

Experiment ET Energy Transformation & Specific Heat

We have introduced different types of energy, which help us describe many processes in the world around us: mechanical, electrical, chemical and heat energy. We have distinguished between energy stored in some system, potential energy: and energy associated with the motion of objects, kinetic energy. We have described some of the conversions or transformations in which one kind of energy turns into another kind, and we have pointed out that the final form is invariably heat. Consider Niagara Falls: the water's gravitational potential energy turns into kinetic energy as it falls. The turbines and alternators spin and electrical energy is generated. It's sent to you and your soldering iron turns it into heat, or your refrigerator turns it into mechanical energy to make the refrigerant flow to remove heat from the inside to the outside. There are an immense number of processes like that going on in both the man-made and the natural world.

In the Part I of the experiment you will calibrate an electrical temperature sensor, called a "thermistor" by immersing it in water whose temperature is measured with a glass thermometer. The thermistor (smaller and faster in response than the glass thermometer) is a compressed pellet of semi-conducting metal oxides whose resistance depends on temperature. Calibrating the thermistor means finding a relation between its electrical resistance and the temperature.

In the Part II of the experiment, electrical energy will be transformed into thermal energy resulting in the heating up of a sample of water. You will thus be able to find the specific heat, c_w , of water. The specific heat is the energy it takes to heat one kilogram one degree Kelvin (or equivalently one degree Celsius).

Part I Calibrating the Thermistor

Apparatus

Start by soldering two wires, each about 1 foot long, to the thermistor.

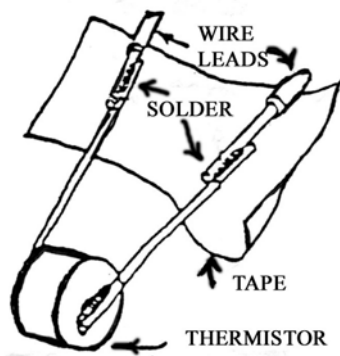


Figure 1: Thermistor

(It is a small cylindrical object with two leads; see Figure 1.) Use tape to prevent electrical shorts. Treat the thermistor gently, as the leads can be pulled or melted off rather easily.

Set the digital multimeter (DMM) to " $\text{K}\Omega$ " (kilo-ohms = 1000Ω) and connect it to the thermistor with the clips or with your clip leads. A reading of about 100Ω should appear. Breathe on the thermistor and note its speed and sensitivity compared to the glass thermometer.

You will make many resistance readings with the DMM or the magnetic multimeter (MMM) and these use battery power. Get in the habit of turning off the DMM when not actually making resistance readings, and don't leave the MMM with its test leads connected for long periods.

Clear a work area so that if water spills there is no problem. Go to a nearby lavatory and fill two of your four styrofoam cups $2/3$ full, one with hot water and the other with cold water. Do experiments in a third cup, and use the fourth to hold water when you're through with it. In these experiments you should watch out for heat sources like lights or heaters, and for drafts from windows and doors. It generally improves your measurements if you stir the water by gentle shaking to make sure it's well mixed and therefore at one temperature.

You can put the 1157 lamp into the hot water cup as an immersion heater to warm up water as needed. Connect the 8 W filament directly to the wall transformer (no LVPS). The 8W filament will maintain a cup of water near 45°C . We provide a lid for the experiment cup, which may be helpful in reducing heat loss, especially, that due to evaporation when using hot water.

Calibrating the Thermistor

Put enough hot water into the third cup (the experiment cup, which serves as a calorimeter) to cover the end of the thermometer and the thermistor. Take and record temperature and resistance readings and also the time as the water continues to cool. Stir the water with the thermometer (or gently shake the cup) before each reading.

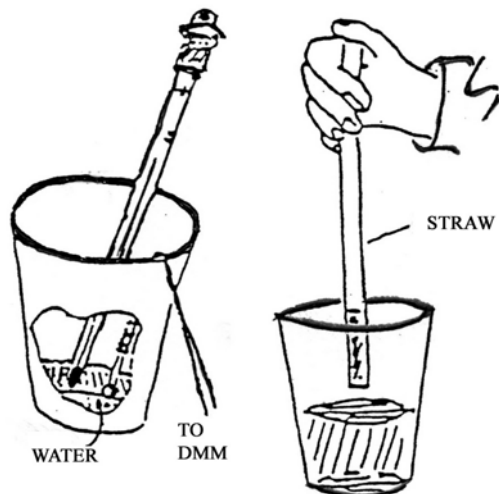


Figure 2: calibrating the Thermistor

When cooling slows, continue the calibration by adding cold water so as to cover the range from hot (45 C to 50 C) to cool (20 C to 25 C), taking data at about 10 intermediate values. You can use a soda straw as a pipette to add small amounts of water. **Plot the thermistor resistance versus temperature, with temperature along the horizontal axis. (See Data Analysis at end of lab write-up.)**

Part II Measuring the Specific Heat of Water

Now that you have calibrated the thermistor you can do the second experiment. You'll put the 1157 light lamp in a cup containing a known amount of water and measure the electric power delivered to the lamp and the rate of temperature rise of the water. This rate of rise, together with knowledge of the rate of energy input, will give you the specific heat, c_w , of the water in units of $[J/kg \cdot K]$ if you assume energy conservation during the transformation. The actual value is $c_w = 4185 J/kg \cdot K$.

Apparatus

The calorimeter is the experiment cup used previously. Fill it to a depth of 35 mm. You can mark this depth with a pen mark on the inside of the cup. Use a lid for the cup to prevent evaporation. Use your calibrated thermistor and the DMM to measure water temperature.

Before starting the experiment, stir the water with a glass thermometer, and take a temperature reading to check the correctness of your thermistor reading at one point.

Carefully fold back the wires soldered to the 1157 lamp as shown and tape over the end of the lamp base with black tape so as to insulate it electrically from the slightly conducting water in the cup. This will prevent current from flowing, which could affect the thermistor reading.

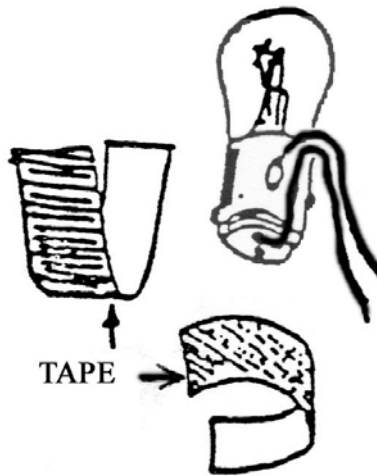


Figure 3: Heat Source

Locate the Alloy 800 resistance wire (stiff, thick, uninsulated wire of length ~ 0.3 m). It's resistance is 1.02Ω per meter of length, so the resistance of your piece is about 0.3Ω . (Your DMM is quite inaccurate in this regime, but it will indicate $0.3 - 0.5\Omega$.)

Measuring the Electric Power

Connect the 8 W filament of the 1157 lamp in series with the Alloy 800 resistance wire and the LVPS output (see sketch). Then disconnect the minus lead of the LVPS and plug in the wall transformer.

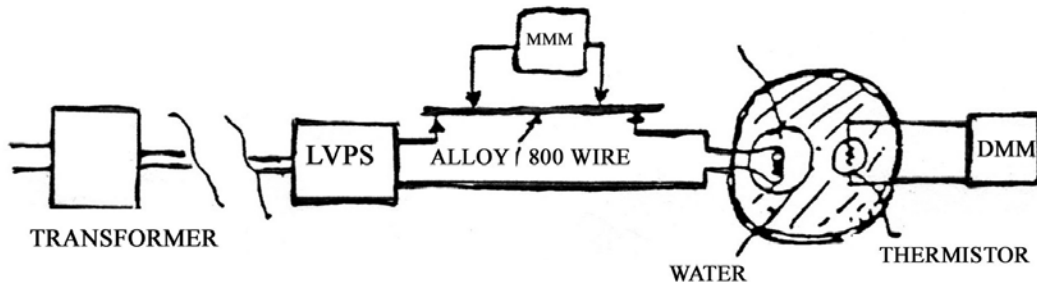


Figure 4: Circuit Diagram for Experiment ET

Use the MMM on the 25 VDC range to set the voltage of the LVPS to 10.0 V. Reconnect the minus lead of the LVPS and the lamp should light up but the regulator should keep the voltage at 10.0 V. Once the voltage is set, disconnect the MMM and rotate the MMM rotary knob to the " $50\ \mu\text{A}$ ($250\ \text{mV}$)" position on the DCA (DC Amperes) range, *not* the 250 mA position. The meter will then read 250 mV full scale; use the "250" scale on the face. Clip the MMM leads across a *carefully measured* length of the resistance wire (see sketch above), e.g. 0.25 m and **measure the voltage across this portion of the resistance wire**. Then unplug the wall transformer.

Doing the Experiment

Put water (approx. room temp.) in the cup to a depth of 35 mm. Wedge the 1157 lamp (which tends to float) in the bottom of the cup. Make a small notch in the rim of the cup for the leads and pass them through the notch bending them and taping them in place (see sketch). Put the thermistor approximately in the middle of the water on one side of the lamp, bend its leads over the rim (again with a small notch), and tape. Make sure that the thermistor doesn't touch the cup or the lamp. Allow time for the entire apparatus to come close to room temperature. The thermistor readings give the water temperature. The thermometer can be used to keep track of room temperature. (As usual, watch out for drafts and unwanted sources of light and heat).

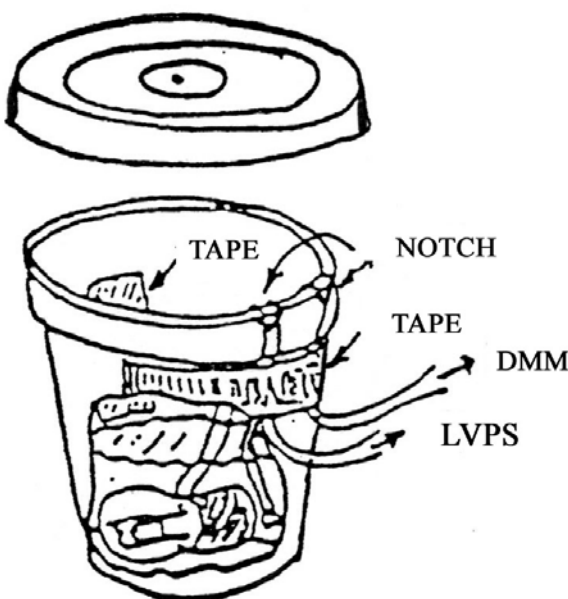


Figure 5: The Calorimeter

Press the lid onto the cup. You may need to make a few vertical cuts (say 4) around the cup rim to make it fit the lid. Work the lid on gently; a piece of tape will hold it on.

Disconnect the LVPS minus output lead. (You don't want to start heating the water until you're ready to take data.) Plug in the wall transformer, and set the LVPS output again to 10.0 V. Connect the DMM (set on the 250 mV range) across the same carefully measured points on the resistance wire.

Taking Data

Since the lid on the cup prevents you from stirring with a thermometer, you should agitate the water by moving the cup in a horizontal circle about 1 to 1.5 inches in

diameter about twice a second, reversing direction every few seconds. The electrical connections had better be firm and the wires must have enough slack.

With the transformer plugged in, but the LVPS minus lead still not connected, start agitating and read resistances every 15 seconds. **One partner should agitate the water and keep track of the time. The other partner reads thermistor resistance values and records them with the time. When the readings are steady, or changing only 0.1 or 0.2Ω, reconnect the LVPS minus lead and note the MMM reading. Continue taking data every 15 seconds for 5 minutes. After 5 minutes, disconnect the LVPS, and continue agitating and recording resistances so as to get a value for the initial rate of cooling.**

Data Analysis

Part I: Fitting the Calibration Data

The decreasing exponential can fit the plot of your thermistor data,

$$R(T) = R_0 e^{-\alpha T}$$

where $R(T=0) = R_0$ and α are constants and $R(T)$ is the resistance at Celsius temperature T . Note that R goes to 0 as T goes to 0. You can linearize this expression by taking the natural log (ln) of both sides,

$$\ln R = -\alpha T + \ln R_0$$

This becomes a linear equation if the dependent variable is taken to be $\ln R$. Your data, if truly exponential, should follow a straight line on a plot of $\ln R$ versus T .

Plot $\ln R$ versus T and fit a straight line to the data points (by eye and ruler). This yields the constants $\ln R_0$ (the intercept at $T = 0$) and α (negative of the slope). The temperature T can then be obtained from

$$T = (\ln R_0 - \ln R) / \alpha$$

for any measured value of R . Check it for a couple of the values of R you measured to see if you get the proper temperatures.

Part II Determining the Specific Heat of Water

Determining the Electrical Power of the Lamp

The measured voltage ΔV across the resistance wire allows you to deduce the current flowing in the circuit. Suppose there is 0.25 m of resistance wire between the clips on the

MMM leads, and the measured voltage across the wire is $\Delta V = 100 \text{ mV}$ (still using the "50 μA (250mV)" setting and the "250" scale on the meter face). Ohm's law then gives

$$I = \frac{\Delta V}{R} = \frac{0.10 \text{ V}}{0.25 \Omega} = 0.40 \text{ A}$$

The power dissipated in the lamp is $P = I\Delta V_L$ where ΔV_L is the voltage across the lamp, i.e.,

$$P = I\Delta V_L = (0.40 \text{ A})(10.0 \text{ V} - 0.10 \text{ V}) = 3.96 \text{ W}$$

Determining the Mass of the Water

You can estimate the mass of water in the calorimeter from its depth, d , before inserting the lamp and estimated 'average' radius (measured with one of your rulers). More precisely, use the bottom radius, r_1 , and the top radius, r_2 , of the cup and its height h . Here's the formula for the volume V of the water (can you derive it?).

$$V = \pi r_1^2 d + \pi r_1 \left(\frac{r_2 - r_1}{h}\right) d^2 + \frac{1}{3} \pi \left(\frac{r_2 - r_1}{h}\right)^2 d^3$$

For the styrofoam cup we provide, with $r_1 = 2.0 \text{ cm}$, $r_2 = 3.4 \text{ cm}$, and $h = 8.2 \text{ cm}$, this yields a volume in [cm^3]:

$$V(\text{cm}^3) = 12.6d + 1.07d^2 + 0.03d^3$$

From the measured depth d in cm and you can find the water volume V in cm^3 and the mass in grams (numerically equal, closely enough). Convert your value for the mass of your volume into kilograms. Is your answer consistent with your first estimate?

Analyzing the Data

Use the thermistor calibration to convert resistances to degrees C. Plot the temperature versus time, using an expanded ordinate scale that includes only the range of temperatures encountered, i.e., do not start the ordinate at 0°C ; start it at $\approx 20^\circ \text{C}$. Fit a straight line by eye which goes through the data points, and determine the slope dT/dt in units of [deg/s] for both the heating and cooling parts of your graph.

The quantity of heat Q required to increase the temperature ΔT of a mass m_w of water is equal to

$$Q = m_w c_w \Delta T$$

where c_w is the specific heat capacity of water.

The rate that heat is flowing in time, the power, is the time derivative

$$P = \frac{dQ}{dt} = m_w c_w \frac{dT}{dt}$$

Treat the water as a system. Electrical power flows into the water via the 8W filament of the 1157 lamp.

$$P_{in} = I \Delta V_L$$

Power also flows out of the water during the heating process via the radiant heat loss, which you can approximate by

$$P_{out} \cong m_w c_w \left| (dT / dt)_{cooling} \right|.$$

This is approximate because the radiant power loss varies as a function of temperature and we are only using the power loss after the water has already been heated.

The power absorbed by the water is

$$P_{absorbed} = m_w c_w (dT / dt)_{heating} .$$

The difference between the power in and the power out is the power absorbed by the water,

$$P_{in} - P_{out} = P_{absorbed}$$

thus

$$I \Delta V_L - m_w c_w (dT / dt)_{cooling} \cong m_w c_w (dT / dt)_{heating} .$$

From your data you can obtain a value for the specific heat, c_w , of water in [J/kg · K].

Error Analysis

Estimate the error on the slope you obtain as well as other input quantities to obtain an error for c_w . You may find that your experiment could have been done with more care regarding heat loss, agitating, etc. If so, try it again, it doesn't take long.

How serious was heat loss during your runs? (You might wish to devise a way to correct for it.) What is the approximate effect of the heat capacity of the light lamp, which has a mass of about 9 g (note that $c_{glass} \approx 1000 \text{ J/kg} \cdot \text{K}$ and $c_{brass} \approx 300 \text{ J/kg} \cdot \text{K}$)? The effect of heat absorbed by the cup mass, 1.6 g is negligible.

Experiment ET: Parts List

4	Styrofoam cups		1 ft	Resistance wire, alloy 800 (in Red box)
1	lid for same	1		#1157 lamp (in LVPST)
1	drinking straw	1		thermometer (in Red box)
1	thermistor		4	paper towels