Experiment to investigate the Factors affecting the Energy Transfer Involved in the Cooling of Water

By Clare Dutton

Introduction

Water cools in many different ways due to a variety of different reasons, which depend on the way in which the water is co ntained. I will be considering how water in a plastic cup cools. If I put hot water in a plastic cup I would expect heat to be lost by radiation from the sides and the top, conduction through the base and evaporation from the top. If however, the sides an d base were highly insulated; most heat would be lost by evaporation and radiation from the top.

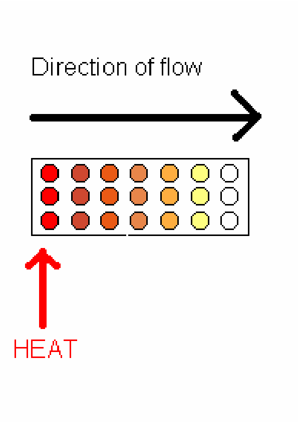
Here are the ways in which heat is lost from cooling water:

1) Radiation

Radiation is the movement of heat energy by electro -magnetic waves. These leave the surface of the object and can pass through a gas or vacuum. The hotter the surface of the radiating object the greater the rate of heat loss. The larger the surface area, the greater the heat lost by radiation. Darker surfaces radiate and absorb more than light coloured surfaces. Shiny surfaces reflect radiation. Examples of radiation are the sun radiating heat through space and a central heating radiator radiating heat into a room.

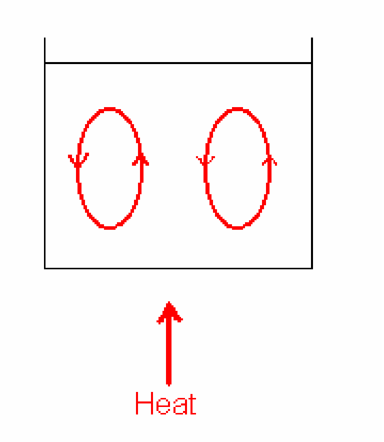
2) Conduction

Conduction can take place in solids, liquids and gases. Wh en a material is heated the particles nearest to the heat gain kinetic energy. They then start to vibrate faster due to this energy and as they do they touch other particles and transfer the kinetic energy to them. This process is repeated and the energy is transferred through out the object from hot regions to cooler regions. As the water looses heat from the sides of the cup conduction will cool the mass of the water. Conduction will also occur through the walls of the cup and then radiate and through the base of the cup into the surface on which the cup stands.



3) Convection

When a liquid of gas is heated (convection can not take place in solids), the molecules move faster and push each other further apart. The fluid expands and becomes less dense. The less dense fluid then rises upwards taking its thermal energy with it. This rising fluid is then replaced by cooler fluid and a convection current is set up. Thermal energy is transferred by the molecules themselves moving from the hot region to the c ooler one.



As the water nearest the sides of the plastic cup cools due to radiation, convection with in the water will cool all the water.

4) Evaporation

When water is heated the molecules gain kinetic energy and move around very quickly. Some of these molecules manage to gain enough energy to break free from the liquid. This process is called evaporation. As the water evaporates it takes away some of the thermal energy. As the temperature of water increases the molecules gain more and more e nergy so the rate of evaporation also increases.

Evaporation can be reduced by sealing the top of the plastic cup with a very small air space above the water. The water vapour will then condense and drip back into the water.

5) Temperature differential

The difference in temperature between room temperature and the temperature of water can alter the rate of which the water cools. If there is a big difference and the water is very hot and the room temperature is fairly low then the rate of cooling will be much larger than if the temperatures were very close together.

6) Insulation

Insulation is a material with low conductivity which is used to reduce the amount of heat lost from a hot object such as a hot water tank. By wrapping the plastic cup with insulation the rate of conduction through the wall of the cup will be reduced. Air is a very good insulator and so many insulators have small air pockets with in them which can prevent large convection currents being set up.

7) Energy

The thermal energy of water can be calculated by measuring the volume of water and its temperature.

The energy change = the specific heat capacity × mass × temperature change

The specific heat capacity of water is 4200 Joules per Kg per °K

For example to heat up 1kg of water by 10 °C would require:

4200 × 1× 10 = 42000 Joules.

The energy loss can then be calculated by measuring the reduction in temperature provided the volume of water remains unchanged.

Plan

I have chosen to investigate the effect of insulation o n the rate of energy loss from the water because it is more easily measured than the other factors. By increasing the thickness of insulation surrounding the water, I can measure the rate at which heat is lost from the water for different thicknesses and determine the relationship between the rate of heat loss and the thickness of insulation. To do this I will need to reduce the loss of heat by evaporation by sealing the top of the container.

In this experiment heat will be conducted through the insulatio n and then radiate into the air. The amount of radiation will change because the surface temperature of the insulation will reduce as the insulation becomes thicker and the external surface area of the insulation increases due to the extra thickness around a circular cup.

Experiment to investigate the effect of insulation on the rate of heat loss from a plastic cup of water

Aim: To investigate the change in the rate of heat loss from a plastic cup by varying the thickness of insulation surrounding the c up and to see if there is a relationship between the rate of heat loss and the thickness of insulation.

Apparatus

Item	Purpose
Plastic cup	To contain the water
Thermometer	To measure the temperature of the water
Digital Timer	To allow measurement of the temperature at regular intervals
Kettle	To heat the water
Measuring cylinder	To measure the quantity of water
Expanded polystyrene sheet insulation used for lining walls under wallpaper. 2mm thick	To wrap around the cup in layers to insulate it
Cling film	To seal the top of the cup from evaporation
Sellotape	To hold the insulation around the cup
Clamp stand and cotton	To suspend the thermometer in the water so that it does not touch the sides or bottom
Foam mat 20mm thick	To stand the cup on so that heat is not lost through the base
Water	
Ruler	To measure thickness of 10 layers of insulation to determine the average thickness.

Preliminary experiment

In order to determine the probable range of results it was necessary to carry out a preliminary experiment by filling the plastic cup with water and measuring how long it took to cool. The following information was found.

1. The quantity of water to fill the cup to leave only a small air space at the top.
2. The starting temperature of the water in the cup was found to be about 85°C so it was decided to start reading the temperatures once the temperature had fallen to 80°C
3. It as found that it took about 25 minutes for the temperature to fall to 60°C with no insulation. With thick insulation it woul d take much longer so it was decided to monitor the temperature for 30 minutes to give a good range of results.
4. It was found that it would be sufficient to take readings at one minute intervals. Otherwise at high levels of insulation the variation in temperature would be very small.
5. It was found that it was possible to measure read the temperature on the thermometer to an accuracy of about 0.25 C.
6. The preliminary experiment confirmed that the set up of the apparatus was correct with the thermometer at the right level and easy to read and that using a digital clock it was possible to time the readings accurately.

Prediction

I would expect that the rate at which the water cools to reduce as the insulation becomes thicker.

While insulation is supposed to s top heat loss it will still act as a conductor of heat. The amount of energy transferred through a conductor is proportional to the thermal gradient. By doubling the thickness of insulation the thermal gradient is halved. So I would expect the energy lost though the insulation to reduce to half.

Insulation has a 'strength' to prevent heat loss which is measured as its 'U' value. The U value is measured as Watts per m² per °C and is for a given thickness of insulation. Double the thickness and the U value will halve.

Rate of heat loss = U value × surface area × temperature difference. So if the insulation doubles in thickness, the U value will halve and the rate heat loss will halve.

Diagram

Method

Room temperature was taken using the thermometer which had been allowed to adjust to the room temperature and this was recorded.

The apparatus was arranged so that a plastic cup stood on a layer of foam insulation with a thermometer suspended from a clamp stand so that the bulb of the thermometer would be hung in the middle of the water in the cup.

For the first test no insulation was wrapped around the cup. For the later tests, layers of insulation were tightly wrapped around the cup using sellotape so that once the air was trapped between them none could escape. This was also done to the base of the cup.

The kettle was boiled and $150ml^3$ of hot water was measured out using the measuring cylinder. This was then poured into the plastic cup. A piece of cling film was then stretched over the top of the cup to form a seal so that no evaporated water could escape. Square pieces of insulation (bigger than the cup) were placed on top of the cup. The number of squares depended on the number of layers of insulation being tested. A hole was pierced through the centre of the lid. A thermometer was then suspended using cotton and the clamp stand and then pushed through the hole so that the end hung in the centre of the cup. The lid was then taped down securely.

When the temperature had fallen to 80 ° C, the stop clock was started and the temperature of the water was taken every minute for 30 minutes. The results were recorded.

After the first test, the cup was emptied and two layers of insulation were fixed around the cup as described above. The test was then repeated for the two layers of insulation. Further tests were then carried out for 4, 6, 8 and 10 layers of insulation. All results were recorded.

Room temperature was taken again at the end of the experiment to see if it had varied.

The average thickness of the insulation was measured by measuring 10 layers and dividing the result.

Fair test

- The thermometer was suspended so that it did not touch the sides of the cup so that the reading was the temperature of the centre of the water.
- Taking room temperature before and after the experiment to see if there had been any change which would affect the results of the experiment.
- The same volume of water was used in each test.
- The layers of insulation were fixed in the same way by the same person each time.
- By repeating the test for a wide range of thicknesses of insulation anomalies would show up as the results are plotted.

Safety

- Safety glasses were worn to protect our eyes from splashes of hot water.
- Gloves were worn to protect hands from the hot water
- Laboratory coats were worn to help protect our bodies from the hot water.
- We stood up so that if the water did spill we could move away quickly
- The experiment was done under supervision.
- The thermometer was suspended so that there was no risk of dropping it.
- The apparatus was set up in a position where it could not easily be knocked over.

Results

Room temperature at start of experiment = 22.5°C
Room temperature at end of experiment = 23.0°C

Table 1 – Temperature change for varying thicknesses of insulation.

Time in Minutes	Temperature in °C					
Layers	0 layers	2 layers	4 layers	6 layers	8 layers	10 layers
0	80.00	80.00	80.00	80.00	80.00	80.00
1	78.50	79.75	80.00	79.00	80.00	79.25
2	77.00	79.00	79.25	78.75	79.00	78.50
3	76.00	78.50	78.75	78.25	78.75	78.00
4	75.25	77.75	78.25	78.00	78.50	77.50
5	74.25	77.25	78.00	77.50	78.00	77.25
6	73.00	76.75	77.25	77.00	77.75	76.75
7	72.50	76.25	77.00	76.75	77.23	76.50
8	71.75	75.75	76.50	76.50	77.00	76.00
9	70.75	75.25	76.00	76.00	76.75	76.00
10	70.00	75.00	75.50	75.75	76.25	75.50
11	69.25	74.50	75.00	75.25	76.00	75.00
12	68.50	73.75	74.75	75.00	75.75	75.00
13	68.00	73.25	74.50	74.75	75.25	75.00
14	68.00	72.75	74.00	74.50	75.00	74.25
15	66.00	72.25	73.50	74.00	75.00	74.00
16	65.25	71.75	73.00	73.50	74.75	73.75
17	65.00	71.25	72.76	73.25	74.25	73.50
18	64.25	70.75	77.25	73.00	74.00	73.25
19	63.50	70.25	72.00	72.50	73.75	73.00
20	63.00	70.00	71.50	72.00	73.50	72.75
21	62.25	69.50	71.00	72.00	73.00	72.50
22	62.00	69.00	70.75	71.50	73.00	72.25
23	61.00	68.50	70.25	71.00	72.75	72.00
24	60.25	68.00	70.00	71.00	72.50	71.75
25	60.00	67.50	69.75	70.50	72.00	71.25
26	59.50	67.00	69.50	70.00	72.00	71.00
27	58.75	66.75	69.00	70.00	71.75	71.00
28	58.00	66.00	68.75	69.75	71.25	70.75
29	57.50	65.75	68.50	69.50	71.00	70.50
30	57.00	65.25	68.00	69.00	71.00	70.25

Energy loss after 30 minutes in Joules	14490	9292	7560	6930	5670	6142

Table 2 – Temperature change at 10 minute intervals

Time in Minutes	Temperature in °C					
Layers	0 layers	2 layers	4 layers	6 layers	8 layers	10 layers
10	10	5.00	4.5	4.25	3.75	4.5
20	17.00	10.00	18.50	8.00	6.5	7.25
30	23.00	14.75	12.00	11.00	9	9.75

Conclusion

The results in Table 1 are shown graphically in Fig.1.

Room temperature changed only slightly, so it will not have affected the results.

From Fig 1 it is clear that the rate of heat loss from the water is reduced by increasing the amount of insulation. With no insulation the temperature fell by 23 °C in 30 minutes. With two layers this reduced to 14.75°C in 30 minutes.

Figure 1 shows that by adding more and more layers of insulation the reduction in energy reduces to a point where it changes very little and may even increase.

Figure 1 also shows that the rate of loss o f heat is almost a straight line but there is a slight curve. This is most clearly seen from the curve with no insulation. This is because; as the water cools the temperature differential between the water and room temperature reduces so the energy loss wi ll reduce. The curves for the insulation are straighter because the change in temperature differential is less.

Table 2 compares the reduction in temperature at 10, 20 and 30 minutes for the various thicknesses of insulation. Fig. 2 shows that the reduct ion in temperature reduces with the number of layers to a low point at about 8 layers and it rises again a little for 10 layers. This is not what I expected in my prediction. This is because of radiation. Insulation can be used to prevent heat loss however it does not prevent heat loss by radiation. Heat which does get through the insulation will be radiated away. The amount of radiation will depend upon the temperature differential between the outside surface of the insulation and room temperature. As the insulation gets thicker less heat passes through and the outside temperature is lower so the amount of radiation should reduce. However, with a circular cup, the surface area of the insulation increases so the amount of radiation also increased and this ma y be what is stopping the reduction in heat loss. The surface area without insulation is approximately 250 cm². The surface area with insulation is 620 cm² which is 2.48 times as much.

The experiment suggests that there is an optimum thickness for the in sulation

Evaluation

Accuracy

Figure 1 shows the curves for the temperature readings. Some of the points do not fit on the smooth 'best fit' curve which could be drawn through the points. This shows that there was an error in the readings for thos e points. However, the errors are not sufficient to affect the overall conclusions.

Table 3 shows the temperature steps between each reading and Fig 3 shows the irregularities for three of the tests.

With this experiment it is not possible to retake or d ouble check readings because the temperature keeps changing. If money were no expense, it would be better to use an automatic measuring system where a computer records the readings at the exact interval rather than allowing for human response. A digital th ermometer would be used to record the temperature because it could readings of 0.1 of a degree rather than 0.25.

From the results in Fig 1, I can see that the time at which the clock is started at 80°C is very critical because the temperature is only fal ling at about ½ a degree Celsius per minute. This could lead to an error of about 2 minutes. This could possibly explain the discrepancy between 8 and 10 layers.

Further investigation

I would like to investigate the effect of adding even more insulation to see if the rate of loss of energy increases due to the increase in surface area increasing the amount of radiation. I would do this because as you can see in Fig 2. The curve begins to slope up showing an increase in change of temperature. I would like to investigate this further and see if this trend continues with more layers of insulation.

The experiment could also be repeated for different temperature ranges between the water and room temperature.

CALCULATIONS

Calculation of the surface area of insulation.

With no insulation, the outside of the cup is approximately a cylinder of 6.5cm diameter and 9.0cm high.

The surface area =

$2 \times 6.5 \times 6.5 \times \pi / 4 + 6.5 \times \pi \times 9.0 = 66.3 + 183.7 = 250.0$ cm²

With 10 layers the outside is a cylinder of 10.7cm diameter and 13.1cm high.

The surface area =

$2 \times 10.7 \times 10.7 \times \pi / 4 + 10.7 \times \pi \times 13.1 = 179.7 + 440.1 = 619.8$ cm².

Calculation of energy loss

Volume of water	=	150ml
Specific heat capacity of water	=	4200 Joules/kg/ °C

Therefore energy loss per °C = 4200 × 150 /1000 = 630 Joules.