Studying cooling curves with a smartphone

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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\(^1\), but rarely expand to Thermodynamics\(^12\). 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).

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.

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\(^17\):

\[
\frac{\text{d}Q}{\text{d}t} \propto (T_{\text{object}} - T_{\text{env}})
\]

(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 \(\Delta T\) 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:

\[
T_{\text{object}}(t) = T_{\text{env}} + \left(T_{\text{i,object}} - T_{\text{env}}\right) \cdot \exp\left(-\frac{t}{\tau}\right)
\]

(2)

with

\[
\tau = \frac{M}{hS}
\]

(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 \(T_{\text{env}}=25.21(5)\text{°C}\), \(T_{\text{i,object}} - T_{\text{env}}=55.72(4)\text{°C}\) and 3877(8) s for the decay time constant.

Fig. 1 Photograph of the experimental setup.

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).
The slope of the $\tau$ 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 $h=58.44 \, W/(m^2 \, °C)$. $h$ 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\cite{19,20,21}. 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\cite{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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18. This is a simplified model for the actual pathways for the transfer of energy. In reality, three major pathways come into play: the free convection from the warm water to the glass flask, the conduction through the flask walls, and the loosely forced convection from the flask to the room air.