The cooling rate of a fluid

As soon as a cup of hot coffee is poured, Newton's Law of Cooling states that the rate of change of the temperature of an object is proportional to the difference between its own temperature and the ambient temperature (i. e. the temperature of its surroundings).

Stated simply mathematically:

dy = k(y-C)

dx

Where y represents the object's temperature, x represents time, C is the surrounding temperature, and k is proportionality constant.

By finding out how water cools we can determine when it is best to add milk to a cup of coffee to bring it to its optimal drinking temperature.

Introduction to the theories behind the experiment

Research is needed into the principles and theories behind any experiment before it is undertaken, so as it can be properly understood. A prediction for results can therefore be made, so as any anomalous results can be spotted. Research is also needed into the equipment that will be used so as that it to may be fully understood and therefore used in the correct manner. This will help to reduce the risk of carrying out an experiment that will produce anomalous results and/or results that have a lot of error in them.

Heat can be lost and gained by bodies, and ultimately transferred through varying media mainly by four main methods. All of these methods involve the transference of energy from areas of high to areas of low concentration.

* Thermal radiation. Thermal radiation is the emitting of energy by a body with greater energy than its surroundings in the form of electromagnetic waves.

* Evaporation. Evaporation is the process by which energy is transferred through a body to its surface molecules so that they may change to gaseous state and leave the body. The act of the newly vaporised particles leaving the body removes energy from the body and therefore transferring it elsewhere cools the body.

* Convection. Convection involves the heating of molecules in a fluid so that they rise through similar but cooler molecules, allowing more cool particles to move into the position where they may gain energy and in turn rise. This results in energy spreading across a concentration gradient so that both sides become equal.

* Conduction. Conduction is the spreading of heat energy through a body from areas of high to areas by interaction of adjacent electrons and molecules. For example, metals have high conductivity as they have many free electrons with which to transfer energy.

We can measure the temperature of the coffee using a thermocouple.

A thermocouple is composed of two pieces of dissimilar metal wire that are connected together in one or more places. For the purposes of this investigation a two-junction thermocouple will be used where there are two junctions between the dissimilar metals.

These two dissimilar metals create a measurable electromotive force that is determined by the metals used and the temperature of the surroundings that the junctions are in, or the difference in temperatures that the junctions are subjected to, depending on whether a one or more junction thermocouple is used. This is known as the thermoelectric effect. By placing one of the thermocouple junctions in water with ice in it we can fix the ambient temperature of that junction to 0ï¿½C. This is because the ice absorbs any energy input into the water, and if energy is removed then water gets converted into ice. As this junction is at a fixed temperature it acts as a reference point, and so the electromotive force that is measured across the entire thermocouple is directly related to the difference in temperatures between junctions.

Thermocouples are exploited widely throughout the world of science and industry, as they are accurate devices for measuring temperatures, are cheap to produce, easy to use and can be made to withstand a variety of environments including those that are potentially hazardous. They are also accurate temperature measuring devices as they can be made accurately and have a fast response time and have a low heat capacity, so do not affect their surroundings temperatures. It is for the aforesaid reasons that I will be using a thermocouple in this experiment.

Newton’s law of cooling, as it has been previously stated, dictates that the rate at which a body heats up or cools down is proportional to the difference between its temperature and its surrounding’s temperature.

Also, the rate of cooling of a body is related to the area through which cooling may take place and the thickness of the material the vessel is made from.

From the initial formula we arrive at:

Q ? A? t Q= heat energy t= temperature A= area

1 ? x k= constant x= thickness ?= change in

Heat energy can also be defined in terms of specific heat capacity. The specific heat capacity of a substance is defined as the amount of energy required to raise one gram of a substance through one degree Celsius and can be given the units Jg-1ï¿½C-1 (joules per gram per degree Celsius). The change in heat is equal to the mass of the body multiplied by its specific heat capacity multiplied by the change in temperature experienced by the body, or:

? Q= m x c x ? t m= mass c= specific heat capacity

It becomes clear at this stage that these ideas can be rearranged and equated, so:

? Q ? -kA . (t1-t2)

? t m x c x (x)

This is a better overall formula as constants such as the thickness of container, temperature difference, surface area and volume are accounted for and it displays the pivotal relationship that states how temperature drop is proportional to these constants.

Cooling is a function that is similar to the exponential graphs for events such as population growth, although the graph for cooling has a negative gradient and never reaches the x axis since it cannot cool to 0ï¿½C without any energy input under standard conditions.

Experiment Preparations

Using a thermocouple to take information from cooling water will result in a set of data where time is related to voltage (mV). To convert these voltages into temperatures a means of conversion is required.

To obtain a means of converting voltage readouts to temperatures, we first had to calibrate the thermocouple.

To do this, boiling water was put in to a test tube that was sitting in a water bath containing 200 ml of water. In to this test tube were also placed a thermometer and one thermocouple junction. The other thermocouple junction was placed in a beaker containing ice and water. The addition of ice to the water in the vessel without the test tube a stable environment for that junction was created, and it stays naturally at 0ï¿½C and so can be used as a reference point for voltage readouts. Across the thermocouple a voltmeter with a suitable millivolt scale was connected to that the size of the potential difference and therefore electromotive force could be measured. By doing this with identical equipment, specific voltages can be determined for fixed temperatures and so provide a means of comparison for the experiment measuring the cooling of the water.

The apparatus was as follows.

(see next page)

The results of this experiment are set out in the table below.

Temperature (ï¿½C)

Potential difference (mV)

100

4. 2

80

3. 3

70

2. 9

60

2. 4

50

2. 1

40

1. 6

30

1. 2

From this set of results a graph can be plotted that will allow us to see if there are any anomalies in the results and therefore if the experiment needs to be corrected and re-done. It will also allow easy conversion from millivolt readings to temperatures in ï¿½C.

(see next page for graph)

The Experiment

To measure the rate of cooling, water was heated to 100ï¿½C and put it straight into a test tube in a water bath, which contained one thermocouple junction. The other junction was in a bath of ice and water to keep it at a fixed 0ï¿½C so it could therefore be used as a reference point for voltage readouts. Across the thermocouple a voltmeter with suitable millivolt scale was connected so the potential difference and therefore electromotive force could be measured. As with the ice regulating the temperature of the fixed thermocouple junction, the water bath should help maintain a static ambient temperature around the subject test tube. This should reduce errors in the experiment through forced convection and heat being transmitted from and to the test tube as the water bath acts as a barrier around the subject test tube, maintaining a static environment.

By fixing the amount of water in the water bath and the amount of water of which the cooling rate will be measured, as well as the material of the containers are constructed from a fair test is ensured and constants are preserved.

The apparatus was as follows.

The results from the experiment are presented in the table below.

Voltage (mV)

Time 1

(Seconds)

Time 2

(Seconds)

Time 3

(Seconds)

Average time (Seconds)

4. 2

0

0

0

0

4. 1

1

1

1

1

4. 0

2

2

2

2

3. 9

3

3

3

3

3. 8

4

4

4

4

3. 7

5

5

6

5. 3

3. 6

6

6

7

6. 3

3. 5

7

7

8

7. 3

3. 4

8

8

10

8. 6

3. 3

9

9

12

10

3. 2

10

10

13

11

3. 1

12

12

15

13

3. 0

13

13

16

14

2. 9

14

15

18

15. 6

2. 8

16

16

20

17. 3

2. 7

19

18

21

19. 3

2. 6

24

24

22

23. 3

2. 5

27

32

27

28. 6

2. 4

30

37

30

32. 3

2. 3

40

40

34

38

2. 2

43

43

38

41. 3

2. 1

47

48

42

45. 6

2. 0

53

53

47

51

1. 9

65

58

51

58

1. 8

81

65

59

68. 3

1. 7

82

80

64

75. 3

1. 6

93

90

84

89

1. 5

110

116

90

105. 3

1. 4

128

129

111

122. 6

1. 3

176

175

144

165

1. 2

271

241

237

249. 6

From these voltage results we can use the calibration graph to determine temperatures in ï¿½C at given time intervals.

Average time (Seconds)

Temp

(ï¿½C)

0

100

1

99

2

98

3

96

4

92

5. 3

90

6. 3

88

7. 3

86

8. 6

84

10

80

11

78

13

76

14

74

15. 6

71

17. 3

68

19. 3

66

23. 3

64

28. 6

62

32. 3

59

38

56

41. 3

54

45. 6

52

51

49

58

46

68. 3

44

75. 3

42

89

40

105. 3

37

122. 6

34

165

32

249. 6

30

We can now plot a graph of temperature against time.

(See next page)

Newton’s law states that the rate of heat loss is proportional to the temperature difference between the temperature of the body and the ambient temperature (the temperature of the surroundings).

This can be re-stated that the gradient of the graph of temperature against time is proportional to t1-t2 where t1 is the temperature inside the test tube and t2 is the temperature outside the test tube.

So if t2 is 20 and t1 is 60, m (the gradient of the graph) ? 40.

By plotting a graph of the gradients of the tangents of the graph showing cooling against temperature difference we can determine whether the rate of heatloss is proportional to the temperature difference between the temperature of the body and the ambient temperature.

If proportionality between these two factors is displayed then the graph should be straight and pass through the origin.

First a graph of the gradients of all the tangents against the temperature difference these tangents were taken from was plotted.

The data used for the first graph is as follows.

Temperature Difference (ï¿½C)

Gradient

72

1. 5

60

0. 7

28

0. 3

19

0. 15

16

0. 1

(see next page for graph)

This graph proved inconclusive as the plotted points showed no conclusive correlation. This lack of direct correlation can be traced back to inaccuracies during the taking of measurements. As the rate of cooling was rapid to begin with (the gradient at the beginning was large and negative), the accuracies for the times of each voltage drop were low as there were so many changes in a small space of time.

However, if we take gradients from later on in the experiment the accuracies for the times will be better as the percentage of error will be smaller.

Data for this graph is as follows.

Temperature (ï¿½C)

Gradient

20

0. 14

16

0. 11

15

0. 08

14

0. 15

13

0. 09

(see next page for graph)

This graph shows a much stronger correlation that is as predicted. Anomalies in this graph can be attributed to the fact that the area on the graph that the gradients were taken from had a generally small overall gradient. This means that to get an accurate tangent drawn to the curve is difficult, and so there is a chance for a large percentage of error. However, the direct correlation of many of the plotted points on the graph means that the graph can be taken as correct along the line of correlation.

We can therefore conclude that the rate at which a body cools is proportional to difference between its temperature and the ambient temperature.

Related to the introduction of this investigation, we can conclude that the best time to add milk to a cup of coffee to get it to drinking temperature as soon as possible is as soon as it is poured, i. e. when time= 0, as this is when it is cooling most rapidly and so introducing a cooler liquid will increase this rate of cooling.

Extension work

The same experiment as for the main body of this investigation can be again conducted, but at a certain interval a sample of cold water can be introduced into the warm water that is cooling. This will affect the rate of cooling, but if the spread of heat through the resultant liquid to even temperature is instant then the graph should be the same as for the cooling of the liquid previously in this investigation.

The apparatus used for this experiment will be the same as for the straight cooling experiment, but two 3 ml pipettes will be used to swap, at the same time, 3 ml of water from the ice bath with 3 ml of water from the test tube containing the hot water.

The results for this experiment are as follows.

(see next page)

Voltage (mV)

Temperature (ï¿½C)

Time (s)

4. 2

100

1

4. 1

99

2

4. 0

98

3

3. 9

96

5

3. 8

92

8

3. 7

90

12

3. 6

88

15

3. 5

86

17

3. 4

84

20

3. 3

80

22

3. 2

78

26

3. 1

76

29

3. 0

74

32

2. 9

71

37

2. 8

68

39

2. 7

66

42

2. 6

64

45

Water was swapped————————————————————————————————

1. 8

44

50

1. 7

42

52

1. 6

40

57

1. 5

37

79

1. 4

34

92

1. 3

32

108

1. 2

30

127

In theory, the spread of heat energy from the hot water to the newly introduced cold water will be instantaneous, and so there should be a drop at the time of the cold water was introduced.

However, the spread of heat will not be instantaneous, and so the drop will not be vertical but merely steep.

(see next page for graph)

As we can see, the graph for swapping water over has the same gradient as the graph for straight at any given point before adding the water, and is parallel to the straight cooling graph after adding the water, with the same gradient.

We can therefore deduce that Newton’s law of cooling holds true when there are affecting factors other then the four methods of heat transfer discussed at the beginning of this report, Thermal radiation, Evaporation, Convection and Conduction, affecting cooling.