# SCHOOL OF PHYSICS
# UNIVERSITI SAINS MALAYSIA

# Procedure Manual

ZCA 191/2 and ZCA192/2

## MECHANICAL HEAT EQUIVALENT

**(SETARAAN MEKANIK HABA)**

## PURPOSE OF EXPERIMENT

The purpose of this experiment is to verify the relationship between mechanical energy, or energy associated with motion, and heat, associated with the transfer of energy between objects because of a temperature difference.

## EQUIPMENT

• Mechanical Equivalent of Heat Apparatus
• Mass hanger
• Mass

## BACKGROUND

The principle of the conservation of energy tells us that if a given amount of work is transformed completely into heat, the resulting thermal energy must be equivalent to the amount of work that was performed. Of course, since work is normally measured in units of Joules and thermal energy is normally measured in units of Calories, the equivalence is not immediately obvious. A quantitative relationship is needed that equates Joules and Calories. This relationship is called the Mechanical Equivalent of Heat.

A Mechanical Equivalent of Heat apparatus allows accurate determination of the Mechanical Equivalent of Heat (to within 5%). The apparatus is shown in Figure 1. A measurable amount of work is performed by turning the crank, which turns the aluminum cylinder. A nylon rope is wrapped several times around the cylinder so that, as the crank is turned, the friction between the rope and the cylinder is just enough to support a mass hanging from the other end of the rope. This insures that the torque acting on the cylinder is constant and measurable. A counter keeps track of the number of turns.

As the cylinder turns, the friction between the cylinder and the rope converts the work into thermal energy, which raises the temperature of the aluminum cylinder. A thermistor is embedded in the aluminum so that, by measuring the resistance of the thermistor, the temperature of the cylinder can be determined. By monitoring the temperature change of the cylinder, the thermal energy transferred into the cylinder can be calculated. Finally, the ratio between the work performed and the thermal energy transferred into the cylinder determines J, the mechanical equivalent of heat.

### Measuring Temperature with the Thermistor

To measure the temperature of the aluminum cylinder, a thermistor is embedded inside. A thermistor is a temperature dependent resistor. If the resistance of the thermistor is known, its temperature can be very accurately and reliably determined. The leads of the thermistor in the cylinder are soldered to the copper slip rings on the side of the cylinder. The brushes provide an electrical connection between the slip rings and the banana plug connectors. By plugging an ohmmeter into these connectors, the resistance of the thermistor, and therefore its temperature, can be monitored, even when the cylinder is turning.

Although the temperature dependence of the thermistor is accurate and reliable, it is not linear. You will therefore need to use the table of Temperature versus Resistance given at the end of this manual to convert your resistance measurements into temperature readings.

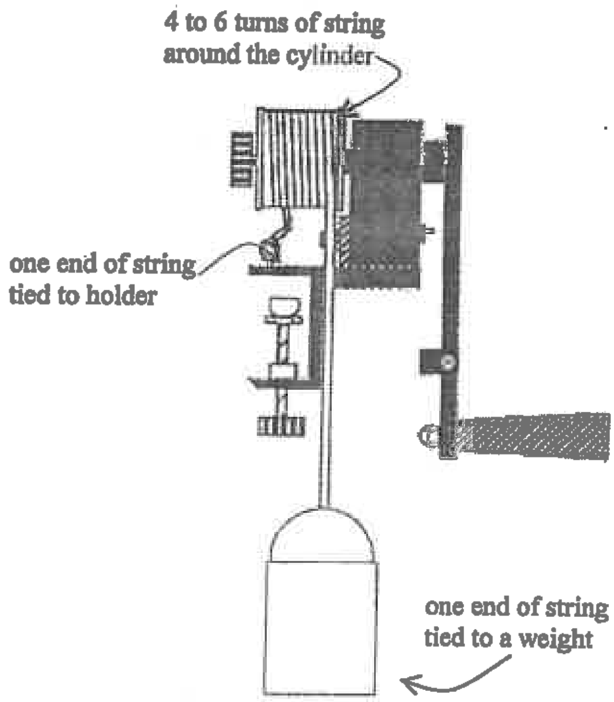


Figure 1. The mechanical heat equivalent apparatus.

## HISTORY

It may not seem strange to us today that there is a thing called energy that is conserved in all physical interactions. Energy is a concept we have all grown up with. A hundred and fifty years ago it was not so evident that there should be an intimate, quantitative relationship between such apparently unrelated phenomena as motion and heat. The discovery that heat and motion can be seen as different forms of the same thing—namely energy—was the first and biggest step toward understanding the concept of energy and its conservation.

Count Rumford of Bavaria, in 1798, was the first to realize that work and heat were related phenomena. At that time, it was commonly believed that heat resulted from the flow of a massless fluid-like substance called *caloric*. It was believed that this substance resided in objects, and that when they were cut, ground, or otherwise divided into smaller pieces, the pieces could not hold as much caloric as the original object. The resulting release of caloric was what we experience as heat.

It was not until the experiments of Joule in 1850, however, that Rumford's ideas about the nature of heat gained popular acceptance. Joule performed a variety of experiments in which he converted a carefully measured quantity of work, through friction, into an equally carefully measured quantity of heat. For example, in one experiment Joule used falling masses to propel a paddle wheel in a thermally insulated, water-filled container. Measurements of the distance through which the masses fell and the temperature change of the water allowed Joule to determine the work performed and the heat produced. With many such experiments, Joule demonstrated that the ratio between work performed and heat produced was constant. In modern units, Joule's results are stated by the expression:

1 calorie = 4.186 Joule.
Joule's results were within 1% of the value accepted today.
(The calorie is now *defined* as equal to 4.184 Joule.)

It was this series of experiments that led Joule, along with several others, to the more general theory that energy is conserved in all physical processes.

## Important Instructions

Below are two experiments to obtain the mechanical heat equivalent. Do experiment A in the first week and experiment B in the second week. After the end of each experiment, complete the worksheets provided and submit them for assessment. Only submit worksheet A for experiment A and worksheet B for experiment B. <u>Do not collect your worksheet A when doing experiment B. If you do, you will not obtain any marks for experiment A</u>.

## EXPERIMENTAL PROCEDURE

The method used in this experiment in finding the mechanical heat equivalent *J*, is by frictional method between a string placed around an aluminum cylinder making at least 4 to 6 turns where one end of the string is tied to the holder and the other end tied to a weight left hanging above the floor (refer to Figure 1). The string tied to the holder and weight is strained at the beginning of the experiment. When the handle is turned steadily, the weight will then be less strained and stay fixed at a particular point. This happens when all the forces acting on the system is in equilibrium. If the cylinder is rotated steadily at equilibrium, work by the frictional force of the string on the cylinder is equivalent to the work by the weight on the string.

### A. Symmetrical Room Temperature Experiment

*1. Method*

a. Measure the resistance of the aluminum cylinder using a digital multimeter in kΩ and then, the corresponding temperature is obtained by the interpolation of data from the table of Resistance versus Temperature given at the back of the manual for its equivalent in °C. Then, take off the aluminum cylinder from the holder of the experimental setup and weigh it (in grams, g). Also measure its diameter.

b. Cool the cylinder in iced water (water mixed with some ice) until its temperature reaches at least 10°C below room temperature (around 10 mins). Then, dry the cylinder (dab dry) and place the cylinder back to its holder quickly. Make sure that the cylinder is inserted into the holder correctly so that the notch on the cylinder fits exactly into the pin of the holder. This is to ensure good electrical contact.

c. Place a string around the cylinder making at least 4 to 6 turns. Be sure that the string lies flat against the cylinder and hangs down. Then, place a weight of between 1.5 to 2 kg on the other end of the string around 3 cm from the floor. This must be done rather quickly to ensure that the temperature of the cylinder has not increased significantly in the process of fitting the cylinder into the holder and getting the experiment set up.

d. Then, measure the resistance again using the digital multimeter and set the counter at '0'. Crank the handle of the cylinder steadily until the corresponding temperature reaches a few °C higher than room temperature. Using the table of Resistance versus Temperature for the thermister, determine the temperature values which correspond to each of your recorded resistance value. After the experiment is over, take down the number of turns, *N* on the counter.

## 2. *Calculating the Mechanical Heat Equivalent*

### Calculating W, the Work Performed

The work performed on the cylinder by turning the crank equals $\tau$, the torque acting on the cylinder, times $\theta$, the total angle through which the torque acts. It would be difficult to directly measure the torque delivered by the crank. However, since the motion of the cylinder is more or less constant through the experiment, we know that the torque provided by the crank must just balance the torque provided by the friction from the rope. The torque provided by the rope friction is easily calculated. It is just:

$$\tau = MgR \tag{1}$$

Each time the crank is turned one full turn, this torque is applied to the cylinder through an angle $2\pi$. The total work performed therefore is:

$$W = \tau\theta = MgR\,(2\pi N) \tag{2}$$

$$W = Mg\frac{D}{2}(2\pi N) = \pi MgDN \tag{3}$$

where $N$ is the number of turns of the cylinder , $R$ [m] is the radius of the aluminum cylinder, $D$ [m] is the diameter of the cylinder, $M$ [kg] is the weight hanging at the end of the string and $g$ is the gravitational acceleration.

### Calculating Q, the Heat produced

The heat ($Q$) produced by friction against the aluminum cylinder can be determined from the measured temperature change that occurred. The calculation is:

$$Q = mC\,(T_f - T_i), \tag{4}$$

where $m$ [g] is the mass of the cylinder, $T_f$ is the final temperature and $T_i$ is the initial temperature of the cylinder.

### Calculating J, the Mechanical Equivalent of Heat

The mechanical heat equivalent is just the ratio of the work performed to the heat produced and calculated by the following equation;

$$J = \frac{W}{Q} = \frac{\pi MgDN}{mC(T_f - T_i)} \tag{5}$$

(Assume that the gravitational acceleration is $g = 9.8\ \mathrm{m/s^2}$ and the specific heat capacity of aluminum is $C = 0.220\ \mathrm{cal/g^oC}$).

## B. Non-Symmetrical Room Temperature Experiment

### *1. Method*

a. For this experiment, the experimental set up is similar to experiment A except that the aluminum cylinder is not cooled. Instead, the aluminum cylinder is initially at room temperature, $T_o$. Take down this temperature, set a stop clock to '0' and begin turning the handle of the holder steadily until its temperature increases and reaches $T_a$, the final temperature of the cylinder. Take down the temperature increased every 20-30 seconds. Don't forget to set the counter to '0' before you begin and take down the number of turns, $N$ at the end of the experiment. The temperature range between $T_a$ and $T_0$ must be at least 10°C or just a little higher. This is the heating part of the experiment. Enter your data into the table given in worksheet B.

b. After the final temperature $T_a$ is reached, stop turning the cylinder and allow it to cool down naturally until it returns to almost room temperature. Continue taking the temperature decreased every 30 seconds to 1 minute. This is the cooling part of the experiment. Enter your data into the table given in worksheet B. Then **plot a heating and cooling graph for aluminum** from the data you have obtained. Refer to Figure 2 for reference.

c. As the surrounding temperature is lower than the temperature of the cylinder $T_a$, some of the heat will be dissipated. If this dissipated heat is taken into account, the true final temperature should have been higher than $T_a$. In order to correct this, we need to know the characteristics of cooling quantitatively. According to Newton's cooling law, the rate of cooling $dT/dt$ for a system to its surroundings is proportional to the difference between the temperature of the system, $T$ and its surroundings, $T_o$ as given below;

$$\frac{dT}{dt} = -K(T - T_0) \qquad (6)$$

where $K$ is the cooling constant for the system.

The value of K can be obtained from the heating and cooling curve. The data is obtained from the increase in temperature of the aluminum cylinder in the experiment to $T_a$ during heating process and the decrease in temperature to room temperature $T_o$ during cooling process.

Solving equation (6), we will obtain the following;

$$ln\frac{(T - T_0)}{(T_a - T_0)} = -K(t - t_a) \qquad (7)$$

By plotting the graph of $ln\frac{(T - T_0)}{(T_a - T_0)}$ versus $(t - t_a)$ which is a straight line curve, $-K$ is the gradient of the curve and can be easily found.

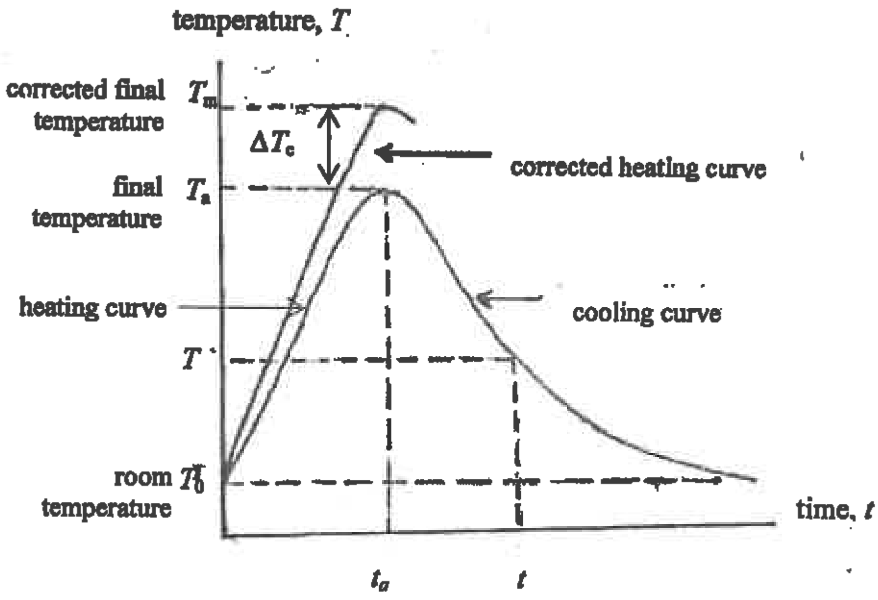


Figure 2. Heating and cooling graph for aluminum.

d. **Plot the graph of** $ln\frac{(T-T_0)}{(T_a-T_0)}$ **versus** $(t-t_a)$ **and find** $K$.

In order to calculate the temperature correction due to heat dissipated to the surroundings, according to equation (6), the change in temperature for each time interval $\Delta t$ is $|\Delta T| = K(T-T_0)\,\Delta t$. During the process of heating, from time $t=0$ to $t_a$ for $n$ intervals of $\Delta t$, we will obtain $t_a = n\Delta t$ so that the subsequent changes in temperature $T_1, T_2, \ldots, T_n$ proceed as the following;

$$\Delta T_1 = K(T_1 - T_o)\,\Delta t$$

which is the temperature correction for temperature $T_1$. The correction $\Delta T_2$ for temperature $T_2$ is

$$\Delta T_2 = K(T_2 - T_o)\,\Delta t + \Delta T_1 = K(T_1 + T_2 - 2T_o)\,\Delta t \quad \text{and so on}$$

Eventually, we will obtain the $n$th correction as follows;

$$\Delta T_n = K(T_1 + T_2 + \ldots + T_n - nT_o)\,\Delta t$$

The expression above is only for the heating process. If the number of time intervals $n$ is considered for the whole process including the cooling process, the above expression need to be multiplied by a factor of $\frac{1}{2}$ so that the real temperature correction for $T_a$ is as follows;

$$\Delta T_a = \frac{1}{2}K(T_1 + T_2 + \ldots + T_n - nT_o)\Delta t \tag{8}$$

If $n$ **is large** enough, the change in temperature for each subsequent time interval will be small and assumed to be the same so that equation (8) above is approximated as below;

$$\Delta T_a = \frac{1}{2}K(T_a - T_o)\Delta t \tag{9}$$

Equation (9) is used for large $n$ which include the heating and cooling processes (the number of time intervals from 0 to $t_a$ for heating and from $t_a$ to $t_n$ for cooling). Here, $\Delta t = t_a - 0$ during heating. However, if $n$ **is small**, then equation (8) is used. Then, the true corrected temperature is calculated as follows;

$$T_m = T_a + \Delta T_a \tag{10}$$

### 2. *Calculating the Mechanical Heat Equivalent*

The calculation of work for the system is the same as in experiment A.

However, the heat absorbed by the cylinder is

$$Q = mC\,(T_m - T_o) \tag{11}$$

The mechanical equivalent of heat is calculated using the ratio, $J = W/Q$

If the experiments are conducted carefully, the expected uncertainty is well within 5%.

# THERMISTER SPECIFICATIONS

| equivalent kiloΩ | temp °C | equivalent kiloΩ | temp °C | equivalent kiloΩ | temp °C | equivalent kiloΩ | temp °C |
|---|---|---|---|---|---|---|---|
| 351.0 | 0 | 95.5 | 26 | 32.3 | 51 | 12.5 | 76 |
| 332.6 | 1 | 91.1 | 27 | 31.0 | 52 | 12.0 | 77 |
| 315.3 | 2 | 87.0 | 28 | 29.8 | 53 | 11.6 | 78 |
| 299.0 | 3 | 83.1 | 29 | 28.6 | 54 | 11.2 | 79 |
| 283.6 | 4 | 79.4 | 30 | 27.5 | 55 | 10.8 | 80 |
| 269.1 | 5 | 75.9 | 31 | 26.4 | 56 | 10.5 | 81 |
| 255.4 | 6 | 72.6 | 32 | 25.4 | 57 | 10.1 | 82 |
| 242.5 | 7 | 69.4 | 33 | 24.4 | 58 | 9.8 | 83 |
| 230.3 | 8 | 66.4 | 34 | 23.5 | 59 | 9.4 | 84 |
| 218.7 | 9 | 63.5 | 35 | 22.6 | 60 | 9.1 | 85 |
| 207.9 | 10 | 60.7 | 36 | 21.7 | 61 | 8.8 | 86 |
| 197.6 | 11 | 58.1 | 37 | 20.9 | 62 | 8.5 | 87 |
| 187.8 | 12 | 55.7 | 38 | 20.1 | 63 | 8.2 | 88 |
| 178.7 | 13 | 53.3 | 39 | 19.4 | 64 | 8.0 | 89 |
| 170.0 | 14 | 51.0 | 40 | 18.7 | 65 | 7.7 | 90 |
| 161.7 | 15 | 48.9 | 41 | 18.0 | 66 | 7.5 | 91 |
| 154.0 | 16 | 46.9 | 42 | 17.3 | 67 | 7.2 | 92 |
| 146.6 | 17 | 44.9 | 43 | 16.7 | 68 | 7.0 | 93 |
| 139.6 | 18 | 43.1 | 44 | 16.1 | 69 | 6.8 | 94 |
| 133.0 | 19 | 41.3 | 45 | 15.5 | 70 | 6.5 | 95 |
| 126.7 | 20 | 39.6 | 46 | 14.9 | 71 | 6.3 | 96 |
| 120.8 | 21 | 38.0 | 47 | 14.4 | 72 | 6.1 | 97 |
| 115.2 | 22 | 36.5 | 48 | 13.9 | 73 | 5.9 | 98 |
| 109.9 | 23 | 35.0 | 49 | 13.4 | 74 | 5.7 | 99 |
| 104.8 | 24 | 33.6 | 50 | 12.9 | 75 | 5.6 | 100 |
| 100.0 | 25 | | | | | | |

Table of Temperature and Resistance Equivalent

(5)

# WORKSHEET A

ZCA 191/2 and ZCA 192/2: LABORATORY PHYSICS 100

**MECHANICAL HEAT EQUIVALENT**

**PLEASE SUBMIT WORKSHEET A ONLY AT THE END OF THE FIRST WEEK EXPERIMENT**

Name : ..........................................................................................................

Group: ..........................................Day: ...................................................

Date of experiment: ........................................................................................

Lab partner's name:

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Grade: ..............................

## OBJECTIVE

To investigate the value of the mechanical heat equivalent by friction method **(Symmetrical Room Temperature Experiment)**

## DATA

Mass of weight at the end of the sting, M =........................[kg]

Mass of aluminum cylinder, m = ........................[g]

Diameter of aluminum cylinder, D =........................[m]

Number of rotations (turns) of the aluminum cylinder, $N$ = ...............

| | Temperature [°C] | Equivalent Resistance [kΩ] |
|---|---|---|
| Room temperature | | |
| Initial temperature of aluminum cylinder, $T_i$ | | |
| Final temperature of aluminum cylinder, $T_f$ | | |

## CALCULATION OF $J$

- Specific heat capacity of cylinder

  $H = mC =$ ..........................................................................................

- Work done by frictional forces

  $W_s =$ ..........................................................................................
  ..........................................................................................
  ..........................................................................................

- Heat absorbed by the cylinder

  $\underline{Q_s = H\,(T_f - T_i) =}$ ..........................................................................................
  ..........................................................................................
  ..........................................................................................

- Mechanical heat equivalent

  $J_s =$ ..........................................................................................
  ..........................................................................................
  ..........................................................................................

- Error calculation of $J_s$

Therefore, the mechanical heat equivalent including error is

$J_s =$ ..................................................................................................................................

## DISCUSSION AND CONCLUSION

## ANSWER THE FOLLOWING QUESTIONS

1. Is it better to crank the aluminum cylinder rapidly? Why and why not?

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2. Is it experimentally possible that the heat absorbed by the cylinder could be greater than the work performed on it? Explain.

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3. Can your value of J be used for determining how much mechanical energy can be produced from a specified amount of thermal energy? Why or why not?

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# WORKSHEET B

ZCA 191/2 and ZCA 192/2: LABORATORY PHYSICS 100

**MECHANICAL HEAT EQUIVALENT**

**PLEASE SUBMIT WORKSHEET B ONLY AT THE END OF THE SECOND WEEK EXPERIMENT**

Name : ..........................................................................................................
Group: ..........................................Day: ........................................................
Date of experiment: ...............................................................................................
Lab partner's name:
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## OBJECTIVE

To investigate the value of the mechanical heat equivalent by friction method **(Non-Symmetrical Room Temperature Experiment)**

## DATA

Number of rotations (turns) of cylinder during heating, $N =$ ...............

| TABLE OF INCREASING TEMPERATURE | | | | | |
|---|---|---|---|---|---|
| **time** | **equivalent resistance** | **temperature** | **time** | **equivalent resistance** | **temperature** |
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**TABLE OF DECREASING TEMPERATURE**

| time | equivalent resistance | temperature | time | equivalent resistance | temperature |
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Graph of $ln\frac{(T-T_0)}{(T_a-T_0)}$ versus $(t-t_a)$

***Show clearly the points where gradient is taken and the calculations***

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Graph of temperature, $T$ versus time, $t$

*Show the corrected temperature in the graph*

..................................................................................................................................

## CALCULATION OF $J$

- From the graph of $ln\frac{(T-T_0)}{(T_a-T_0)}$ versus $(t-t_a)$, explain how you obtained the $K$ constant.

  $K=$ ..............................................................................................
  ..............................................................................................
  ..............................................................................................

- Calculation of the corrected temperature

  $\Delta T_a =$ ..............................................................................................
  ..............................................................................................

  $T_m = T_a + \Delta T_a =$ ..............................................................................................
  ..............................................................................................

- Work done due to friction

  $W_T =$ ..............................................................................................
  ..............................................................................................
  ..............................................................................................

- Heat absorbed by the cylinder

  $Q_T = H(T_m - T_o) =$ ..............................................................................................
  ..............................................................................................
  ..............................................................................................

- Therefore, the mechanical heat equivalent is

  $J_T =$ ..............................................................................................

## DISCUSSION AND CONCLUSION