A simple experiment to study cooling by convection and radiation

Colm O'Sullivan (IE)

Department of Physics, National University of Ireland Cork, Cork (IE)

All convective cooling processes involve a contribution from radiative cooling. The experiment described enables students to study the magnitude of this effect at different temperatures.

1 Introduction

Heat transfer processes play an important role in science and engineering and, accordingly, form part of the curriculum in physics courses and textbooks in schools and universities [1]. In particular, students need to understand the mechanisms by which heat is lost to the surroundings in laboratory bench-top experiments in thermal physics, such as in calorimetric measurements. Even when care is taken to provide thermal insulation, heat losses from convection and radiation can never be completely eliminated. Corrections for such heat loss can be carried out [2] but in such cases the details of the cooling mechanisms need to be well understood.

2 The experiment

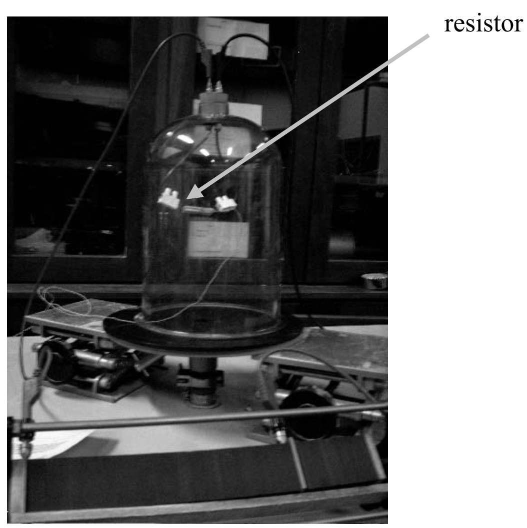

Figure 1: Picture of the apparatus

A convenient way to investigate both convective and radiative heat transfer is shown in figure 1. The body under investigation is a ceramic resistor (typically 10 Ω) through which a steady electric current can be passed; a 12 V power capable of delivering up to 1 A d.c. and a 0 – 20 Ω rheostat connected in series with the resistor prove suitable. The temperature of the resistor is monitored by a K-type thermocouple (0 – 250 °C) in thermal contact with the surface of the resistor and interfaced to a data acquisition system [3]. Since the surface area of the resistor needs to be determined, the resistor should have regular shape (approximately 7 mm x 7 mm x 30 mm parallelepiped in the case described below).

The resistor with the attached thermocouple are placed in a bell-jar (figure 1) which may be evacuated when required. Cooling of the resistor when suspended in vacuum is predominantly by radiation (possibly with a small contribution from thermal conduction through the electric wires). Using the rheostat to control the current flowing in the resistor enables the temperature of the resistor to be raised to any selected value up to the maximum range of the thermocouple. Having switched off the current once steady state conditions have been reached, cooling curves are recorded by the data acquisition system for four different cooling environments, viz.

(1) cooling in vacuum
(2) natural cooling within the bell-jar enclosure (without evacuation)
(3) natural cooling in the laboratory (bell-jar removed)
(4) forced cooling in the laboratory as a result of a constant flow of air directed at the resistor by a fan

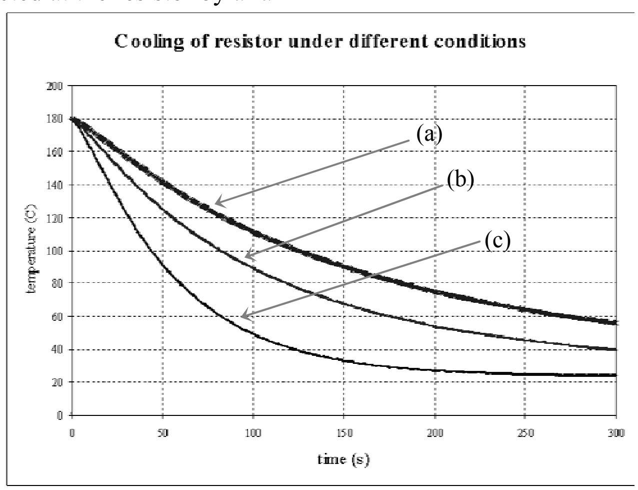

Figure 2: Cooling curves for (a) cooling in vacuum, (b) natural cooling and (c) forced cooling

In practice, if strong draughts can be eliminated, little difference is observed between environments (2) and (3). Figure 2 shows typical cooling curves obtained for situations (1), (2) and (4). It is immediately clear from the plots that, at least in this situation, the contribution from radiative cooling is significant.

3 Contribution from cooling by radiation

An estimate of the relative amount of contribution from radiative cooling to both the natural and forced cooling processes may be obtained by determining the electrical power required to maintain the same steady current in each case. Typical calculations (table 1) indicate that the contribution from radiation to each process are in excess of 60% and 30%, respectively, at 180 °C.

Table 1: Electrical power required to keep 10 Ω resistor at 180 °C

	current / A	power / W	% radiation
cooling in vacuum	0.57	3.2	100%
natural cooling	0.71	5.0	64%
forced cooling	0.92	8.5	38%

Such large contribution from radiation may surprise pupils who have investigated Newton's law of cooling in a previous context. This law, which is used to describe cooling processes in which convection dominates, assumes that the rate of heat loss from a body is proportional to the difference temperature of the body and that of the surrounding air. This assumption predicts an exponential cooling curve. In the case described here (> 60% contribution from radiation), however, the observed cooling curve is also fitted quite well by an exponential function (figure 3). Students may be persuaded that such observation merits further detailed investigation.

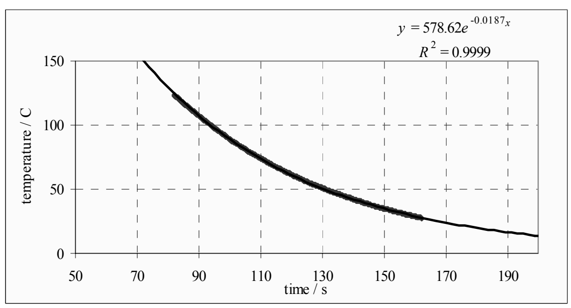

Figure 3: Exponential curve fitted to data for natural cooling

4 Use of *dT/dt* versus *T* plots

Radiative cooling is described by the Stefan-Boltzmann law which states that the rate of heat loss per unit surface area of a body at temperature T is proportional to $T^4 - T_s^4$, where T_s is the mean temperature of the surrounding radiation sources. In most laboratory experiments T_s can be taken to be the same as the temperature of the surrounding air. Thus the combined rate of heat energy loss from a body of surface area S due to both convection and radiation is $hS(T - T_a) + \varepsilon\sigma S(T^4 - T_s^4)$, where the constant h is the 'heat transfer coefficient' for pure convection and depends on the cooling conditions (speed of the air flow over the surface, shape of the body, etc.), ε is the emissivity of the surface and σ is the Stefan-Boltzmann constant. Thus the rate of change of temperature of the body is given by

$$\frac{dT}{dt} = \frac{hS}{C}(T - T_{\text{air}}) + \frac{\varepsilon\sigma S}{C}(T^4 - T_s^4) \qquad (1)$$

where $C = \Delta Q/\Delta T$ is the heat capacity of the body.

Since there is no prospect of integrating equation (1) to obtain an analytical time-dependence of temperature, cooling curves cannot be used directly to analyse the experimental data. Because of the nature the equation, however, it would seem to be productive to concentrate the data analysis on the variation of *dT/dt* with temperature. *dT/dt* versus time behaviour can be determined from the cooling curves by invoking, for example, the SLOPE(y2;y1,x2;x1) function in Excel.

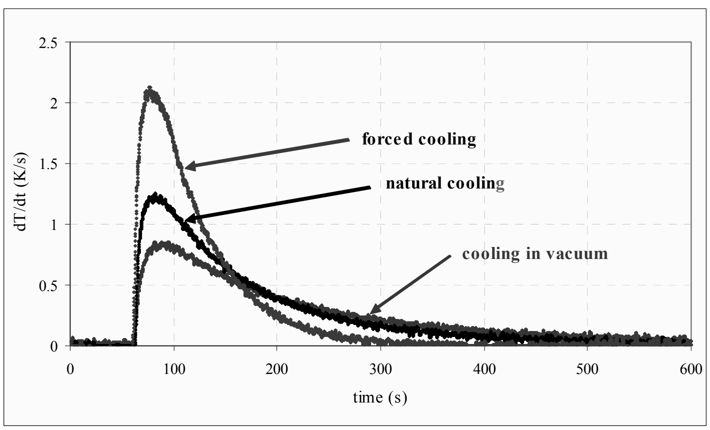

Figure 4: Rate of fall of temperature plotted as functions of time

Figure 4 shows *dT/dt* curves plotted as functions of time for the cooling conditions studied. It can be seen that after the current has been switched off it takes up to 30 s for thermal equilibrium to be established within the resistor; thus only data to the right of the 100 s mark is used in the analysis. This data can now be used to generate *dT/dt* versus temperature plots for all three cooling conditions (figure 5). Since *dT/dt* is directly proportional to the rate of change of heat energy, the data in figure 5 can also be used to determine the fraction of heat energy lost due to radiative cooling in each case (figure 9); the results are consistent with the values obtained from electrical power considerations described above.

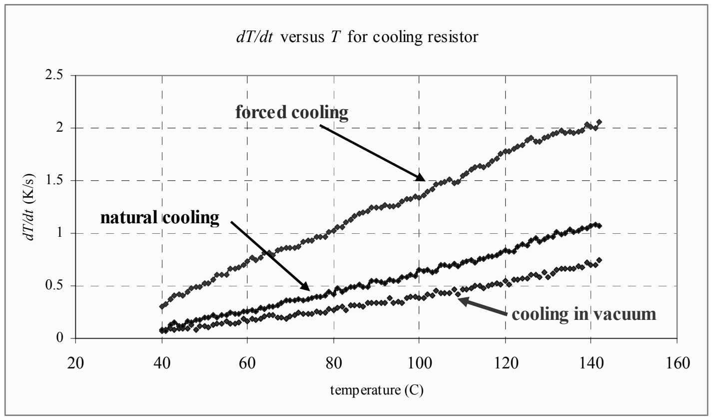

Figure 5: Rate of change of temperature plotted as functions of temperature

5 Purely convective cooling

The fraction of cooling due to radiation can now be subtracted from the observed rates of cooling to determine the contribution to the cooling process from true convection. Since the observed rate of heat energy loss is given by

$$\left(\frac{dQ}{dt}\right)_{\text{observed}} = \left(\frac{dQ}{dt}\right)_{\text{convection}} + \left(\frac{dQ}{dt}\right)_{\text{radiation}}$$

then

$$\left(\frac{dQ}{dt}\right)_{\text{convection}} = \left(\frac{dQ}{dt}\right)_{\text{observed}} - \left(\frac{dQ}{dt}\right)_{\text{radiation}} = C\left(\left(\frac{dT}{dt}\right)_{\text{observed}} - \left(\frac{dT}{dt}\right)_{\text{radiation}}\right)$$

and so for pure convection

$$\left(\frac{dT}{dt}\right)_{\text{observed}} - \left(\frac{dT}{dt}\right)_{\text{radiation}} = \frac{hS}{C}(T - T_{\text{air}})$$

The corresponding *dT/dt* dependence on temperature determined in this way is shown in figure 6 for both natural cooling and forced cooling. As expected the results are consistent with linear behavior in both cases. A linear curve-fitting routine can be invoked from which the constant of proportionality (*hS/C*) may be extracted (see figure 6).

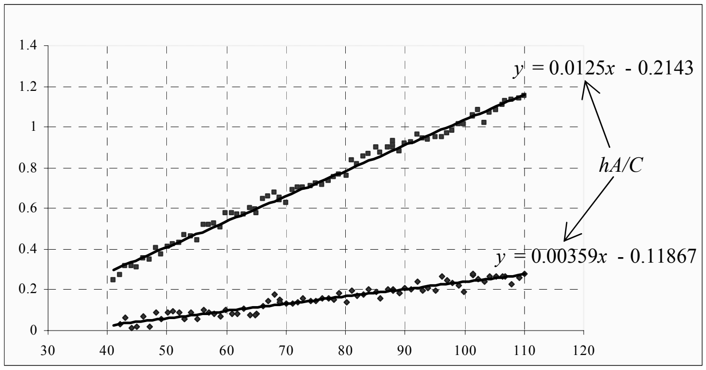

Figure 6: Linear fits to *dT/dt* versus *T* curves for forced cooling (above) and natural cooling (below)

The heat capacity of the body may be determined from a heating curve like that in figure 7.

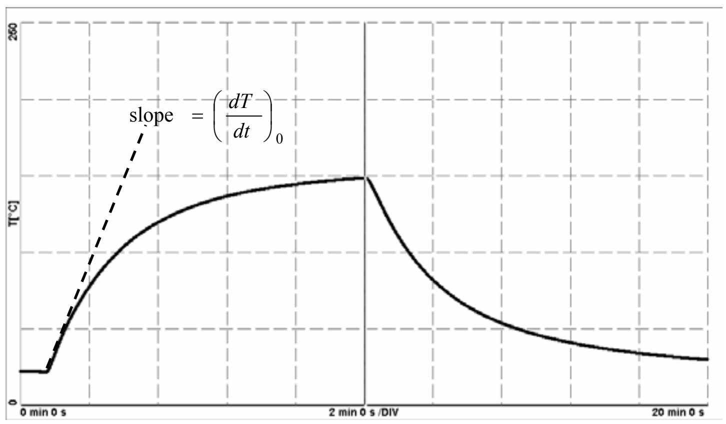

Figure 7: The heat capacity of the resistor is determined from a heating curve

At the instant when the current is switched on there is no energy flow due to cooling. Thus, at this moment, the electric power is balanced by the rate of heating, that is

$$\left(\frac{dQ}{dt}\right)_0 = C\left(\frac{dT}{dt}\right)_0 = RI^2$$

Thus the value of the heat capacity of the resistor can be determined from the slope of the temperature-time plot at the instant that the current begins to flow. Provided that the resistor has a regular shape its total surface area (S) can be determined by geometric measurement. Thus the 'true' heat transfer coefficient due exclusively to convection may be calculated.

6 Comparison with theory

The rate of drop in temperature resulting from the combination of convection and radiation is given by equation (1). Using the values of h, S and C determined as described above and putting $\varepsilon = 1$ and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, theoretical dT/dt versus T curves for all three cooling processes investigated may be plotted and compared to the observed experimental results (figure 8). Good agreement, within the accuracy of the experiment, is observed.

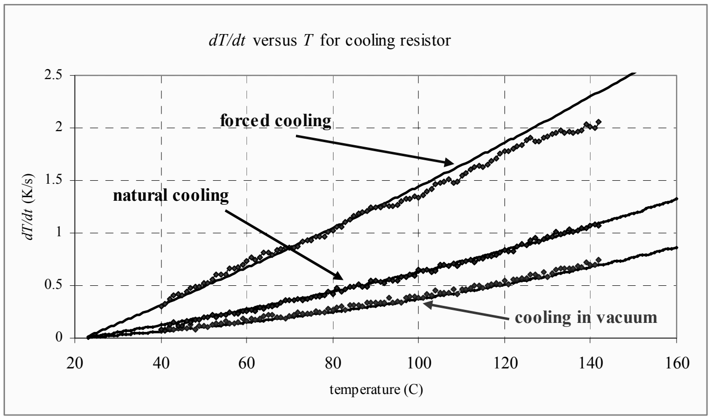

Figure 8: Comparison of theory and experiment for *dT/dt* versus *T* plots

The observed fractional contribution to each of the two processes from radiative cooling may be compared to theoretically determined values and again good agreement is observed (figure 9). The systematic excess in the experimental data in both figures may be attributed to a small contribution to the heat loss from conduction through the electric wires.

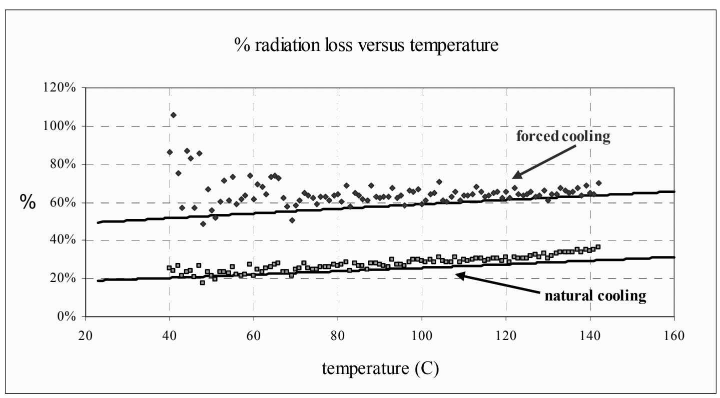

Figure 9: Percentage heat loss due to radiation (comparison of theory and experiment)

A study of the theoretical curves in figure 8 provides an insight into why the cooling curves fit Newton's law of cooling so well, as in figure 3. It can be seen that even in the case of pure radiative cooling the *dT/dt* versus *T* plot does not deviate too much from linearity over the temperature range of the experiment. Thus, even in the situation where over 50% of the cooling is due to radiation, the rate of heat loss remains proportional to $(T - T_a)$, at least provided $T_s \approx T_a$ [4]. Indeed, since $(T^4 - T_s^4) = (T - T_s)(T + T_s)(T^2 + T_s^2)$, we see that, if $(T - T_s)$ is reasonably small compared to T_s, then

$$T^4 - T_s^4 \approx 4T_s^3(T - T_s) \approx 4T_a^3(T - T_a)$$

Thus, from equation (1),

$$\frac{dT}{dt} \rightarrow \left(h + 4\varepsilon\sigma T_a^3\right)\frac{S}{C}\left(T - T_a\right) = \frac{h'S}{C}\left(T - T_a\right)$$

where h' is an 'effective heat transfer coefficient' for combined convective and radiative cooling. Since, for $\varepsilon = 1$ and $T_a = 25$ °C, the value of $4\varepsilon\sigma T_a^3$ is around 6 W m^{-2} K^{-1}, it can be concluded that cooling by radiation is a significant factor unless the cooling conditions are such that the heat transfer coefficient corresponding to pure convective cooling is significantly greater than 6 W m^{-2} K^{-1}.

7 Conclusion

The experiment described provides a convenient method whereby students can investigate the different processes that contribute to cooling in standard laboratory experiments in thermal physics. In particular, the measurements obtained by students enable them to clarify the relative contributions from convection and radiation.

8 Acknowledgments

The data acquisition system used (eProLab) was developed at the University of Ljubljana under the EU Leonardo da Vinci Community Vocational Training Action Programme, project N^{O} SI 143008 *Computerised Laboratory in Science and Technology Teaching* (ComLab2). The work described in this paper was assisted by the same programme. Support received is gratefully acknowledged. Further information may be obtained by visiting the Comlab website [3].

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9 References

[1] Michael Mansfield and Colm O'Sullivan, *Understanding Physics*, sections 11.5 – 11.7, John Wiley & Sons 1998.

[2] C. T. O'Sullivan, Correction for cooling techniques in heat experiments. *Physics Education,* **25**, 176 - 179 (1990).

[3] The data acquisition system (datalogger) used was the eProLab system developed under the Leonardo da Vinci Programme ComLab2 (project N^{O} SI 143008); website www.e-prolab.com/comlab/.

[4] In some situations differences between T_s and T_a may be important; see, for example, C. T. O'Sullivan, Newton's law of cooling - a critical assessment, *Amer. J. Phys.,* **58** (10), 956 - 960 (1990).