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Very fast temperature measurement with a thin lamp filament

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Abstract

We construct a thermometer exploiting the electric resistance of the filament of a small lamp used in micro-illumination settings. The instrument may guarantee a response time better than 10 ms, i.e. much faster than commercial thermocouples or other quite expensive devices. This makes our thermometer a useful one in several processes which are characterized by a rapid time evolution.

Introduction

The characterization of a measuring instrument in the undergraduate laboratory usually regards the study of its precision and its accuracy as the most important aspects needed to make decisions about its appropriateness to study a given process. Time responsiveness is not always taken into account in an introductory physics laboratory. Yet the time of response is a critical aspect when relatively fast processes are at issue. As is well known, if the time of response of the instrument is longer than the timescale of the process under study, certain features of the observed physical phenomenon could be partially or totally non-accessible to the instrument itself. Several thermodynamic processes observed in an undergraduate physics laboratory are studied in equilibrium conditions and develop in a period of time which is long enough to be readily measured with a simple bulb thermometer or a commercial thermocouple. For instance, water phase transitions or the measurement of latent heats of common solids and liquids, including water, are readily and accurately measured with a thermometer of 0.1 °C precision regardless of its response time. Yet things are very different for non-equilibrium processes. In table 1 we show a short list of different cases with their

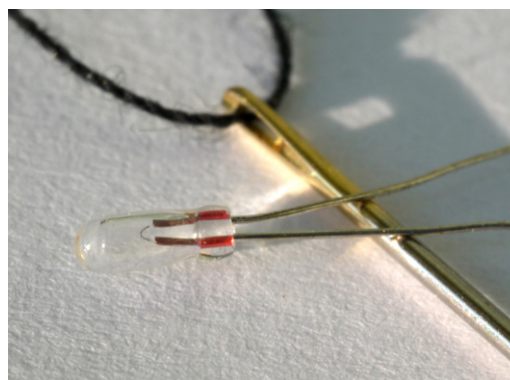


Figure 1. A small lamp (3 mm length, here shown for comparison purposes with the eye of a needle) contains a very thin filament (6 μm diameter) which may serve as a quick response thermometer.

characteristic timescales and the thermometers used to observe the behaviour of the systems with sufficient detail.

In this work we characterize a thermometer constructed with a very small resistance enclosed in a commercial micro-illumination lamp (see figure 1). The tungsten wire diameter is 6 μm , as obtained by direct observation with a scanning

Table 1. Characteristic timescales of different temperature measurements along with the corresponding appropriate thermometers.

Temperature measurement in	Timescale of the process	Sensing device
Ambient still air	$\approx$ hours	Galilei's thermometer
A water bath	A few minutes	Bulb thermometer
Mixing of ice and salt	A few seconds	Fast commercial thermocouple ($\approx 50 \mu\text{m}$ wire diameter)
Fast adiabatic expansions and wind draughts	$< 10^{-3}$ s	Filament and ultrafast thermocouples ($< 10 \mu\text{m}$ wire diameter)

electron microscope. It is wound in a spiral shape whose diameter is about $50 \mu\text{m}$. It is the minuteness of the filament, resulting in a correspondingly small thermal capacity, that allows an extremely fast time response to changes in electrical resistance (and temperature). Larger filaments can also be used with this same aim, but one has to expect a longer time of response [1].

Experimental setup and procedure

As a standard procedure, we use an electrical circuit in order to obtain current/resistance variations related to temperature changes. The simplest, yet most stable and accurate electrical configuration is achieved with a Wheatstone bridge [2], whose scheme is shown in figure 2. Once the bridge has been balanced, the voltage difference measured by the circuit allows retrieval of the effective value of the lamp's resistance. Temperature values are obtained after conversion of electrical resistance according to standard tabulated coefficients (we assume for this aim that our filament is a standard tungsten–rhenium 5% alloy).

To practically exploit the filament as a thermometer and to establish its operative features, we heated it by using pulses of hot air. The finite duration (about 0.1 s) of such pulses was achieved by using a camera shutter whose time of opening was measured using a photodiode. Two TC-K (chromel–alumel) thermocouples (a commercial one with a $50 \mu\text{m}$ wire diameter, TC_1 , and a specifically built one with a $13 \mu\text{m}$ wire diameter, TC_2) were also exposed to the hot air pulses by being placed close to the filament for comparison purposes (see figure 3). In order to completely

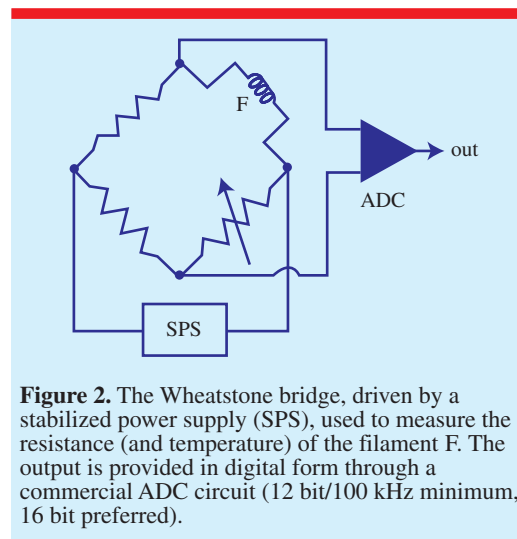


Figure 2. The Wheatstone bridge, driven by a stabilized power supply (SPS), used to measure the resistance (and temperature) of the filament F. The output is provided in digital form through a commercial ADC circuit (12 bit/100 kHz minimum, 16 bit preferred).

expose the filament to the external environment, the glass bulb of the lamp was broken.

As shown in figure 4, we notice the time delay between the opening of the shutter and the response of the thermocouples and the filament due to the time the jet of air takes to reach the sensors. We also observe that, in the time period of the shutter, the commercial thermocouple does not reach equilibrium at the actual temperature of the hot air, while the homemade thermocouple and the filament provide a similar response. Yet the homemade thermocouple is much more expensive than the filament.

Analysis of the time response

To study the time response of our thermometer we proceeded to heat the filament with a square electrical impulse, for a time period of about a

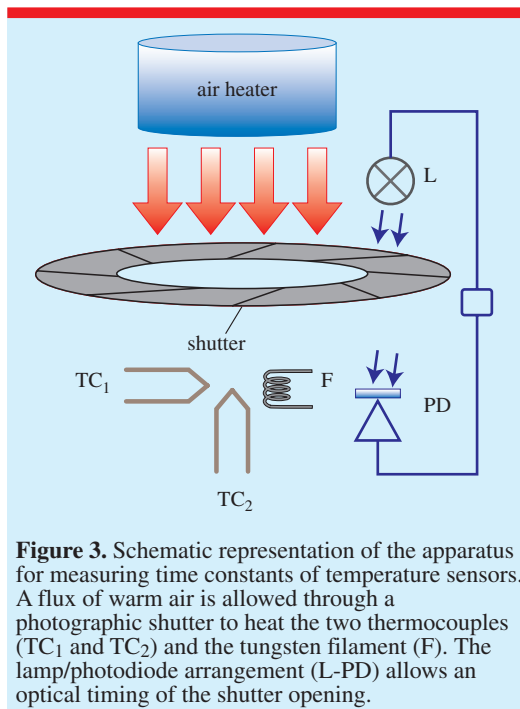


Figure 3. Schematic representation of the apparatus for measuring time constants of temperature sensors. A flux of warm air is allowed through a photographic shutter to heat the two thermocouples (TC₁ and TC₂) and the tungsten filament (F). The lamp/photodiode arrangement (L-PD) allows an optical timing of the shutter opening.

tenth of a second, and study its cooling curve as a function of time. A classical analysis of this curve using Newton's cooling law allows retrieval of the time constant of the filament, i.e. the reciprocal of the coefficient multiplying time in the standard exponential law.

During the heating process with the voltage impulse the filament was ventilated using a jet of air at ambient temperature. The purpose of this is twofold: first, it avoids an excessive heating of the filament which could blow up; second, it allows measurement of its time constant as a function of the wind velocity.

In figure 5 we show the temperature of the filament as a function of time for a voltage impulse of less than a tenth of a second. We can see that ventilation improves the time constant dramatically, as expected. According to the Newtonian (exponential) cooling law, it is possible to provide a sensible theoretical model for the time constant in terms of various physical parameters of the filament and the surrounding medium. Since in this work we do not address specific details of heat transfer processes, here we limit ourselves to summarizing the main results. Further insights into this field can be found in several references (see, for example, [3]). The time constant of the

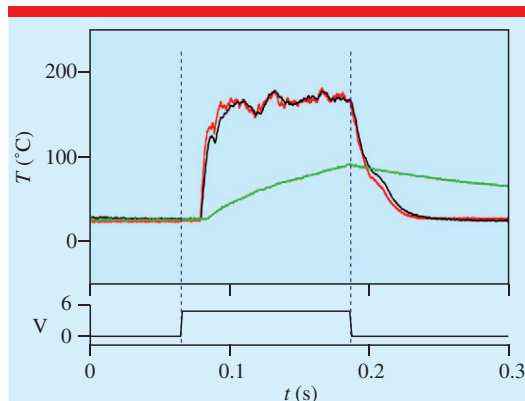


Figure 4. Temperature measured as a function of time for the filament (red line), the commercial thermocouple TC₁ (green line) and the homemade thermocouple TC₂ (black line). The opening time of the shutter is shown at the bottom of the figure.

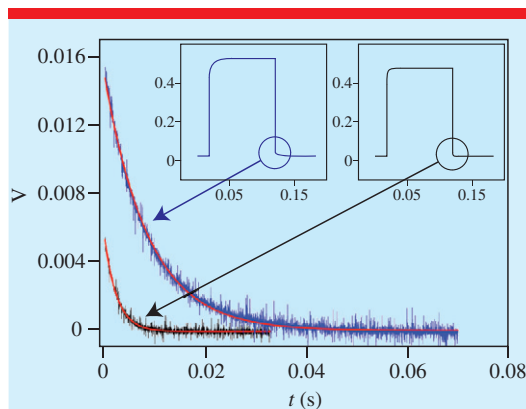


Figure 5. Detail of the difference in the response of the filament to the voltage impulse, as a function of time, for a null wind speed (blue line) and for a wind speed of 21 m s⁻¹ (black line) (air was issued at ambient temperature). Red lines are the fitting curves based on a simple exponential (Newton) cooling law.

filament in the flux of air (forced convection of heat) can be expressed as $\tau = \rho c d^2 / (4kNu)$, in which ρ is the density of the filament, c its specific heat, d the effective wire diameter (which is not necessarily its physical diameter when the wire is wound in spiral form) and k the air conductivity. We also introduce the Nusselt number, Nu , which is a function of the relative importance of heat conduction and convection at a given fluid speed (Nu can also be expressed in terms of the Reynolds number of the moving fluid). Assuming the simplest case of a filament

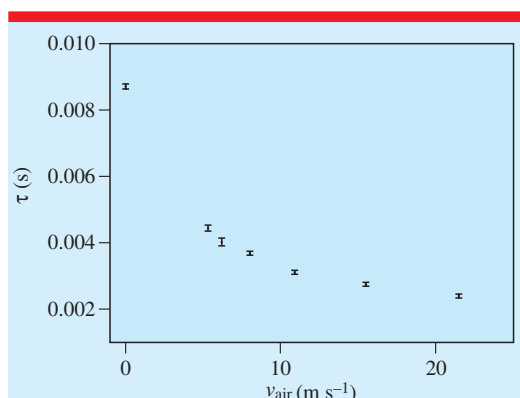


Figure 6. Experimental values of the time constant of the filament as a function of the wind speed.

in still air (no forced ventilation) and an effective wire diameter of $35 \mu\text{m}$ we obtain a value for the time constant of about 10 ms, in fair agreement with the experimental value of 8.7 ms. It is important to stress that this is the worst scenario: in the presence of air ventilation (either forced or natural) the time response will be even shorter, as shown in figure 6. A more extended theoretical treatment can account also for more subtle effects related to e/m radiation energy transfer as well as to the thermal capacity of the wire support in the lamp. Such effects are, however, shown to be negligible in the theoretical estimation of the actual time constant of this device. As stated above, this calculation is not the main focus of our work.

Conclusions

A very small lamp filament can be used, with some simple expedients, as a very fast thermometer with a characteristic time constant of the order of a few milliseconds. This inexpensive instrument can be very useful in the study, at a didactic level, of fast processes such as out-of-equilibrium transformations like rapid adiabatic expansions, fast changes in temperature due to strong wind draughts, or high precision anemometry. As a practical, yet quite simple, application, we suggest consideration of the (quasi)-adiabatic expansion/cooling of air contained in a soda bottle

which, after its pressurization with a normal bike pump, is quickly opened and exposed to atmospheric conditions. One can observe the air temperature dropping in a few hundredths of a second, making the fast thermometer described in this work a definitely necessary device for reliable measurements.

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