the temperature constant? Explain the process.

- Watch the video on isothermal compression and perform the activity.
- Observe the liquid flow analogy of this video.

If you find any difference between the answers that you gave and the observations that you made in each of T, Q, P, W and ΔU, explain the difference, if there is a difference.

1. Did you observe any change in the temperature of air inside the container during compression? Explain your answer?

2. What can you infer about the change in the internal energy of the system ($\Delta U = mc_v \Delta T$)? Explain.

3. Net Heat Flow, Q

   In the activity, did you see any change in the heat flow meter reading? Did the reading change in positive direction or negative direction? What did that mean? Explain your answers.

4. What is the work done in the process? Is it positive or negative? Why?

5. With the answer in the questions above write down the first law of thermodynamics with proper sign conventions for this process.

Appendix G

Students' interview responses

The interviews with the students were conducted mainly for obtaining clarification of their written responses. This appendix presents interview responses which are for cycle 1, 2 and 3 for the module on thermal equilibrium and similarly for the 3 cycles of the module on the first law of thermodynamics.

The responses provided are representative excerpts from the interview sessions conducted. Kindly note that they are not verbatim transcripts made using latest transcription software. The researcher and his assistant copied the actual conversation as they listened to the conversation between the researcher and the student. This was as in old-fashioned stenography. In many cases the students were not comfortable with conversational English as it often happens in India, even though the medium of instruction is English. Such students express themselves in their mother tongue Marathi/Hindi which the researcher also was familiar with. I have translated these responses to English and reproduced them. Below I give here a typical transcript of the researcher - student conversation in case of each cycle of both the modules. The label 'R' represents the questions posed by the researcher and the label 'S' represents the common responses received from most of the students in the group. Some of the noticeably different responses received for these questions have been labeled as S_1, S_2, S_3...

G.1 Thermal equilibrium

G.1.1 Cycle 1

I interviewed 6 students. A typical conversation is reproduced below.

Nature of the curve

The discussion refers to the Chapter 5 - cycle 1. This discussion was held after the activity and post-test. Here, students found it difficult to frame a meaningful opinion about the final temperatures of copper and wooden cubes. This refers to the figure 5.11.

R: Did you find any difference in the nature of two curves?

S: "...No...they all looked the same."

R: Wasn't there even a slightest difference in them (those curves/graphs)?

S: "...Oh! was there any??...I did not notice it...in fact...they (temperature curves for small copper and big copper cubes) look just of the same nature."

R: (hinting at the nature of rise in curves of big copper and big wood by showing them the screenshot) do you notice any difference in this image?

S: "...Oh Yes! there is a slight difference...graph of copper is a bit steeper than wood."

R: How can you interpret the steepness in graph with respect to the temperature rise of the cubes?

S: "...more steepness means faster rise...(after some time)...seems like copper's temperature starts to increase faster than wood."

R: Yes...that's correct. Any specific reason that you could not identify it earlier during post-test?

S: "...nothing major as such...just maybe because it was too many graphs to compare...so got confused."

Students' sketches ignoring equality of temperatures within experimental error

Some of the students' sketches showed that the final temperatures of both the cubes did not reach the same temperature. A sample sketch is shown in figure G.1.

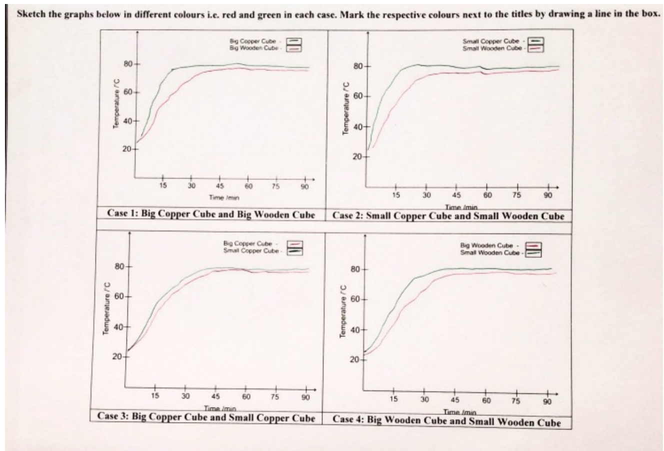


Figure G.1: Temperature profiles of copper and wooden cubes

R: You have mentioned in pre-test that copper will be at higher temperature than wood… and you have maintained the same in post-test. Can you explain why do you maintain your claim?

S: "… the graphs do not meet. They are two separate lines still. because even the values (temperatures - numbers in the interface) shown are not equal. as mentioned in my predictions, the copper will be at higher temperature than wood,...so even the numbers show the same thing."

R: But can't these differences (between the temperatures) be considered within few orders of the least count?

S:"… the differences are greater than the least count shown."

G.1.2 Cycle 2

I interviewed 10 students. A typical conversation is reproduced below.

Realizing Equal temperature

In cycle 2, after the activity, it was observed that students changed their response from 'prediction' stage to 'explanation' stage.

R: Initially you predicted that final temperature of brass will be higher than that of delrin. But after the activity you changed your response to both the temperatures to be equal. Can you justify this change of response?

S: "Yes, initially (before the activity) I thought that brass, being a good conductor of heat, it would conduct heat energy faster and... would always be at a higher temperature than Delrin...I saw, during the activity that brass temperature was higher than delrin in the initial part...but eventually both (temperatures) will be the same. I think I made a mistake (in the prediction)."

R: What was the mistake that you realized?

S: "As brass is a metal...well.....it is a good conductor of heat .....has higher thermal conductivity than delrin... therefore in the initial period, brass had a faster increase (in temperature) than delrin...I guess I mistook this difference (in the rate of rise of temperature), to be eventually continued and seen in the final temperatures attained by them...I could not realize that."

R: Why do you think that the cylinders would eventually reach the water temperature?

S: "...as that was the surrounding temperature in which they (cylinders) were kept."

Role of heat flow in thermal equilibrium

We probed their understanding about what according to them is thermal equilibrium, when they were in consensus that both the cylinders will attain the same temperature as that of water bath.

R: how do you interpret thermal equilibrium now?

S: "When two objects are in contact with each other, their temperature becomes equal."

R: Is there anything that you would like to add to it?

S:" That is all. . . isn't it?"

R: What about the heat flow between the objects?

S: "since (in the activity) water is at higher temperature than the cylinders heat will flow from water to the cylinders."

R: What can you say about the heat flow between the objects when thermal equilibrium is reached?

S:"...well...uhh...I am not sure...it's like...you see temperature changing...heat is energy which we know is flowing but we cannot see it (heat)...so it might probably remain flowing?...don't know exactly what happens to it (heat)...as such we do not have any instrument which can measure it (heat flow)!"

G.1.3 Cycle 3

I interviewed 10 students. A typical conversation is reproduced below.

Analogy between activity 5.4 and 5.1

R: Could you find any similarities between this activity (activity 5.4) and activity 5.1?

S: In the first activity we had cylinders of different materials and sizes and they were kept in water bath of constant temperature...in the last activity we had two measuring cylinders which were connected to a reservoir whose level was maintained...either the sizes (of measuring cylinders) were different or they were connected using pipes of different sizes.

R: What are your observations in terms of the time taken to reach respective equilibrium in both the activities (activities 5.4 and 5.1)?

S: I saw in the first activity that for different materials (but same size) and for different sizes (but same material) the final temperatures were the same... though the time taken to reach final value (equilibrium temperature) was different. Similarly in the last activity the time taken to reach final level (hydrostatic equilibrium) was influenced by diameter of connecting pipes and diameter (base-area) of receiving cylinders.

R: Which way these parameters have affected the time taken to reach equilibrium?

S: "...in first activity brass temperature rises fast... it has high thermal conductivity... .so it is the thermal conductivity which decides which object will have faster increase (in temperature) whereas in liquid flow model, the cylinder connected by a pipe of larger diameter would reach the level of water reservoir faster...

For different sizes of Delrin... both are of same material... smaller delrin cylinder would require lesser heat energy to reach the water temperature.... Similarly....In the liquid flow model, the cylinder with smaller diameter would require lesser volume of water to reach the level of water reservoir."

G.2 First law of thermodynamics

G.2.1 Cycle 1

I interviewed 7 students. A typical conversation is reproduced below.

Adiabatic process

R: Can you describe your observations for the activity that you performed?

S1: "Yes,. . . in this activity, we were given a syringe which was connected to pressure gauge. As we pressed the piston, the pressure increased inside the syringe as volume decreased."

R: Was there any work done in this process?

S1: "Yes. . . as the piston was pressed, air inside the container was compressed and hence the work was done."

R: so was there any change in the temperature of air?

S1: "There was very slight change in temperature of the air."

R: What might have caused this increase in temperature?

S1: it might have resulted due to compression. "

R: Can you comment on the internal energy of the system?

S1:"...Well...uhh...since the process was adiabatic,. . . so I don't think there would be any change in the heat content of the system.

R: What do you mean by no change in 'heat content of the system'?

S1:"...as the container is non conducting, no heat can flow into or out of it ... so the energy content remains the same."

R: But what about the temperature change that you observed, how do you interpret it with regards to internal energy?

S1:"...as I said...there is no heat flow. . . so there should not be any temperature change either...but we do see a slight change over here. . . (after some time) this change (in temperature) might be some random fluctuations."

R: So what happened to the energy transferred due to work done?

S1:"...(after some time) I am not sure."

S2: "...since temperature increases, heat content of the system increases...NO...but the process is adiabatic ...so it should not change.

S3: "...there was a temperature increase as the piston was pushed...and I did equate the work done to change in internal energy and using it found the change in temperature, but this (calculated) value was very high compared to the temperature change I observed... so I am not sure."

Isothermal process

R: Did you observe any change in temperature of air?

S1: "... no. we were asked to push the piston slowly so that temperature does not increase."

R: was there any work done during the process?

S1: "... as the piston was pushed... work is done."

R: What happened to this work done?

S1: "I am not sure."

R: What happened to the internal energy of the system?

S1: "There was no indication regarding heat flow as there was no heating that was carried out... so I don't know what happens to heat content of the system... I am not sure about this too..."

R: But didn't you say initially that the temperature of the system remained constant?

S1: "Yes the temperature was constant when we pressed the piston... I am not sure about energy... (after thinking) if the temperature remained constant it means there was no heat flow into or out of it (the system)..so there should not be any change in heat content too."

S2:"...when air is compressed, work is done and it has to result in something as per energy conservation law... so it might increase the heat content of the system..."

G.2.2 Cycle 2

I interviewed 6 students. A typical conversation is reproduced below.

Adiabatic process

R: Did you observe any temperature change when the piston was pushed?

S1: "Yes the temperature increased."

R:Was there any heat flow during the process?

S1: "...no...the sensor (peltier device) did not show any reading."

R: Can you comment on the change in the internal energy of the system?

S1: "...since heat flow was zero, heat content of the system does not change...that means internal energy remains constant."

R: But if you refer to the relation between temperature change and change in internal energy, (showing the information sheet to the student) how would you explain the temperature change then?

S1: "...well change in internal energy is directly proportional to the change in temperature...as energy remains constant...so...temperature should also remain constant... wait... (after thinking some time) uhh...here we do see change in temperature...would that be an error??...I don't know exactly...I am bit confused."

S2:"...temperature does not change as there is no heat supplied to the container and also the walls of container are insulating...so some error might have showed the change (temperature change)?"

S3:"...here temperature should not change as there is no heat supply... moreover how will work done change the heat content of the system?... So even the work done will not change the temperature..."

R: But you did observe a temperature change?

S3:"...yes...it might be due to some friction (between piston and container wall) or some instrumental error..."

Isothermal process

R: Did you observe any change in temperature?

S: “No.”

R: Can you comment on heat flow in isothermal process?

S: “...the heat flow indicator reading did not change much...if there would have been any heat flow the temperature would have definitely changed. . . so not sure...”

G.2.3 Cycle 3

I interviewed 12 students. A typical conversation is reproduced below.

Work done as energy transfer mechanism

R: Do you think work is done in this activity?

S: "...yes...when blades rotate they stir the water along with them..."

R: So how is work done?

S: "...... blade does work on the water...by churning it"

R: Did you see any change in the temperature of the water?

S: "...yes...it (temperature) increased slowly and steadily...

R: Was there any heat transfer in the process?

S: "...no...the heat flow indicator reading was zero..."

R: What might have increased the temperature of the water?

S: "...the rotation of the blades."

R: Can you explain what happens to the internal energy of the system?

S:"...as temperature of water changes, the internal energy changes (student showing the relation between change in internal energy and change in temperature from the information sheet)...as the change in temperature is proportional to the change in internal energy..."

R: (hinting student towards the statement of the first law of thermodynamics in the information sheet) Can you make use of the statement of first law to explain what might have led to an increase in internal energy?

S1: "... well...uhh... since heat transfer is zero here... the work done is equal to the change in the energy (of the system)... from the first law it will have to be the internal energy of the system... or in other words, ... there is no heat flowing (into the system),... the energy 'pumped in' due to work done has to result in changing the internal energy..."

Adiabatic compression using fire syringe

R: Could you generate the glow?

S: "...Yes. . . I mean initially I could not (generate the glow)...but later as I increased my speed and hit the piston fast and hard. . . I could do that...in the initial trials though...even if I could not generate the glow...I could smell half (partial) burning of cotton..."

R: Can you comment of work done in the process?

S: "...work is done by it (the piston). . . on air inside..."

R: What can you say about the sign convention of the work?

S: "... it (piston) does work on air inside...so work should have negative sign"

R: Can you give an estimate about the temperature of the glow?

S: "...not really...but as there was a yellowish glow...it must be pretty high...after all there was no cotton left in it (the syringe). . . it must have got completely burnt..."

S: "...in fact the fast movement of the piston (work done) resulted into a large change in temperature (of air) inside the container."

R: What about heat flow?

S: "...though the cotton burnt inside, I could not feel the external walls (of acrylic container) hot. . . the heat flow indicator also showed zero reading...".

R: so can you comment on the internal energy of the system (air)?

S: "...the air inside the container was heated by the movement of piston...since temperature change is proportional to internal energy change (pointing to the information sheet)... the internal energy of the system increased."

R: Can you now look at the statement of the first law of thermodynamics and apply the law to this process?

S: "...since there was no heat transfer, the ' energy pumped in' due to work done on the system resulted in the change in temperature."

Isothermal compression

R: Could you maintain the temperature constant?

S: "...initially for few trials, I thought I was pressing it slow... but as I pressed it, the temperature started increasing... but later I realised that to keep the temperature constant I had to push the piston very very slowly..."

R: What can you interpret about the internal energy?

S:"...as the temperature remains constant...(using the information sheet) internal energy also remains constant..."

R: What can you say about heat flow in the process? **S**: "...oh yes...the heat flow indicator showed negative reading..."

R: What did negative reading indicate?

S: "...the negative sign of the heat flow indicator reading means that heat is flowing out of the system (referring to information sheet)... in fact...heat started flowing out of the system as the piston was pushed slowly..."

R: Why do you think heat has to flow out of the system?

S: "...if it remains in the system, then the temperature of air would have increased which did not happen...so somehow it has to be thrown out of the system...and even the sign convention in the information sheet shows it (heat flow) negative..."

R: Can you now apply the statement of the first law of thermodynamics to this process?

S: "...the pumped in energy due to work done did not change the temperature i.e. internal energy of the system...so where else can it go?...(pointing to the statement of the first law of thermodynamics)...it has to result in heat flowing out of the system."