Understanding thermal equilibrium through activities

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Abstract
Thermal equilibrium is a basic concept in thermodynamics. In India, this concept is generally introduced at the first year of undergraduate education in physics and chemistry. In our earlier studies (Pathare and Pradhan 2011 *Proc. episteme-4 Int. Conf. to Review Research on Science Technology and Mathematics Education* pp 169–72) we found that students in India have a rather unsatisfactory understanding of thermal equilibrium. We have designed and developed a module of five activities, which are presented in succession to the students. These activities address the students' alternative conceptions that underlie their lack of understanding of thermal equilibrium and aim at enhancing their understanding of the concept.

1. Introduction

Students try to understand the physical world using their own naive concepts. These concepts might have developed due to their observations and investigations of the physical world [1]. When students are exposed to some problem in everyday life, they try to solve it using their naive concepts, which are often rooted so deeply in the minds of the students that they form frameworks of explanations that are alternative to standard ones. Alternative conceptions in physics are well documented in the literature [2–4]. Concepts in thermodynamics are directly related to the physical environment of living organisms [5], but at the same time they are not directly observable. This is often the origin of students' alternative conceptions. Several other sources like culture, language and textbooks contribute to students' alternative conceptions in thermodynamics [6, 7]. It is thus obvious that they come to thermodynamics class with many common alternative conceptions in the subject. Our earlier study [8] of students' understanding of thermal equilibrium revealed a major alternative conception, namely, students do not believe that objects kept in a constant temperature enclosure for a sufficiently long time will attain thermal equilibrium and reach the same temperature as the enclosure. They rather believe that the temperature reached by such objects depends on the size and on the material of the objects. Given this finding, we designed and developed an activity-based module to address this alternative conception.

A number of approaches based on well-structured activities that actively engage students have been designed to address such alternative conceptions. These approaches not only focus on the content to be delivered, but also on the instructional method used. Some of the well-known approaches in the field of physics education

  0031-9120/15/020146+13$33.00

research are predict–observe–explain (POE) [9], interactive lecture demonstrations (ILD) [10], investigative science learning environment (ISLE) [11] and interactive video vignettes (IVV) [12]. Four volumes of *Real time physics: active learning laboratories* are a useful resource in the field of the active learning environment [13]. The instructional methods used in these approaches differ from one another depending on the research requirements. Many physics education researchers emboss the importance of the active learning approaches by claiming a positive shift in the way the students think and understand natural phenomena [14].

For presenting our module to the students we used the POE method. For each activity, we asked the students to predict the outcome of the activity before it was actually demonstrated to them. They were asked to justify their predictions, which would be based on their original understanding, and were asked to write their responses individually so as to get them committed to their reasoning and belief. Then they observed the activity and were asked to simultaneously note down their observations and answer questions based on these observations. If the outcome of the activity is at variance with their prediction, they were urged to explain the discrepancy between the prediction and the observation. The cognitive conflict arising as the module develops helps the students deal with their alternative conception and arrive at the scientifically correct conception.

The sample for our study is 112 second year undergraduate students from colleges in Mumbai, India. These students have undergone a basic course in thermodynamics in their first year of undergraduate studies.

2. Activities

In our module, five activities related to the concept of thermal equilibrium were developed and demonstrated. These activities were as follows.

Activity 1: this was the main activity in which students observed the temperature profiles of two objects placed in a constant temperature bath. This activity had two parts: In part I, the two objects were of different materials but of the same volume, and in part II they were of different volumes but of the same material.

Activity 2: in this activity a liquid flow model was used to demonstrate hydrostatic equilibrium to the students with an objective to establish analogy between hydrostatic and thermal equilibria.

Activity 3: this activity used a heat flow model to demonstrate to the students the thermal equilibrium.

Activity 4: this activity was the liquid flow analogue of activity 1. It brings out the dependence of the rate of approach to equilibrium on different parameters of the flow channel and receiving container.

Activity 5: this activity uses the method of mixtures to test the students' understanding of thermal equilibrium developed through the first four activities.

2.1. Activity 1: main activity

This activity had two parts. In both parts, two cylinders which were initially at room temperature, were immersed simultaneously in a water bath maintained at a constant temperature (60 °C). The temperatures of both the cylinders were measured using thermocouples and a profile of these temperatures as they rise was obtained using a data acquisition system. In part I, the two solid cylinders of the same volume, but of different materials (one brass and the other delrin) were used (figure 1). In part II, two cylinders were of the same material (delrin) but of different volume (figure 2). For both the parts, the students were asked (i) to predict the final temperature of each of the cylinders, (ii) to predict which of the two cylinders will have a faster rise in its temperature, and (iii) to show graphically how the temperature rise for both cylinders looked like. They were provided with a sheet of parameters such as thermal conductivity, specific heat and density of different materials (including brass and delrin).

2.1.1. Prediction for part I. In this part, two solid cylinders of equal volume and the same shape but different materials (brass and delrin) were used. All 112 students indicated that both the cylinders would reach a constant temperature. Only 19, however, predicted (see table 1) correctly that both cylinders would reach 60 °C, the temperature of the water bath. One student predicted that both the cylinders would reach an equal temperature but this would be greater than the temperature of the

Figure 1. The brass and delrin cylinders.

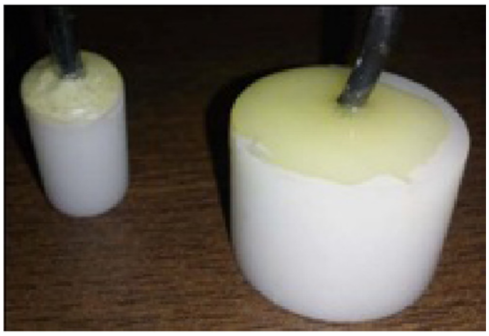

Figure 2. The small and large delrin cylinders.

water bath. Among the students giving incorrect responses, a sizeable number (74) predicted that the final temperature of the brass cylinder would be greater than the final temperature of the delrin cylinder. The reasoning was that brass has a larger thermal conductivity than delrin and takes up heat faster. Out of 74 students, 43 predicted that the final temperature of the brass cylinder would be the same as that of the water bath. A significant number of the students (27 out of 74) predicted that the final temperature of brass would even exceed the temperature of the water bath, whereas delrin would reach 60 °C. However, a few students (5 out of 74) thought that delrin being a thermal insulator would not 'conduct' heat at all and would remain at room temperature. A few students (4) felt that neither cylinder would reach 60 °C.

Some students (18) predicted the opposite, that is, the final temperature of delrin would be higher than the final temperature of brass. Their argument was that the specific heat of delrin is greater than that of brass. The majority of these students (11 out of 18) predicted that delrin would reach the temperature of the water bath, but brass would not. Out of these 18 students, 7 predicted that the delrin cylinder would have a temperature of more than 60 °C.

The students were also asked to predict the rate at which the temperature of both cylinders would rise; 91 predicted correctly that the temperature of the brass cylinder would rise faster than the temperature of the delrin cylinder.

2.1.2. Prediction for part II. In this part, two solid cylinders of the same material (delrin) and of the same shape but of different volume were used (figure 2). In this case, all (112) the students indicated that both cylinders would reach a constant temperature. Out of 112 students (see table 2), only 34 predicted correctly that both cylinders would reach 60 °C, the temperature of the water bath. Some (20) thought that both cylinders would reach an equal temperature, but 18 thought that this temperature would be less than 60 °C and 2 thought that this temperature would be greater than 60 °C.

Some students (34) predicted that the temperature of the smaller cylinder would be greater than the temperature of the larger cylinder. They compared the surface to volume ratio of these cylinders. Of these, a few (7 out of 34) believed that the smaller cylinder would exceed 60 °C and the larger would reach 60 °C. Out of 34, 3 predicted that the larger delrin cylinder would remain at room temperature and 2 predicted that both cylinders would reach a temperature less than 60 °C.

Out of 112 students, 24 predicted that the cylinder with larger volume (larger mass) would have a greater temperature than the smaller delrin cylinder. They compared only the volumes of the cylinders and mentioned that the larger delrin cylinder would have a greater capacity to store heat and hence would have a greater 'temperature'. Out of these 24 students, 11 predicted that the larger delrin cylinder would have a temperature greater than 60 °C.

Out of 112, 60 students predicted correctly that the temperature of the smaller delrin would rise faster than the temperature of the larger delrin cylinder, whereas 34 predicted that the temperature of both cylinders would rise at an equal rate.

It was clear that most of the students had difficulty in understanding the concept of thermal equilibrium. They did not seem to realize that the

Table 1. Student responses about the material dependence.

Material dependence							
Pre (total students = 112) [$T_{\text{waterbath}} = 60\,°\text{C}$]							
$T_{\text{brass}} > T_{\text{delrin}}$				$T_{\text{brass}} < T_{\text{delrin}}$		$T_{\text{brass}} = T_{\text{delrin}}$	
74				18		20	
$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} < 60\,°\text{C}$ 38	$T_{\text{brass}} > 60\,°\text{C}$ $T_{\text{delrin}} = 60\,°\text{C}$ 27	$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} = \text{T}_{\text{room}}$ 5	$T_{\text{brass}} < 60\,°\text{C}$ $T_{\text{delrin}} < 60\,°\text{C}$ 4	$T_{\text{brass}} < 60\,°\text{C}$ $T_{\text{delrin}} = 60\,°\text{C}$ 11	$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} > 60\,°\text{C}$ 7	$(T_{\text{brass}} = T_{\text{delrin}}) = 60\,°\text{C}$ 19	$(T_{\text{brass}} = T_{\text{delrin}}) > 60\,°\text{C}$ 1
Post (total students = 112) [$T_{\text{waterbath}} = 60\,°\text{C}$]							
$T_{\text{brass}} > T_{\text{delrin}}$			$T_{\text{brass}} < T_{\text{delrin}}$		$T_{\text{brass}} = T_{\text{delrin}}$		
29			1		82		
$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} < 60\,°\text{C}$ 17	$T_{\text{brass}} > 60\,°\text{C}$ $T_{\text{delrin}} = 60\,°\text{C}$ 11	$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} = \text{T}_{\text{room}}$ 1	$T_{\text{brass}} < 60\,°\text{C}$ $T_{\text{delrin}} = 60\,°\text{C}$ 0	$T_{\text{brass}} = 60\,°\text{C}$ $T_{\text{delrin}} > 60\,°\text{C}$ 1	$(T_{\text{brass}} = T_{\text{delrin}}) < 60\,°\text{C}$ 5	$(T_{\text{brass}} = T_{\text{delrin}}) = 60\,°\text{C}$ 72	$(T_{\text{brass}} = T_{\text{delrin}}) > 60\,°\text{C}$ 5

Table 2. Student responses about the size dependence.

Size dependence								
Pre (total students = 112) [$T_{waterbath} = 60\,°C$]								
$T_{smalldelrin} > T_{largedelrin}$				$T_{smalldelrin} < T_{largedelrin}$		$T_{smalldelrin} = T_{largedelrin}$		
34				24		54		
$T_{smalldelrin} = 60\,°C$ $T_{largedelrin} < 60\,°C$	$T_{smalldelrin} > 60\,°C$ $T_{largedelrin} = 60\,°C$	$T_{smalldelrin} < 60\,°C$ $T_{largedelrin} = T_{room}$	$T_{smalldelrin} < 60\,°C$ $T_{largedelrin} < 60\,°C$	$T_{smalldelrin} < 60\,°C$ $T_{largedelrin} = 60\,°C$	$T_{smalldelrin} = 60\,°C$ $T_{largedelrin} > 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) < 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) = 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) > 60\,°C$
22	7	3	2	13	11	18	34	2
Post (total students = 112) [$T_{waterbath} = 60\,°C$]								
$T_{smalldelrin} > T_{largedelrin}$			$T_{smalldelrin} < T_{largedelrin}$		$T_{smalldelrin} = T_{largedelrin}$			
17			14		81			
$T_{smalldelrin} = 60\,°C$ $T_{largedelrin} < 60\,°C$	$T_{smalldelrin} > 60\,°C$ $T_{largedelrin} = 60\,°C$	$T_{smalldelrin} < 60\,°C$ $T_{largedelrin} = T_{room}$	$T_{smalldelrin} < 60\,°C$ $T_{largedelrin} = 60\,°C$	$T_{smalldelrin} = 60\,°C$ $T_{largedelrin} > 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) < 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) = 60\,°C$	$(T_{smalldelrin} = T_{largedelrin}) = T_{room}$	$(T_{smalldelrin} = T_{largedelrin}) > 60\,°C$
9	7	1	11	3	6	72	2	1

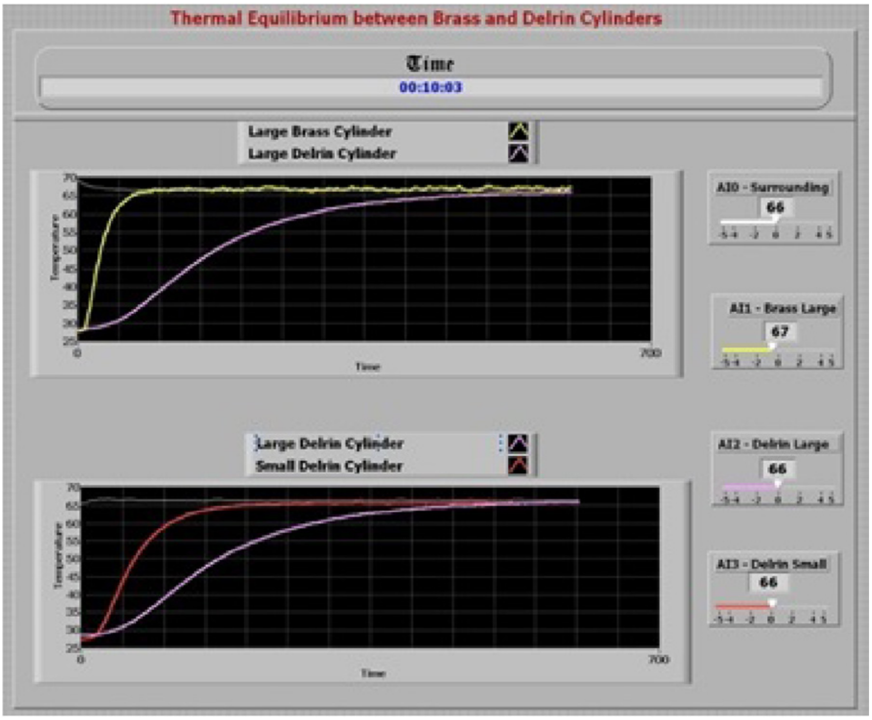

Figure 3. The output screen of the main activity.

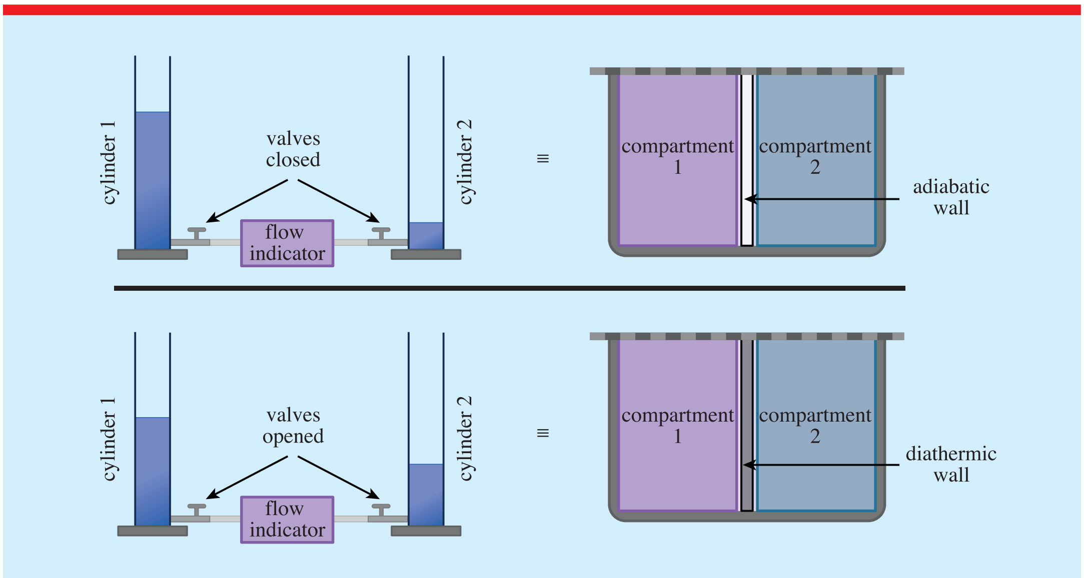

Figure 4. Analogy between liquid flow model and heat flow model of thermal equilibrium.

nature of the objects kept in a constant temperature enclosure affects only the rate at which the thermal equilibrium is attained.

2.1.3. Observation. The students observed how the temperature of the two cylinders rose and after a sufficiently long time became equal to the temperature of the bath (figure 3). During the activity the temperature of the water bath was maintained at 66 °C.

They observed that the temperature of the cylinders became equal to the temperature of the water bath irrespective of the material or size difference. The students were asked to explain the discrepancies between what they had predicted and later observed in the present activity, not immediately, but after the first four activities of the module were completed. Tables 1 and 2 summarize the students' predict (pre) and explain (post) responses.

As seen from table 1, after the first four activities, 72 students realized that the temperature of the brass and the delrin cylinders would be equal to the temperature of the water bath. Only 19 had predicted this before the activities began. There were still a few students who believed that though both the cylinders were at equal temperature, their temperature would be greater than the temperature of water bath (5) or less than the temperature of the water bath (5). The number of students claiming that the temperature of the brass cylinder to be greater than the temperature of delrin cylinder decreased from 74 to 29. Similarly the number of students claiming the temperature of the delrin cylinder to be greater than the temperature of the brass cylinder decreased from 18 to 1.

In part II of the activity (see table 2), 72 students responded correctly that both the smaller and the larger delrin cylinders would have temperature equal to the temperature of the water bath. Only 34 had predicted this before the activities began. A few (7) realized that the temperature of both cylinders would be equal, although 6 responded that this temperature would be less than 60 °C and 1 responded that this temperature would be greater than 60 °C. Two students still remained firm that with delrin being an insulator, the temperature of both cylinders would remain at room temperature. The number of students claiming greater temperature for the smaller delrin cylinder than the larger delrin cylinder decreased from 34 to 17. The number of students claiming greater temperature for the larger delrin cylinder than the smaller delrin cylinder decreased from 24 to 14.

Out of 112 students, 96 (compared to 91 during prediction) realized that the rate of increase in the temperature of the brass cylinder was larger than the rate of increase in the temperature of the delrin cylinder and 87 (compared to 60 during prediction) agreed that the rate of increase in the temperature of the smaller delrin cylinder was greater than the rate of increase of temperature of the larger delrin cylinder. The number of students claiming that both cylinders would have an equal rate decreased from 34 to 9.

At this point the students, however, were still not clear about thermal equilibrium and how the material of the cylinders or their volume affected the rate at which thermal equilibrium was attained. We believed that the analogy of thermal equilibrium with hydrostatic equilibrium, with which the students are quite familiar, would help. We designed the next activity from this point of view.

2.2. Activity 2: a liquid flow model

In the analogy between thermal and hydrostatic equilibria, heat flow is seen to be similar to liquid flow. Hydrostatic equilibrium between two hydrostatic systems is characterized by net liquid flow being zero. Similarly, thermal equilibrium between two systems is characterized by zero net heat flow between them.

For simplicity we may take the hydrostatic systems to be two liquid containers connected with a flow pipe. In the case of hydrostatic equilibrium, the heights of the liquid columns measured from a common reference point in the two containers are equal. For thermal equilibrium the corresponding quantity to height is temperature. When two systems are in thermal equilibrium, the temperatures are equal.

In this activity two cylinders of equal volume filled with water up to different levels were connected to each other through a flow tube fitted with a flow indicator, as shown in figure 4. The state of control valves of the flow tube being closed corresponds to an adiabatic wall which does not allow any heat flow between two thermal systems. On the other hand the state of control valves open corresponds to a diathermic wall which allows heat flow between two thermal systems (figure 4).

In this activity, two 250 ml measuring cylinders, A and B, were filled up to different levels initially (figure 5).

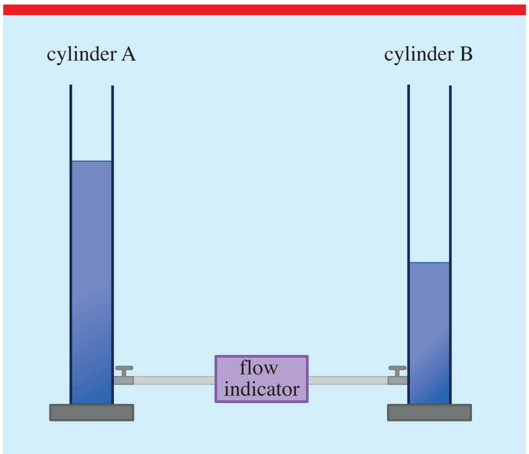

Figure 5. Set up with two cylinders with liquid at different levels.

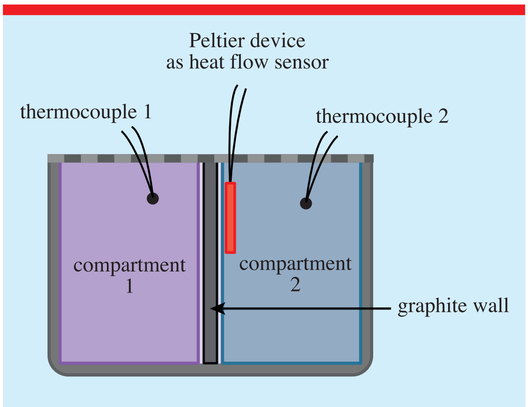

Figure 6. Schematic diagram of the apparatus with graphite wall in contact with both the compartments.

Cylinder B was covered so that the level of water was not seen. The flow control valves were then opened, allowing flow between the two cylinders as indicated by the flow indicator. When the flow stopped the cover of cylinder B was removed. The students were asked to predict the level of the water columns in cylinders A and B, before cylinder B was uncovered.

2.2.1. Prediction. The case of hydrostatic equilibrium in this activity being rather familiar to the students, most of them (87) predicted rightly that the heights of the water column in the cylinders would be equal.

2.2.2. Observation. When cylinder B was uncovered, the students observed that both water columns had the same height as most of them (87) had predicted.

2.3. Activity 3: a heat flow model

In this activity, students observed a heat flow model analogous to the liquid flow model of activity 2.

The apparatus used in this activity consisted of two compartments separated by an air gap which acted as an adiabatic wall. When a diathermic wall in the form of a graphite sheet was inserted in this air gap the two compartments exchanged heat. The heat exchange was monitored using a thermoelectric (Peltier) device used as a heat flow sensor [15] (figure 6).

The output terminals of thermocouple 1, thermocouple 2 and the heat flow sensor were connected to a data acquisition system. Compartment 2 was filled with water at room temperature and compartment 1 with water at 60 °C. The output of thermocouple 2 was not shown to the students. They were asked to predict the final temperature of the water in compartment 2. They were also asked to predict, by drawing, the nature of the graphs for variation in the outputs of thermocouple 1, thermocouple 2 and the heat flow sensor.

2.3.1. Prediction. Most of the students (80 out of 112) could see the correspondence of the heat flow in this activity to the liquid flow in activity 2. The nature of the graphs drawn by them was correct. They also predicted that the temperature of the water in compartment 2 would be equal to the temperature of the water in compartment 1 as the heat flow sensor reading reached zero. They were then shown the activity.

2.3.2. Observation. Figure 7 shows the output screen of this activity. The upper graph showed the output of the heat flow indicator. The lower graph showed the outputs of the thermocouples in compartment 1 and compartment 2, respectively. (When water at 60 °C was poured in compartment 1, there was an initial surge in the output of thermocouple 1 and heat flow indicator reading.)

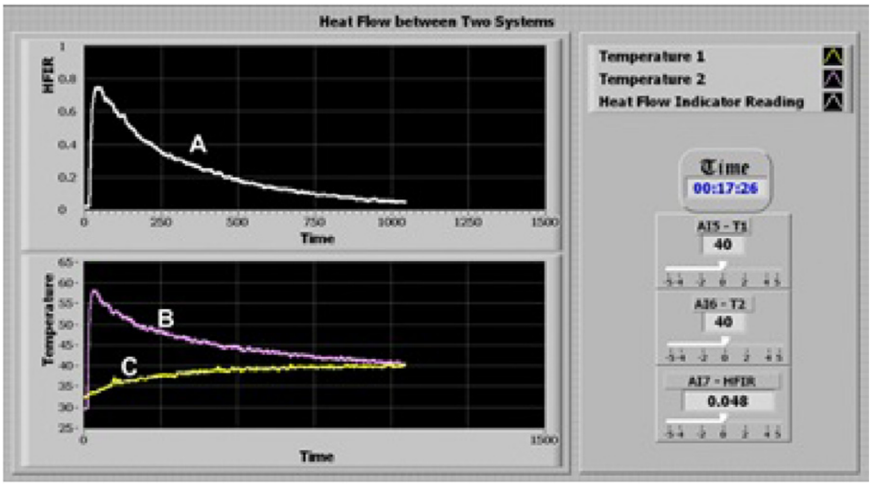

Figure 7. Output screen of heat flow activity.

The students were asked to explain the nature of the regions in the graphs indicated by letters A, B and C. From their explanations, it was clear that they understood that as the heat flow between the two systems approached zero, thermal equilibrium was established. At this point the temperatures of water in the two compartments were equal.

Since the students were exposed to both the liquid and the heat flow models, they were asked to match the concepts from the two models. The liquid flow model concepts were: liquid flow, control valve in the closed state, control valve in the open state, liquid flow rate, height of the liquid column and the heat flow model concepts were: heat flow, adiabatic wall, diathermic wall, heat flow rate and temperature.

Most of the students (75 on average) could correctly relate the concepts from one model to the other.

2.4. Activity 4: liquid flow analogy of activity 1

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 2). The situation is exactly like the discharge of a charged capacitor or radioactive decay. The height difference here decreases exponentially with a characteristic time constant. The larger the time constant, the slower the attainment of equilibrium will be.

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). These factors are usually combined, assuming viscous flow, into a single factor, hydrodynamic resistance, $R_h = 8\eta l / \pi r^4$. (Volume of liquid flowing from one cylinder to another per unit time is equal to the pressure difference between the ends of the flow tube divided by the hydrodynamic resistance.) The time constant will also involve the density of the liquid (ρ) and the acceleration due to gravity (g), since these relate the pressure difference to height difference. It will also involve the common base area of the two cylinders, since it relates the volume of liquid transferred to difference in height. (For simplicity, the cylinders in activity 2 were taken to be of the same base area.)

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. The time constant which will characterize the attainment of equilibrium in this case will depend on the thermal resistance of the heat channel and the difference between the heat capacities of the two containers. Referring to activity 1, in which the water in the bath is maintained at a definite temperature, the time constant will involve (i) an effective thermal resistance factor (= effective length of the conducting channel / (thermal conductivity × area of cross-section of the channel)), (ii) the mass and (iii) the specific heat of the object kept in the bath. The time constant thus involves the thermal conductivity, the specific heat and the density of the object (material factors) as well as the size of the object. The material factors may be combined into a single factor, namely, thermal diffusivity (= thermal conductivity / (density × specific heat)) of the material of the object.

Activity 4 is a liquid flow analogy of activity 1. This activity brings out, for hydrostatic equilibrium, how the rate of attaining equilibrium changes if the time constant is changed. This is illustrated by changing two of the factors on which the time constant depends (as discussed above).

In this activity, a cylinder used as a reservoir had the water level in it maintained at a constant value. This is analogous to the hot water bath maintained at a constant temperature. The reservoir was connected to two cylindrical containers through connecting pipes. The two parameters that were varied in this case 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).

2.4.1. Part I: studying the effect of the radius of cross-section of the connecting pipes. In this part, two containers of equal volume (500 ml) were connected to the reservoir through connecting pipes of equal length but of different radii of cross-section. Container A was connected using a pipe of inner radius of 5 mm and container B using a pipe of inner radius 1.5 mm (figure 8).

The students were asked to predict, by drawing, the nature of the graphs of the rise of water in both containers when the water was allowed to flow from the reservoir to the containers.

Most of the students could correctly predict that the water level in container A (with a connecting pipe of larger radius) would rise faster than the water level in container B (with a connecting pipe of smaller radius), and finally the levels of water in both containers would be equal to the level of water in the reservoir (figure 9).

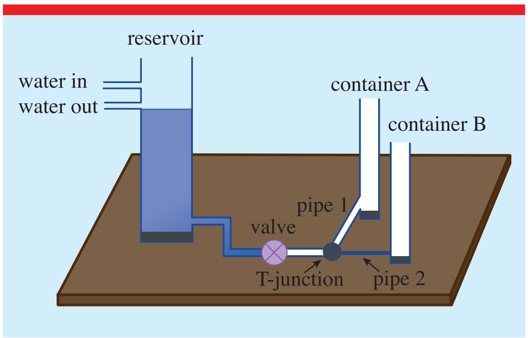

Figure 8. Schematic diagram of the apparatus.

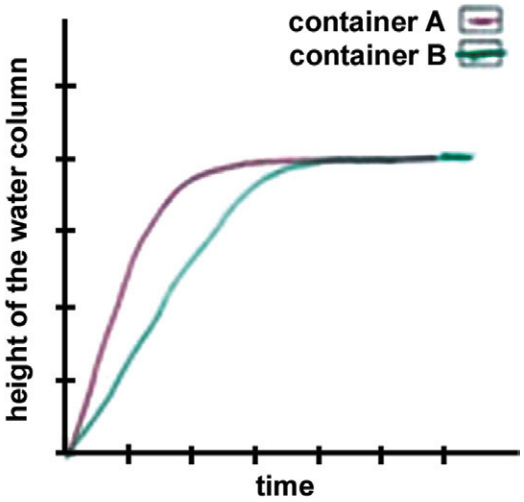

Figure 9. Student's drawing of water levels.

2.4.2. Part II: studying the effect of the base area of the receiving container. In this part, the two containers A and B were of different base area (the diameter of the base of container A was 4.3 cm and that of container B was 6.9 cm). They were connected to the reservoir through connecting pipes of equal length and equal radius of cross-section (5 mm) (figure 10). As in the earlier case the students could predict the nature of the graphs, correctly justifying that the water level in container A (with smaller base area) would rise faster than the water level in container B (with larger base area), and finally the water levels in both containers would reach the same level as the water level in the reservoir (figure 11).

The students could correspond this activity to activity 1. They could infer from what they

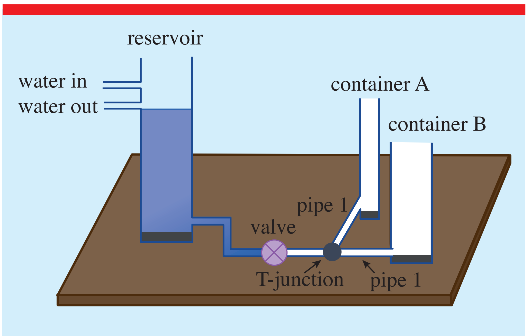

Figure 10. Schematic diagram of the apparatus.

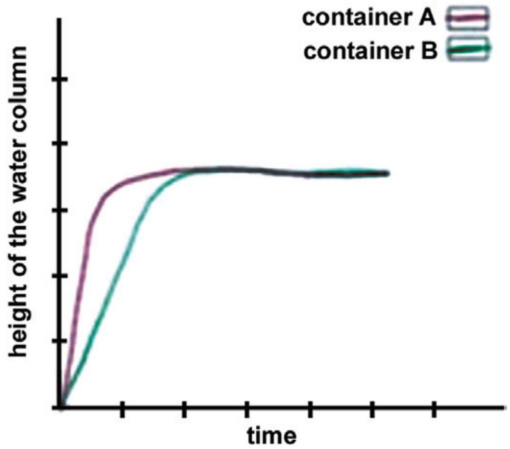

Figure 11. Student's drawing of water levels.

observed in this activity that the time constant in activity 1 would depend on the material and the size of the object kept inside the enclosure. Interviews with 10 of the students clearly brought this out.

2.5. Activity 5: method of mixtures

This activity was developed as a simple check to test the students' understanding developed through the above four activities. This was tried with 76 students. They 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 12). 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. The students were asked to predict how the temperatures of the brass cylinder and the water in the test tube would change. The majority of the students (63 out of 76) could predict correctly that the temperature of the brass cylinder would decrease and the temperature of the water would increase. They also predicted that the final temperature attained by both would be the same and this would be intermediate between the initial temperatures. Their prediction was confirmed by the activity.

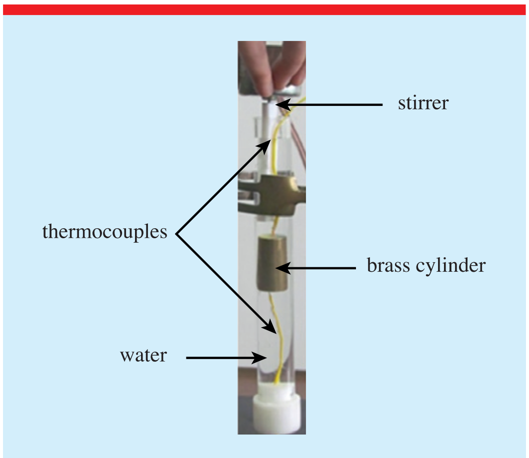

Figure 12. Photograph of the assembly.

3. Discussion and conclusion

A module consisting of five activities designed to help students understand thermal equilibrium was developed and tested. Activity 1 demonstrated that the final temperature attained by any object is the same as the temperature of the (constant temperature) enclosure in which it is kept, although the rate at which this happens depends on the size and the material of the body. Activity 2 helped the students to recollect their understanding of hydrostatic equilibrium. The hydrostatic equilibrium is identified by zero net liquid flow between two hydrostatic systems. At this point the heights of the liquid columns in the two systems from a common reference point are equal. In activity 3, by analogy with the liquid flow model, students learned that thermal equilibrium is identified by zero net heat flow between two thermal systems. At this point the temperatures of two systems are equal. We believe that linking thermal equilibrium and temperature through a demonstration of zero net heat flow makes it easier for students to understand these concepts.

Equipped with the basic correspondence between liquid and heat flows, the students proceed to activity 4 to study on what parameters the approach to equilibrium depends in the case of the liquid flow model, and by relating this understanding to what they observe in activity 1, they learn on what parameters the approach to thermal equilibrium depends. They are now equipped to deal with their basic alternative conception, which we referred to in the introduction. This was confirmed in the interviews of 10 students at the end of the module. Out of 112 students, whereas initially only 19 could justify that both delrin and brass cylinders would attain the temperature of the water bath, finally 72 could satisfactorily justify the same. Similarly, the number 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 34 to a final 72 (out of 112). When presented with a different situation (method of mixtures), 63 out of 76 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. We believe that our module presents an effective activity to introduce to the students the basic concept of thermal equilibrium. Students' qualitative responses also supported this. In fact these responses indicated that the students themselves felt the need of demonstrations in elementary thermodynamics classes, which is not usual practice in India.

Acknowledgments

We would like to thank all the students for patiently answering the questionnaires, Professor Vijay Singh and Professor Anwesh Mazumdar for their valuable suggestions, and the referees for their instructive comments.

Received 25 June 2014, in final form 18 August 2014
Accepted for publication 18 September 2014
doi:10.1088/0031-9120/50/2/146

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