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Studying cooling curves with a smartphone

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This paper describes a simple procedure for the study of the cooling of a spherical body, using a standard thermometer and a smartphone. For a more thorough analysis of the data, a computer can also be used. Experiments making use of smartphone sensors have been described before, contributing to an improved teaching of Classical Mechanics[1-11], but rarely expand to Thermodynamics[12-14]. In this experiment, instead of using a smartphone camera to slow down a fast movement, we are using the device to speed up a slow process. For that we propose the use of FrameLapse free app[15] to take periodic pictures (in the form of a time-lapse video) and then of VidAnalysis Free app[16] to track the position of the mercury inside the thermometer, thus effortlessly monitoring the temperature of a cooling body (Fig. 1).

Fig. 1 Photograph of the experimental setup.

The experiment consists in filling a round-bottom flask (five flasks with standard sizes -50, 100, 250, 500 and 1000 mL- were borrowed from the chemistry lab) with hot water, placing a mercury thermometer in the opening and taking periodic pictures of it. Framelapse app allows the user to set the time interval between pictures (30 s was found to be a suitable choice) and it is a way of automatically monitoring a lengthy experiment (ca. 2 hours for the 1 L flask).

The video is then processed in the smartphone using VidAnalysis. This intuitive and easy-to-use app requires the setting of the axes, a length scale -which can be done by using the thermometer scale- and the tracking of the mercury position through screen touching (Fig. 2, right), frame by frame, generating temperature versus time graphs. The data can then be exported into a .csv file. The file can be further manipulated to allow logarithmization or fitting of the experimental curves directly in the smartphone using Google Sheets app (other popular free apps cannot open .csv files) or in a computer with OpenOffice Calc or MS Excel.

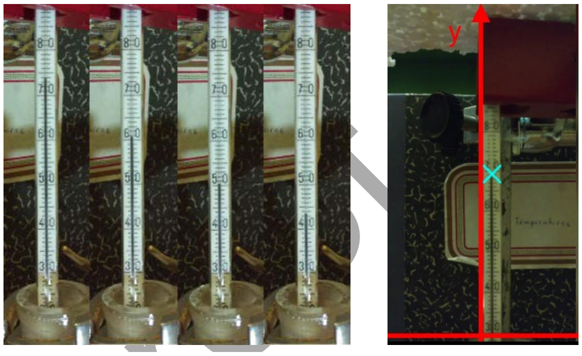

Fig. 2 Some of the frames taken during the cooling of the hot water with Framelapse app (*left*) and mercury position tracking with VidAnalysis app (*right*).

Newton's law of cooling

The temperature of a hot object placed in a cooler surrounding will slowly decrease until it matches that of the environment. It decreases by a combination of three phenomena: conduction, convection and radiation. The heat flow coming from conduction and convection depends linearly on the difference of the temperature of the object and that of its surroundings[17]:

$$\frac{dQ}{dt} \propto (T_{\text{object}} - T_{\text{env}}) \qquad (1)$$

On the other hand, the heat flow coming from radiation is ruled by the Stefan-Boltzmann law with a dependence on the fourth power of T. The net heat flow from the object radiation and the surroundings radiation is linearly dependent on ΔT only for very small temperature differences.

Anyhow, for cases where the radiative processes are not predominant –as the one discussed herein–, Newton's cooling law holds:

$$T_{\text{object}}(t) = T_{\text{env}} + \left(T_{i_{\text{object}}} - T_{\text{env}}\right) \cdot \exp(-t/\tau) \qquad (2)$$

with

$$\tau = Mc/hS \qquad (3)$$

M being the mass of the body, S the outer surface, c the specific heat per unit mass and h the convective heat transfer parameter.

Fig. 3 shows the variation of the temperature of the spherical body made of water. One can see that the temperature of water decreases following an exponential curve. For instance, a least-squares fit using a simple exponential (LOGEST function in Google Sheets app) yields T_{env}=25.21(5)ºC, $T_{i_{\text{object}}} - T_{\text{env}}$=55.72 (4)ºC and 3877(8) s for the decay time constant.

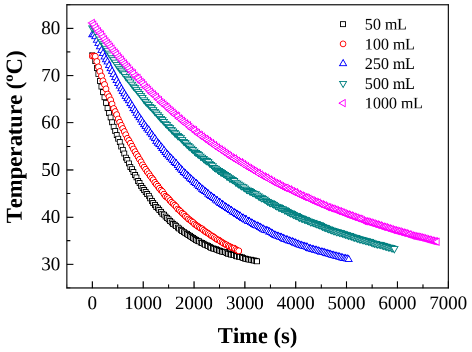

Fig. 3 Plot of decay of water temperature as a function of time for the five round-bottom flasks.

Linear dependence on *M*/*S* quotient

By applying logarithms on both sides of equation 2, a linear dependence is obtained:

$$\ln\left(T_{\text{object}} - T_{\text{env}}\right) = \left(T_{\text{i}_{\text{object}}} - T_{\text{env}}\right) - t/\tau \qquad (4)$$

A fit of the plotted data (using LINEST function) yields the slope value, that is, the inverse of τ. On its own, τ depends on four parameters (equation 3): c is kept constant and h is also approximately constant (since the conditions of the experiment were kept as close to each other as possible: a fan at medium speed was kept in a corner of the room to keep the ambient air conditions as similar as possible in all the runs)[18]. The other two parameters, M and S, were changing in the five performed runs. Their quotient depends only on the radius of the outer surface:

$$\frac{M}{S} = \frac{\rho\frac{4}{3}\pi R^3}{4\pi R^2} = \frac{\rho}{3}R \qquad (5)$$

where ρ is the density of water and R is the radius.

The τ values obtained using this procedure are summarized in Table I and plotted in Fig. 4.

Table I. Mass, outer surface and decay constant values for the five runs.

Flask	*M* (kg)	*R* (cm)	*S* (m^2)	*M*/*S* ($kg{\cdot}m^{-2}$)	τ (s)
#1	0.056	2.45	0.0075	7.42	1294.46
#2	0.115	3.13	0.0123	9.37	1509.87
#3	0.275	4.25	0.0227	12.12	2159.60
#4	0.530	5.25	0.0346	15.30	2983.80
#5	1.052	6.75	0.0573	18.37	3926.34

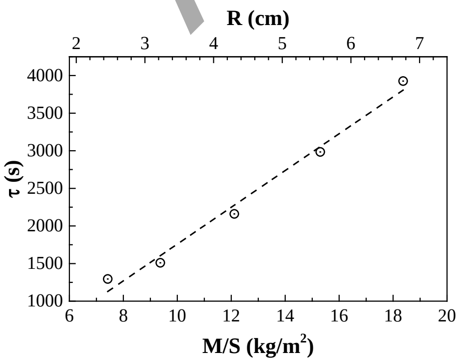

Fig. 4 Plot of τ as a function of *M*/*S* quotient (or *R*) with a least-squares linear fit.

The slope of the τ versus M/S linear fit (with R^2=0.9853) yields the constant c/h=244.61. Using c=4.186 J/(g °C), one gets h=58.44 W/(m^2 ºC). h is dependent on the geometry, flow orientation, surface roughness and combination of material/fluid.

The proposed experiment can be useful for the introduction of exponential functions at introductory levels, and can be easily changed to investigate the heat capacity of materials by letting blocks of different materials to cool in air or water[19-21]. Since the procedure can be readily adapted to allow the simultaneous tracking of several thermometers, it may also prove useful for investigating the cooling of a non-homogeneous body (e.g., simulating the estimation of the time since death of a human body[22], if our students are CSI fans!). This experiment benefits from the small size and portability of the setup, from running autonomously once set (freeing both students and teachers to other tasks) and from using a device that students bring voluntarily to class (although a sophisticated camera plus a computer can replace the smartphone). Profiting from the above characteristics, more complex experiments in non-ambient conditions (e.g., inside a fridge) can also be envisaged.

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