Principles of Physics II (PHY112)

Lab

Experiment no: 8

Name of the experiment: Determination of the mechanical equivalent of heat

Theory

Once heat was thought of a weightless 'gas'. 'Calorie' was assumed to be the substance of this 'gas', which can move from a hotter body to a colder body.

Now, we know that heat is a form of energy. There is no such 'gas' which increases the temperature of a body when it enters the body or decreases the temperature when it leaves. When a work is done on a body due to the conversion of any form of energy, this may increase the average kinetic energy of the constituent particles of the body. The body gains a 'form of energy' which causes the rise of temperature. This is heat energy.

The ancient *Caloric Theory* of heat is now abandoned, but the term *calorie* is still used in different branches of science. Present day's interpretation of 'calorie' is- it is a unit of energy, used specially to measure heat.

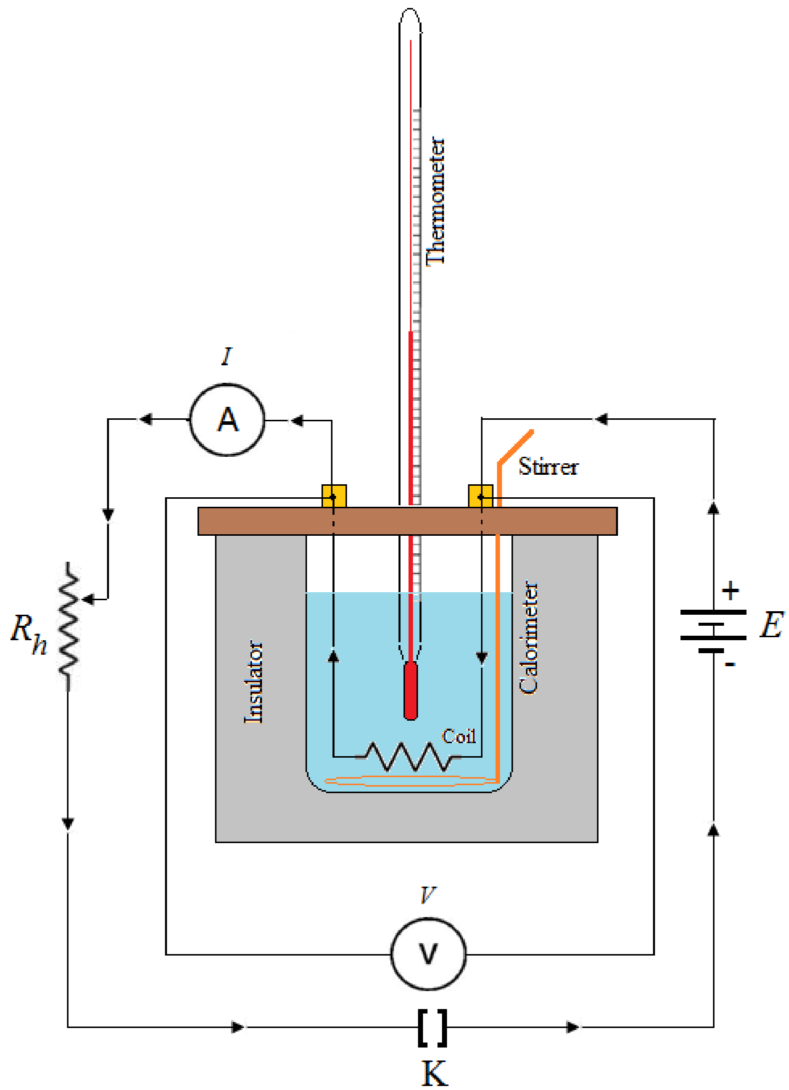

Figure 1: Arrangement of performing the experiment on the determination of the mechanical equivalent of heat

The amount of heat energy absorbed by 1 gram of water to increase its temperature for 1 degree Celsius at 1 atmosphere pressure is defined to be 1 calorie of heat.

Since, heat is a form of energy, 1 calorie amount of heat can be expressed in terms of Joule which is the unit of energy, as well as work. Joule was originally defined to measure mechanical work done. If due to the application of 1N (one Newton) amount of force on a body, the point of application of the force gets displaced for 1m (one Meter) along the direction of the force, then the amount of work done by the force is 1 J (one Joule).

In this experiment we have to determine the *Mechanical Equivalent of heat*. The amount of mechanical work (in the unit of Joule) which is required to be done to increase one unit of heat, i.e., 1 Calorie of heat, is called the *Mechanical Equivalent of heat*.

If W Joule work is required to be done to produce H Calorie of heat, then the *Mechanical Equivalent of heat* is defined by:

$$J = \frac{W}{H} \text{ J/cal} \tag{1}$$

In this experiment, an amount of electrical energy (measured in Joules) will be converted to heat (measured in Calorie). The law of conservation of energy equates the two quantities. Finally, we can calculate what amount of Joules is equal to one calorie.

We take a calorimeter (a beaker of copper) with a stirrer (also made of copper). Then, we fill it with a liquid (water), keep it inside an insulating chamber, immerse a coil in the liquid and cover the system with an insulating lid. The lid has four holes. The central one is for inserting a thermometer into the liquid. Two holes are for inserting the two copper rods which are connected with the coil as shown in the Figure 1. The rest one is for inserting the stirrer into the liquid.

Suppose, I Ampere of current is allowed to pass through the coil for a duration of t seconds. If q Coulomb charge has passed through the coil during this time then according to the definition of current (amount of charge passing through any cross section of a conductor per unit time) we can write,

$$I = \frac{q}{t} \Rightarrow q = It \tag{2}$$

Say, during this time the voltage difference across the coil is V Volts. Voltage difference between two points is defined by: “the amount of work done to move one unit of positive charge (1C) from one point to another is the potential difference (voltage difference) between those two points.”

If 1 Coulomb charge passes through the coil then amount of work done is V Joule.

$\therefore$ If q Coulomb charge passes through the coil then the amount of work done is Vq Joule.

Therefore, total work done, W Joule = Vq Joule

$$\Rightarrow W = Vq = VIt \text{ (according to equation 2)} \tag{3}$$

We have found the work done in Joule. Now, we have to find out the amount of heat absorbed by the liquid, calorimeter and stirrer.

Suppose, the initial temperature of the liquid, calorimeter and stirrer was θ_1°C. After I Ampere of current has passed for t seconds, the temperature increases up to θ_2°C. Hence, the change of temperature of the liquid, calorimeter and stirrer is $(\theta_2 - \theta_1)^\circ$C.

Specific heat capacity of the material of a body is defined by: "the amount of heat absorbed by a body of one unit mass (1gm) to increase its temperature for one unit (1°C) is called the specific heat capacity of the material of the body".

Let, the specific heat capacity of the liquid is s_l cal/gm/$^\circ$C and the mass of the liquid is m_l. According to the definition of specific heat capacity,

Heat absorbed by 1 gm of liquid to increase its temperature for 1°C is s_l cal.

$\therefore$ Heat absorbed by m_l gm of liquid to increase its temperature for $(\theta_2 - \theta_1)^\circ$C is $m_l s_l (\theta_2 - \theta_1)$ cal.

Let, the specific heat capacity of the material the calorimeter and the stirrer is s_c cal/gm/$^\circ$C and the mass of the calorimeter and stirrer is m_c. According to the definition of specific heat capacity,

Heat absorbed by 1 gm of calorimeter & stirrer to increase its temperature for 1°C is s_c cal.

$\therefore$ Heat absorbed by m_c gm of calorimeter & stirrer to increase its temperature for $(\theta_2 - \theta_1)^\circ$C is $m_c s_c (\theta_2 - \theta_1)$cal.

The total heat absorbed by the liquid, calorimeter and stirrer is,

$$H \text{ cal} = \{m_c s_c (\theta_2 - \theta_1) + m_l s_l (\theta_2 - \theta_1)\}\text{cal}$$

Therefore, $$H = (m_c s_c + m_l s_l)(\theta_2 - \theta_1) \tag{4}$$

By using equation (3) and (4) in equation (1) we get the working formula of deducing the *Mechanical Equivalent of heat*:

$$\boxed{J = \frac{VIt}{(m_c s_c + m_l s_l)(\theta_2 - \theta_1)} \quad \text{J/cal}} \tag{5}$$

Radiation Correction

To derive equation (5) we assumed that the whole amount of electrical energy *VIt* Joule is used to increase the temperature of the liquid, calorimeter and stirrer. However, a portion of this energy will be lost due to the radiation, i.e., heat energy will be radiated from the surface of the liquid. For this reason, the final temperature, θ_2°C recorded in the experiment will be lower than the final temperature if no radiation loss had occurred. The amount of temperature which is reduced due to radiation should be added with the $(\theta_2 - \theta_1)$ term of the equation (5).

According to the cooling law of Newton, we know that the rate at which the surface of body radiates heat (and eventually the rate at which the temperature is reduced due to this radiation) with respect to time is directly proportional to the difference of the temperature of the surface and that of its surroundings. If the present temperature of a surface is θ°C. and that of its surrounding is θ_0°C, and then the rate at which the temperature gets reduced for radiation is,

$$-\frac{d\theta}{dt} \propto (\theta - \theta_0) \Rightarrow -\frac{d\theta}{dt} = \kappa(\theta - \theta_0) \tag{6}$$

Here, κ is a constant of proportionality.

Since, we are heating up the system the temperature θ°C will also change. When the temperature is θ_1°C the rate of the change of temperature is

$$-\left.\frac{d\theta}{dt}\right|_{initial} = \kappa(\theta_1 - \theta_0) \tag{7}$$

When the temperature rises up to θ_2°C the rate of the change of temperature is

$$-\left.\frac{d\theta}{dt}\right|_{final} = \kappa(\theta_2 - \theta_0) \tag{8}$$

However, the initial temperature of the liquid, calorimeter & stirrer is θ_0°C, i.e., $\theta_1 = \theta_0$. So, $-\left.\frac{d\theta}{dt}\right|_{initial} = 0$ and $-\left.\frac{d\theta}{dt}\right|_{final} = \kappa(\theta_2 - \theta_1)$

A good approximation of the average rate of cooling is the arithmetic mean of these two rates. Therefore,

$$-\left.\frac{d\theta}{dt}\right|_{averagel} \approx \frac{\left(-\left.\frac{d\theta}{dt}\right|_{initial}\right) + \left(-\left.\frac{d\theta}{dt}\right|_{final}\right)}{2} = \frac{1}{2}\left(-\left.\frac{d\theta}{dt}\right|_{final}\right) \tag{9}$$

Now, we want to approximate the temperature loss due to radiation during the time interval when the temperature rises from θ_1°C to θ_2°C. Suppose, Δt s is the time interval between the moments θ_1 and θ_2 are recorded. Hence, the temperature loss is

$$\Delta\theta \approx \frac{1}{2}\left(-\left.\frac{d\theta}{dt}\right|_{final}\right)\Delta t \tag{10}$$

After the temperature reaches the maximum value of θ_2°C, we wait for another Δt s. During this interval temperature will reduce at the rate of $-\left.\frac{d\theta}{dt}\right|_{final}$. Suppose Δt s later the temperature gets reduced down to θ_3°C. Therefore,

$$-\left.\frac{d\theta}{dt}\right|_{final} = \frac{\theta_3 - \theta_2}{\Delta t} \tag{11}$$

Now, from equation (10) we get the approximate temperature loss during Δt s when the temperature rises from θ_1°C to θ_2°C.

$$\Delta\theta \approx \frac{1}{2}\left(-\left.\frac{d\theta}{dt}\right|_{final}\right)\Delta t = \frac{1}{2}\frac{(\theta_3 - \theta_2)}{\Delta t}\Delta t = -\frac{(\theta_2 - \theta_3)}{2} \tag{12}$$

Negative sign represents the temperature loss.

Finally, the radiation correction is $\frac{(\theta_2 - \theta_3)}{2}$ degree Celsius. We have to add this with $(\theta_2 - \theta_1)$ term of the equation (5).

Corrected rise of temperature, $\Delta\Theta = (\theta_2 - \theta_1) + \frac{(\theta_2 - \theta_3)}{2}$ (13)

The final working formula of determining the *Mechanical Equivalent of heat* is

$$\boxed{J = \frac{VIt}{(m_c s_c + m_l s_l)\Delta\Theta} \quad \text{J/cal}} \tag{14}$$

Apparatus

A calorimeter with stirrer, a thermometer, a voltmeter, an ammeter, a rheostat, a DC voltage source, a switch, a triple beam balance, copper wires of insignificant resistance, liquid (water).

Procedure

1) Clean the calorimeter (the container made of copper) and the stirrer with a piece of tissue paper.
2) Measure the mass of the calorimeter with the stirrer, m_c gm by using the triple beam balance.
3) Take some liquid (water) in the calorimeter. Measure the mass of the calorimeter, stirrer and water, m_{total} gm by using the triple beam balance again.
4) Find the mass of the liquid, m_l gm by subtracting m_c from m_{total}.
5) Look up the specific heat capacity of the liquid (water) s_l cal/gm/$^\circ$C and that of the material the calorimeter & stirrer s_c cal/gm/$^\circ$C in the text book.
6) Place the calorimeter in the insulating chamber.
7) Immerse the coil into the liquid.
8) Cover the lid of the calorimeter. Insert a thermometer through the central hole of the lid. Make sure that the bulb of the thermometer is immersed in the liquid but does not touch the coil.
9) Construct the circuit in the way shown in Figure 1. A wire comes from the positive terminal of the DC power supply to one of the copper rods holding the coil. Another copper rod (holding the coil) is connected with an Ammeter in SERIES combination. Other end of the Ammeter is connected with one end of a rheostat. Other terminal of the rheostat in connected with one end of a switch K. The other end of K is connected with the negative terminal of the DC voltage source. A Voltmeter is connected with the coil in PARALLEL combination.
10) Record the initial temperature of the liquid, calorimeter & stirrer (which are in thermal equilibrium), θ_1°C.
11) Turn on the switch K and simultaneously turn on the stop watch.
12) In every one minute interval of time record the temperature from the thermometer, voltage across the coil from the Voltmeter and the current passing through the coil from the Ammeter. Very gently and cautiously stir the liquid by moving the stirrer up and down to make sure that the heat is being uniformly distributed in the system and hence the temperature remains almost uniform throughout the system at every moment. Make sure that the stirrer does not touch the coil or the thermometer. Do not do it too fast. Kinetic energy of the stirrer may be converted to heat which you are not taking into account.
13) Keep recording these data until the temperature exceeds $(\theta_1 + 8)^\circ$C.
14) When after an INTEGER multiple of a minute the temperature shown in the thermometer is more than $(\theta_1 + 8)^\circ$C, turn off the switch K. Record the time and temperature at that moment BUT DO NOT turn off the stop watch. Time in seconds recorded at the moment when you switch off K is the value of *t* which is the duration of passing electrical energy through the coil.
15) The temperature may still keep increasing, even after you have switched off K. This is because of the reason that heat transfer occurs in convection method in the liquid. So the heat produced out of electrical energy in the coil may take some times to reach the bulb of the thermometer by

means of the locomotion of liquid molecules in the convection process of heat transfer. When the temperature shown in the thermometer becomes stable, keep its record AND THE TIME when this stable value of temperature is achieved. This is θ_2°C- the maximum value of the temperature. This time is Δt s which is the time required to cause the increase of temperature from θ_1°C to θ_2°C. Δt s may be slightly larger than t s (which is the duration of passing electrical energy through the coil).
However, you may not see the temperature to increase much after you switch off K. This is when the distance between the thermometer's bulb and coil is small. Heat does not take much time to reach thermometer's bulb from the coil. Do not worry. Then Δt and t will be almost same.

16) Wait for another Δt s of time after the moment when temperature reaches the maximum θ_2°C. The temperature will decrease due to radiation. By the end of this waiting period record the temperature θ_3°C.
17) Calculate the radiation correction and the corrected rise of the temperature $\Delta\Theta^{\circ}$C according to equation (13).
18) Calculate the average voltage across the coil and the average current passing through the coil.
19) Finally, determine the value of J by using the equation (14).

Read carefully and follow the following instructions:

- **Please READ the theory carefully, TAKE printout of the 'Questions on Theory' and ANSWER the questions in the specified space BEFORE you go to the lab class.**

- **To get full marks for the 'Questions on Theory' portion, you must answer ALL of these questions CORRECTLY and with PROPER UNDERSTANDING, BEFORE you go to the lab class. However, to ATTEND the lab class you are REQUIRED to answer AT LEAST the questions with asterisk mark.**

- **Write down your NAME, ID, THEORY SECTION, GROUP, DATE, EXPERIMENT NO AND NAME OF THE EXPERIMENT on the top of the first paper.**

- **If you face difficulties to understand the theory, please meet us BEFORE the lab class. However, you must read the theory first.**

- **DO NOT PLAGIARIZE. Plagiarism will bring ZERO marks in this WHOLE EXPERIMENT. Be sure that you have understood the questions and the answers what you have written, and all of these are your own works. You WILL BE asked questions on these tasks in the class. If you plagiarize for more than once, WHOLE lab marks will be ZERO.**

- **After entering the class, please submit this portion before you start the experiment.**

Name: ______________________ ID: ______________ Sec: ___ Group: __ Date: __________

Experiment no: ___

Name of the Experiment: ____

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Questions on theory (all diagrams should be drawn by using a pencil and a scale)

*1) What is 1 calorie of heat? [0.5]

Ans:

*2) Define specific heat capacity of a material. [0.5]

Ans:

*3) Define Mechanical Equivalent of Heat. [0.5]

Ans:

*4) Draw the arrangement of performing the experiment. [1]

Ans:

*5) Find out an expression of work done due to electrical energy when I A of current passes through a coil for t s time and the voltage across the coil is V Volts. [1]

Ans:

*6) Find out an expression of heat absorbed by the liquid, calorimeter and stirrer in terms of their masses, specific heat capacity and the rise of the temperature. [1]

Ans:

*7) Find out an expression for the Mechanical Equivalent of Heat. [0.5]

Ans:

- **Draw the data table(s) and write down the variables to be measured shown below (in the 'Data' section), using pencil and ruler BEFORE you go to the lab class.**

- **Write down your NAME and ID on the top of the page.**
- **This part should be separated from your Answers of "Questions on Theory" part.**
- **Keep it with yourself after coming to the lab.**

Data

Mass of the calorimeter & stirrer, m_c (in gm) =

Mass of the calorimeter, stirrer & liquid, m_{total} (in gm) =

Mass of the liquid, m_l (in gm) =

Specific heat capacity of the liquid, s_l (in cal/gm/$^\circ C$)=

Specific heat capacity of the material of the calorimeter & stirrer, s_c (in cal/gm/$^\circ C$) =

Initial temperature of the liquid, calorimeter and stirrer, θ_1 (in $^\circ C$) =

Table: Data for calculating J

Time t seconds	Voltage V Volts	Current I Amperes	Temperature $\theta^\circ C$

The time when K is turned off, t (in second) =

The maximum value of the temperature, θ_2 $^\circ$C =

The time required for the rise of temperature from θ_1 $^\circ$C to θ_2 $^\circ$C, Δt (in seconds) =

The temperature after Δt s since the moment the system reached the maximum temperature of θ_2 $^\circ$C is θ_3 $^\circ$C =

Average value of the voltage across the coil, V (in Volts) =

Average value of the current passing through the coil, I (in Amperes) =

- **READ the PROCEDURE carefully and perform the experiment by YOURSELVES. If you need help to understand any specific point draw attention of the instructors.**
- **DO NOT PLAGIARIZE data from other group and/or DO NOT hand in your data to other group. It will bring ZERO mark in this experiment. Repetition of such activities will bring zero mark for the whole lab.**
- **Perform calculations by following the PROCEDURE . Show every step in the Calculations section.**
- **Write down the final result(s)**

Calculations

Radiation correction =

Corrected rise of the temperature, $\Delta\Theta$ (in degree Celsius) =

Work done by electric energy, W (in Joules) =

Heat produced out of electric energy, H (in calorie) =

Mechanical equivalent of heat, J =

Results:

- **TAKE printout of the 'Questions for Discussions' BEFORE you go to the lab class. Keep this printout with you during the experiment. ANSWER the questions in the specified space AFTER you have performed the experiment.**
- **Attach Data, Calculations, Results and the Answers of 'Questions for Discussions' parts to your previously submitted Answers of 'Questions on Theory' part to make the whole lab report.**
- **Finally, submit the lab report before you leave the lab.**

Name: ___________________________ ID: ___________________

Questions for Discussions

1) See the Figure 2.

   In the experiment what you have performed, electrical energy is converted to heat.
   On the other hand, the Figure 2 shows an experiment where mechanical energy is converted to heat. A turbine is immersed in the liquid. The axle of the turbine is wound by a rope of negligible mass. The rope passes over a smooth pulley. The bottom end of the load is connected with a load of mass M. when the load falls down for *h* distance, it rotates the turbine. Rotational kinetic energy of the turbine heats up the liquid. The temperature rise can be measured by the thermometer.

   Find out an expression for the mechanical equivalent of heat for this experiment. [1]

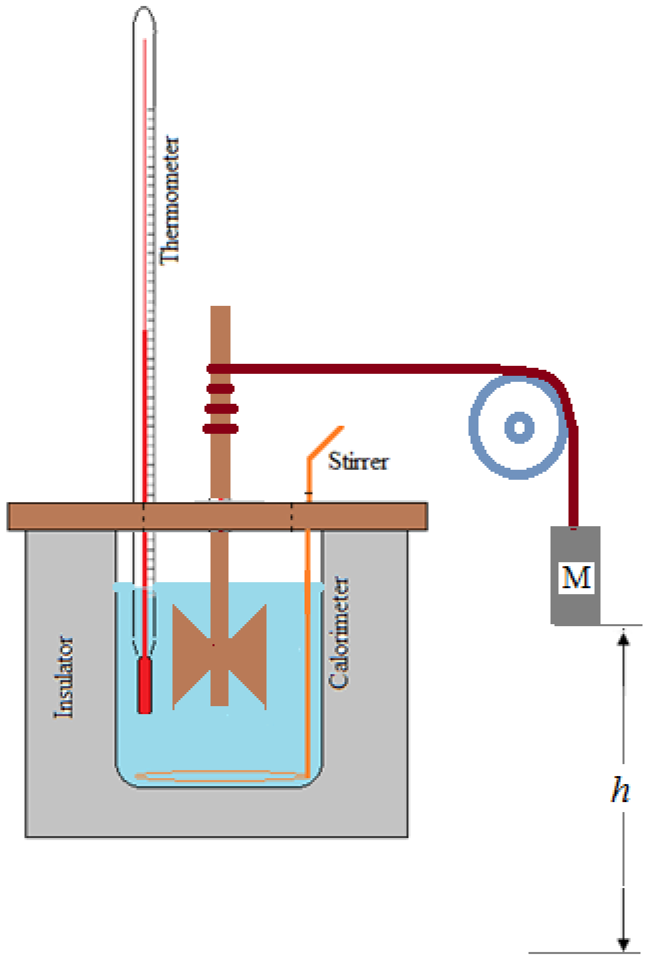

Figure 2: Arrangement of an experiment to determine J by converting mechanical energy to heat

   Ans:

2) How did you approximate the radiation correction in the experiment which you have performed? Briefly discuss the theory. Why is it important to make radiation correction? [1] (You may use additional page.)

   Ans: