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Playing with a bulb lamp: RTL measurements and modelling

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Abstract

The electric, thermal and optical behaviour of an incandescent lamp was studied by a real time laboratory (RTL) apparatus, using two voltage probes and a light probe. The software *STELLA* was used to model the phenomena and to analyse the transient behaviour in absence of thermal equilibrium. We show how the Joule-heating effect explains the non-linear current/voltage relation and how the filament thermal capacity affects the phase lag of light peaks with respect to input power peaks.

1. Introduction

The rapid improvements of the modern electronics will soon make obsolete the *light bulbs*, the traditional light sources of past century, now superseded by the white-LED, more efficient, fast and durable. This will make the use of light bulbs difficult as tools for experiments aimed at studying the important electro-optical phenomenon frequently named *blackbody radiation* (our suggestion to the future physics teacher is to buy and store safely in their laboratory a full set of bulb lamps that will soon disappear from normal shops).

The two experiments hereafter described may offer a wide choice of useful classroom discussions on *electrical*, *thermal* and *optical* phenomena, without involving complex calculus. They also provide an opportunity for comparing experimental data with predictions achievable through easy and powerful modelling software, now available at a low cost.

The first experiment is performed using only a real time data acquisition system, voltage and light sensors and an intermittent bulb lamp. In the second one we used a normal bulb lamp and a triangular wave signal generator.

2. The experimental setup

Using a common 3.5 V–0.35 A *intermittent lamp* (that includes a bimetallic switch [1]) and a dc power supply, we obtain light pulses at low frequency.

The filament *nominal resistance* R_n may be calculated from the volt-amperometric data $R_n = V/I$. In our case we get $R_n = 10\ \Omega$; however with a digital ohmmeter we measure the actual resistance (at room temperature T_o) $R_o = 1.0\ \Omega$, which is much smaller than the nominal one (at working temperature).

Assuming a constant tungsten temperature coefficient ($\alpha = 0.0053\,\mathrm{K}^{-1}$) we might evaluate the working temperature to be approximately 2000 K. More accurate evaluation [2–8] gives, using the relation $T = To(R/Ro)^{\beta}$ (where T is the absolute temperature and $\beta = 0.833$), an estimated working temperature of about $T = 2040\,\mathrm{K}$.

The bimetallic switch (figure 1) consists of a thin strip placed in series with the filament that is Joule-heated by the electric current flowing across it. The different expansion coefficient of the two metals induces a deformation of the strip

Figure 1. Bimetallic switched lamp.

that eventually leads to switching-off the current. When the current flow is stopped, the strip cools down until the electrical contact is restored and the cycle repeats. This relaxation oscillation [9] is the process that originates the light pulses in the intermittent lamp.

3. Experimental results

To investigate this process we powered the lamp with a 9.0 V dc battery in series with a potentiometer R_2 (50 Ω) and a resistor R_1 (10 Ω), as shown in figure 2.

We connected a *voltage probe* [10] across the resistor R_1 (to monitor the current intensity) and we measured the light emitted by the filament through a *light sensor* [11]. In this first experiment we used a Vernier system (*LabPro* as datalogger and *Logger pro* as software), but any equivalent system may be used [12].

The first set of measurements was taken by trimming the potentiometer in order to obtain a working current of about 300 mA, a bit smaller than the nominal one (350 mA).

Figure 3 shows a typical record of the measured signals. Light intensity, in this and in all the following graphs, is given in arbitrary units. Here the current flow starts (at time $t_0 = 0.0$ s), when the bimetallic strip is at room temperature (switch closed). The voltage across the 10 Ω resistor R_1 shows a peak of 3.66 V, corresponding to a current of 366 mA. After a short transient T_1 (≈0.5 s) the voltage drops to about 3 V, corresponding to the working current of 0.3 A, due to the fast increase of the filament resistance (Joule heating).

At the time $t_1 \approx 0.5$ s a long transient T_2 begins: the power input ($P = RI^2$) is *almost balanced* by the power output (dissipation by radiation and by conduction through the electrodes that hold the filament), so that the current intensity is nearly stable and the filament emits radiation of nearly constant intensity.

After $T_2 \approx 9.2$ s the bimetallic strip temperature reaches the value at which the strip deformation breaks the electric contact, and the current drops to zero ($t_3 = 9.8$ s).

At this time the power input stops and the temperature of the filament suddenly drops; the strip temperature starts decreasing (due to thermal coupling to the ambient) until the electric contact is restored, and the cycle is completed (approximately at time $t = 10.4$ s). From this time the cycle repeats with a frequency of about 0.8 Hz (period T_3 of about 1.3 s).

Note that during the ON–OFF cycling, the current peaks are smaller than the first one (they reach approximately 340 mA), due to the fact that the filament resistance never returns to the initial value R_o (the value measured at ambient temperature) that produced the first higher peak (366 mA).

4. Modelling the process

In order to get a quantitative evaluation of the described phenomenon one may use modeling and simulation [13]. We used the modelling software *STELLA* [14], assuming that the filament is an 'energy tank' whose temperature changes as a function of its thermal capacity and of the input/output energy flows. The filament temperature is calculated as the ratio between the internal energy and the thermal capacity C_{fil}; this latter is evaluated from the known value of the tungsten specific heat and its mass (the filament mass is estimated from its dimensions and from the tungsten density). The input energy flow is due to Joule heating: $P_{joule} = V^2/R$.

The output energy flow is calculated estimating the various dissipation processes. The

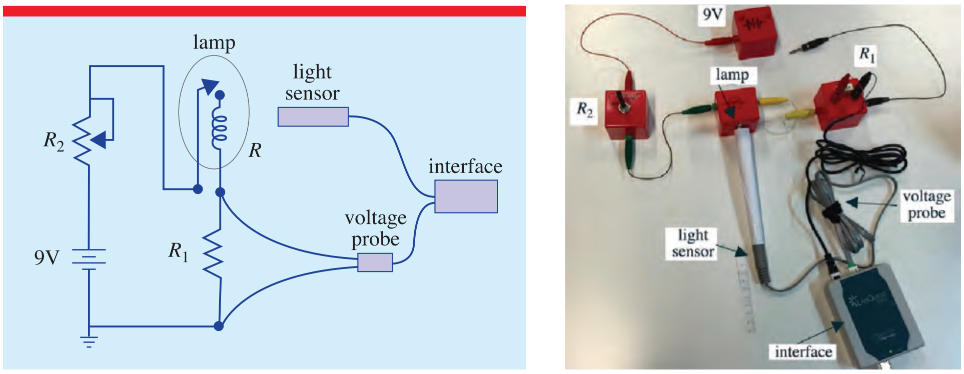

Figure 2. Sketch of the first setup.

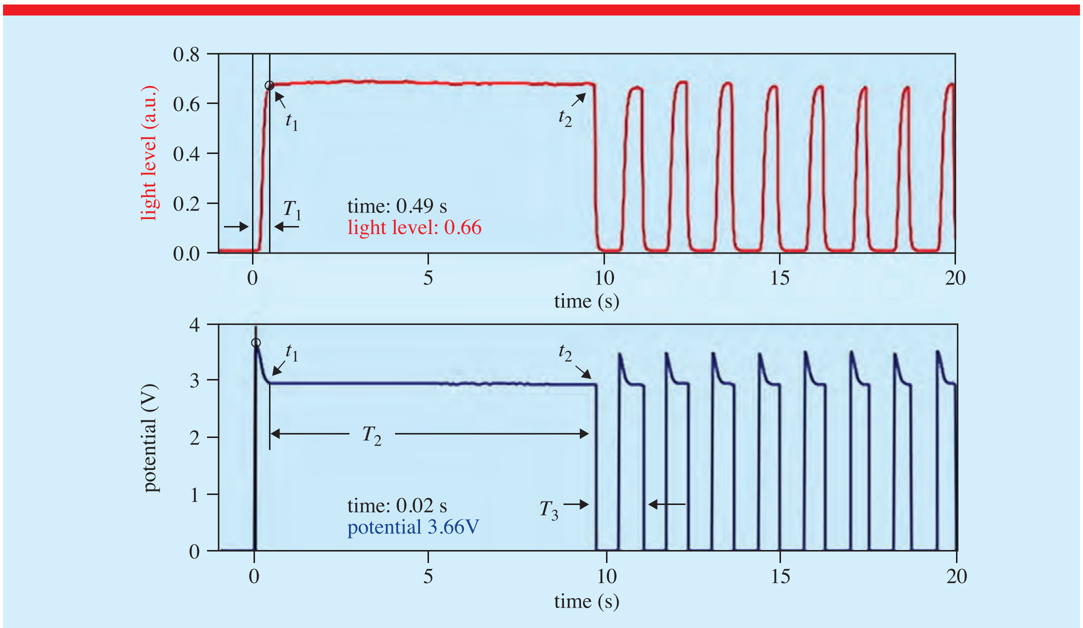

Figure 3. Light pulses (top) and voltage drop across the resistor R (bottom).

irradiated power is $P_{\mathrm{rad}} = \sigma\varepsilon A\ (T_{\mathrm{fil}}^4 - T_o^4)$, where σ is the Stefan–Boltzmann constant, ε the emissivity coefficient and A the surface area of the filament, estimated through the measured diameter D and length L.

Some energy is also dissipated by conduction through the lead-in wires: this may be written as $P_{\mathrm{cond}} = C\ (T_{\mathrm{fil}} - T_o)$, where C is a coefficient to be evaluated. Usually this contribution is neglected in the analysis of normal bulb lamp thermal behaviour; because it has been shown that the conduction-term is much smaller than the radiation term, particularly for low-power lamps [15]. In the intermittent lamp, where the bimetallic strip is thermally coupled to the filament it is difficult to evaluate which fraction of energy is transferred by conduction or by radiation. We assume that the strip is *cooled* only by conduction so we can neglect the *radiation term*, because the strip temperature is always much lower than the filament temperature.

The filament geometrical dimensions were estimated after breaking the lamp glass envelope and observing the filament through a cheap webcam (Rainbow Compact [16]): an image is shown in figure 4.

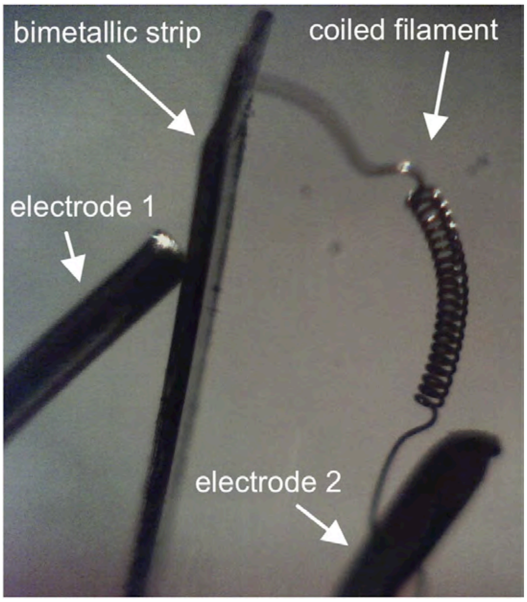

Figure 4. Image of the lamp filament taken at 20 × by a modified Rainbow Compact webcam.

The estimated filament diameter is $D = (37 \pm 5)$ μm. The length measurement required to stretch the coiled wire: the measured length is $L = (16 \pm 2)$ mm.

The *STELLA* block diagram and the source code for the model used for this first experiment are reported in the appendix. The model results for the electric current, the light output (radiated power) and the strip temperature are shown in figure 5.

The model assumes two threshold temperatures for the bimetallic strip (T_L switch-on and T_H switch-off; we provide a flow control that switches-on the current when the upper threshold T_H is crossed while the strip temperature T_{strip} is *increasing*, and switches-on the current when the lower threshold T_L is crossed while T_{strip} is *decreasing*.

Figure 5 also reports the simulated behaviour of the strip temperature with $T_H = 469$ K and $T_L = 474$ K. These values were set by a *trial-and-error* procedure (until we achieve a good match with experimental results) because we cannot measure directly the strip temperature (see appendix).

5. A run with smaller current

We reduced the current through the filament by increasing the value of the resistance R_2 (potentiometer).

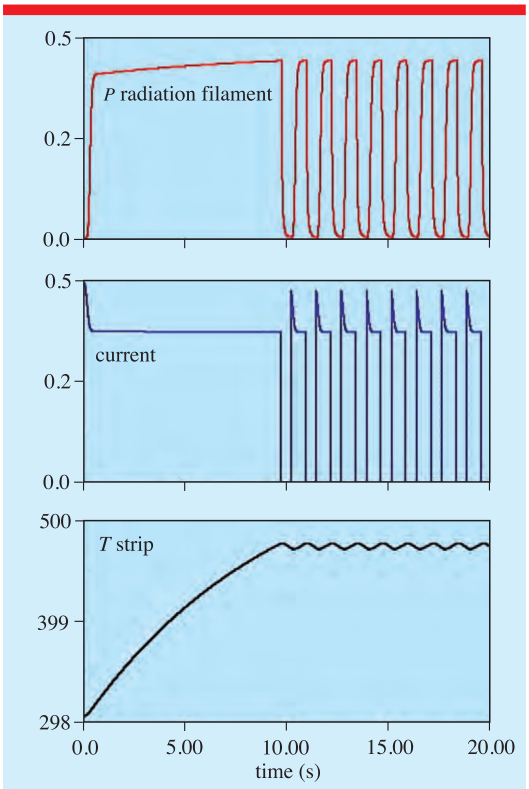

Figure 5. Model results for filament radiation (P_{rad}) current intensity (I) and strip temperature (T_{strip}).

A typical record taken with a current of about 270 mA is shown in figure 6.

The smaller current, by reducing the bimetallic strip heating, increases both the short first transient T_1 (from 0.5 s to 0.6 s) and the second transient T_2 (from 9.2 s to 13 s). The proof that now the filament temperature is lower (than in the first run) is given by the lower intensity measured for the light signal (the value obtained with $I = 270$ mA is about 45% of the value measured with $I = 300$ mA). The smaller power input does also increase the cycle period from 1.3 s to 1.45 s.

The results of the *STELLA* simulation obtained using a smaller current (by changing the R_2 potentiometer resistance value from 11.7 Ω to 15.3 Ω) is shown in figure 7. The essential features of the studied phenomenon are reproduced by our model: the reduced current does increase the transients T_1 and T_2, and the period T_3: the model predicts a reduction of the pulse-frequency when the current is reduced.

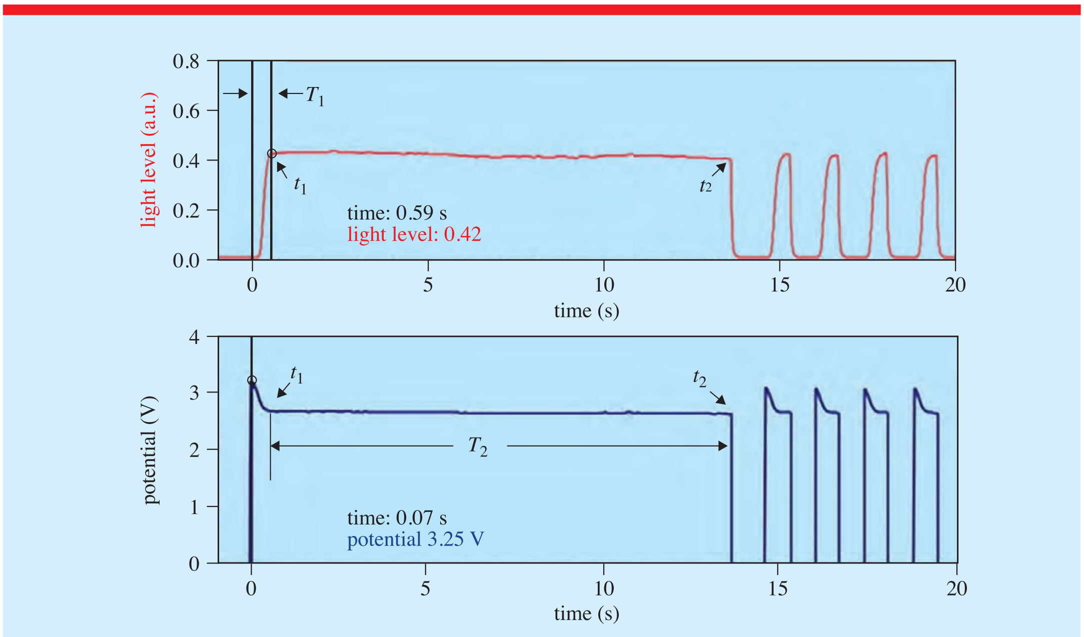

Figure 6. Pulses of the switched lamp fed by a smaller current.

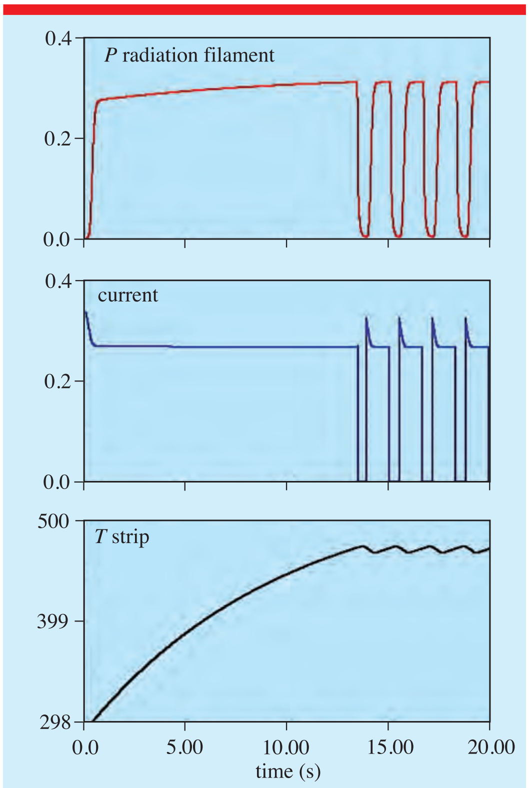

Figure 7. Model results with $R_2 = 15.3\ \Omega$ (reduced current).

6. Second experimental setup

In this second experiment we used a PASCO *850 Universal Interface* with *Capstone* software [12], and a 6 V–2 W lamp. This lamp has a *nominal resistance* $R_n = 18\ \Omega$ (obtained from the relation between the output power P and the working voltage V: $P = I^2/R_n$); however with a digital ohmmeter we measure (at room temperature) the resistance $R_o = 1.7\ \Omega$. This gives a working temperature of approximately 2100 K.

To study in detail the resistance–current relation we modulate the current in a linear way using the ramp generator included in the PASCO datalogger. We use (figure 8) two voltage probes to monitor both the current ($I = V_1/R_1$) and the generator output signal V_2; a light sensor measures the light output, and a 10 ohm resistor R_1 is used to monitor the current.

Figure 9 shows the records of V_1 and V_2 obtained using a sampling rate of 40 Hz, with a ramp frequency of 0.3 Hz.

By comparing the V_1 and V_2 voltage plots we see that the current ($I = V_1/R_1$) does not follows the linear behaviour of the supply voltage V_2, due to the variable value of the filament resistance R.

The value of resistance R may be easily calculated as $R = (V_2 - V_1)/I = (V_2 - V_1)R_1/V_1$.

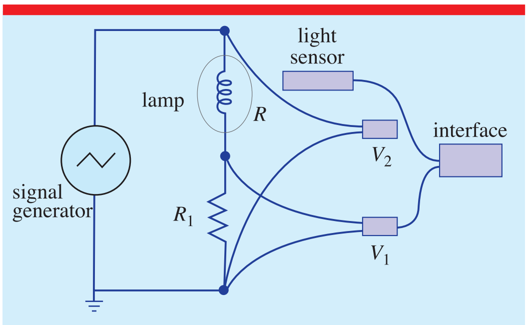

Figure 8. Schematics of the experimental setup using a ramp generator.

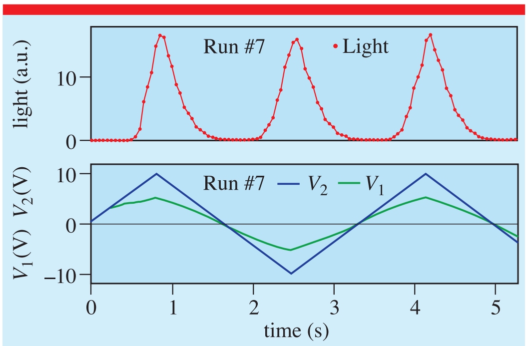

Figure 9. Light signal (top) and voltage signals (bottom).

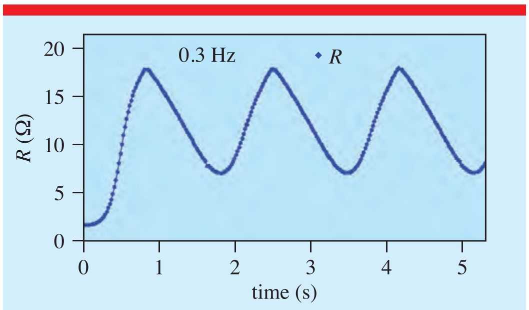

Figure 10. Filament resistance.

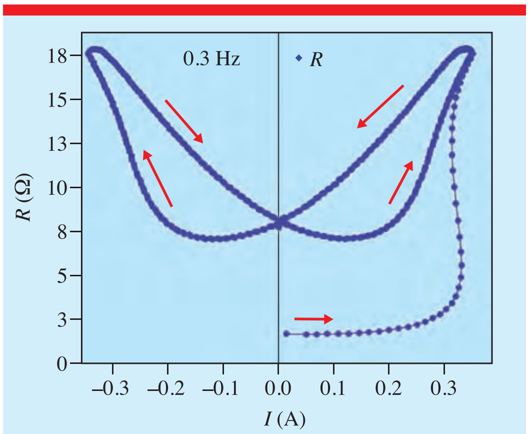

Figure 11. Filament resistance versus current at 0.3 Hz.

The time evolution of the resistance R is shown in figure 10.

The filament resistance oscillates from 7 Ω to 18 Ω.

In figure 11 the filament resistance is plotted as a function of the current, and it clearly shows hysteresis [17]; the R values, while current *decreases*, are always higher then the R values corresponding to the same current values when current is *increasing*. This shows that the filament temperature values delay with respect to the power input values, as a consequence of the finite thermal capacity of the filament.

The filament temperature T_{fil} values may be estimated [7] as $T = T_o(R/R_o)^{0.833}$, where T_o is the room temperature in K; the corresponding plot is shown in figure 12.

By plotting both filament temperature and light intensity versus time (figure 12) we see that light emission occurs for filament temperature above approximately 1200 K (marked by the gray horizontal segment in the graph).

The power input to the filament may be calculated as $P = RI^2$. A plot of P and of the light intensity (figure 13) shows that the light emission *onsets* do lag behind the power input *rising* edges. On the other hand the light emission *decay records* are roughly in-phase with the power input *falling* edges.

This behaviour is due to the (small but not negligible) thermal capacity of the filament, which is thermally coupled to the environment (by heat conduction through the strip and the electrodes, and by irradiation); the difference between the power input by Joule heating and the power output (conduction and irradiation), scaled by the thermal capacity, determines the rate of change of the filament (and strip) temperature.

A steady state may be achieved only if the energy flows are balanced, i.e. only if the changes of the electric current are sufficiently slow. We guess therefore that the hysteresis would disappear for extremely low frequency values of the triangular wave.

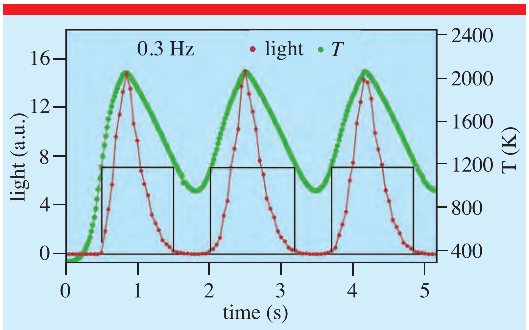

Figure 12. Temperature and light intensity versus time.

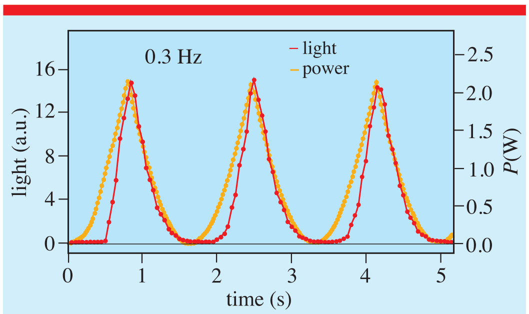

Figure 13. Light intensity and power input versus time.

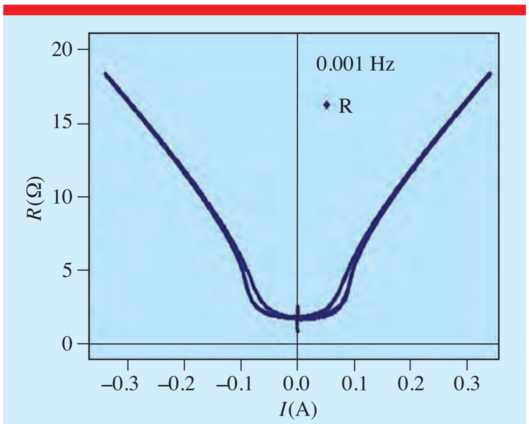

Figure 14. Filament resistance versus current at 0.001 Hz.

A new run was therefore performed with triangular wave at 0.001 Hz. The result is shown in figure 14: here hysteresis is almost absent.

Using *STELLA* we may compare the predictions of our model with the experimental results. The triangular signal is built by using the first 6 Fourier components (see figure A3 in the appendix).

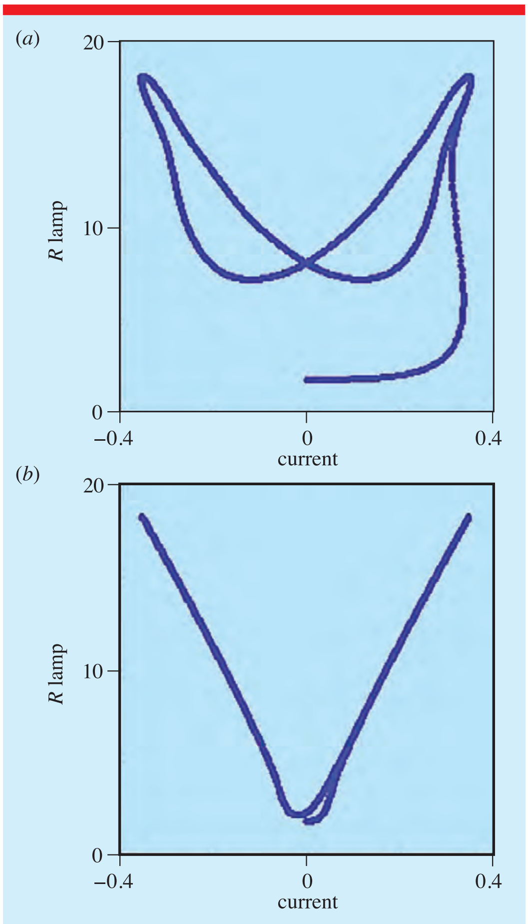

Figure 15. Model results of resistance versus current for frequencies 0.3 Hz (A) and 0.001 Hz (B).

Figure 15 shows the model results obtained for triangular waves at 0.3 Hz and 0.001 Hz.

When the power is fed at very low frequency (0.001 Hz) the hysteresis disappears.

When the triangular wave frequency increases, the delay of the changes of the filament temperature with respect to the changes of the power input becomes more evident: it may be observed as a *phase lag* of the light pulses with respect to the peaks of the power input.

In figures 16 and 17 the experimental results obtained at 6.0 Hz give an example of such phase lag.

At higher frequencies, after a short transient, the filament temperature reaches a steady state: for example at 6.0 Hz it oscillates between 13 Ω. and 14 Ω (figure 17).

In figure 18 we report the model results of the process obtained with *STELLA* for 6.0 Hz.

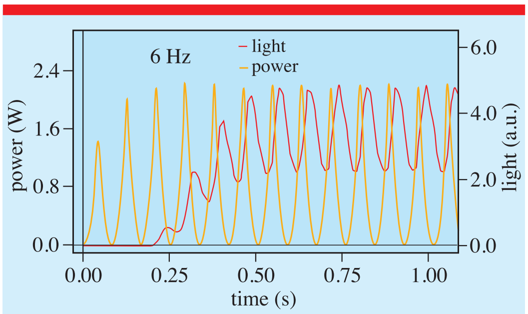

Figure 16. Light intensity compared with power input $P = RI^2$.

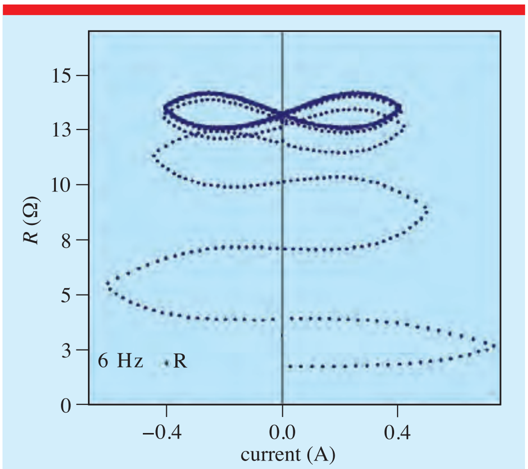

Figure 17. Resistance versus current for 6.0 Hz ramp frequency.

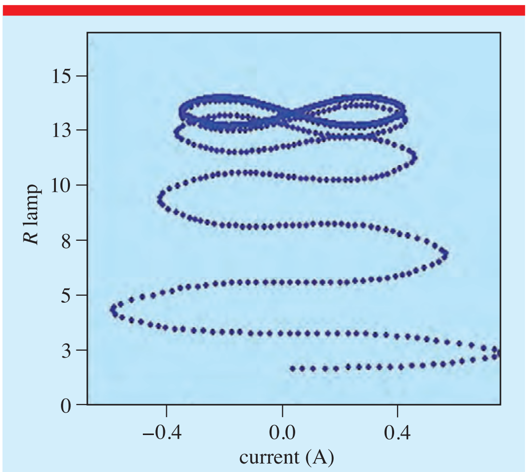

Figure 18. Model results for resistance versus current at 6.0 Hz.

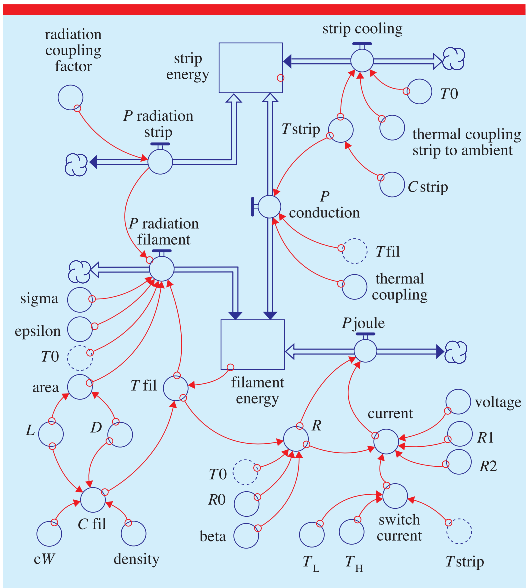

Figure A1. *STELLA* diagram for switched lamp.

7. Conclusions

It is well known to anybody who teaches physics that two of the main limitations of traditional lab activities are the separation among topics of the curriculum contents and the simplification of the lab investigations proposed to the students [18]. The introduction in the student lab of modern technologies like RTL has proved to facilitate the investigation of real phenomena in their complexity and to emphasise the interconnection of different fields of physics knowledge [19].

The present investigation of bulb lamps shows the following advantages:

- it allows students to tackle a rather complex everyday phenomenon and to investigate it at different levels of detail;
- it makes the connections among different physics topics explicit, namely optics, electricity and thermal phenomena;
- it allows students to appreciate the nature of physics investigation by proposing a complete but affordable modeling activity on real phenomena.

A complementary analysis of fluctuating light output of incandescent lamps has been recently proposed by Vollmer and Möllmann [20].

```
filament energy(t) = filament energy(t - dt) + (Pjoule – Pradiation filament – Pconduction) * dt
INIT filament energy = T0*Cfil
INFLOWS:
P joule = (current^2)*R
OUTFLOWS:
P radiation filament = epsilon*sigma*(T fil^4-T0^4)*area
P conduction = thermal coupling*(T fil-Tstrip)

Strip energy(t) = strip energy(t - dt) + (strip cooling + Pradiation strip + Pconduction) * dt
INIT strip energy = Cstrip*T0
INFLOWS:
Pradiation strip = radiation coupling factor*Pradiation filament
Pconduction = thermal coupling*(T fil -Tstrip)
OUTFLOWS
Strip cooling = thermal coupling strip to ambient*(Tstrip-T0)

current = switch current*voltage/(R+R1+R2)
area = PI*D*L
Cfil = L*((D/2)^2)*PI*density*cW
R = R0*((T fil/T0)^(1/beta))
switch current = IF((Tstrip<TH) AND (DELAY(Tstrip,-1)<=Ts))OR((Tstrip<TL)
                 AND (DELAY(Tstrip,-1))>Tstrip) THEN 1 ELSE 0
T fil = filament energy/C_fil
thermal coupling = 2.08e-4 {W/K}
thermal coupling strip to ambient = 1.05e-3 {W/K}
Tstrip = energy/Cstrip
beta = 0.833
cW = 0.13e3 { J/(kg K)}
D = 3.7e-5 {m}
density = 1.9350e4 {kg/m^3}
epsilon = 0.35
L = 0.016 {m}
voltage = 9.0 {V}
R0 = 0.97 {ohm}
R1 = 10 {ohm}
R2 = 15.8 {ohm}
sigma = 5.7e-8 {W/(K^4 m^2}
T0 = 303 {K}
Cstrip = 0.0115 {J/K}
radiation coupling factor = 0.25
TH = 474 {K}
TL = 469 {K}
```

Figure A2. Source code for the diagram of figure A1.

Appendix. Modelling with *STELLA*

In this appendix we present some details of our modeling approach since we believe that the use of a work environment which offers a *graphic interface* (rather an equation solver) allow focusing on the structures which underlay the functional relationships involved in a given phenomenon, enhancing the whole network of physical relations rather than focusing on singles algebraic aspects: such a model indeed can be seen as a conceptual map, informed by quantitative aspects.

Figure A1 shows the flow-diagram used to model the intermittent bulb-lamp experiment. The core of the model is the two energy-balance equations, concerning respectively the filament and the strip. The energy of the filament is related to its thermal capacity (C_{fil}) and its temperature (T_{fil}), so that energy exchanges produce in general a change of the filament temperature.

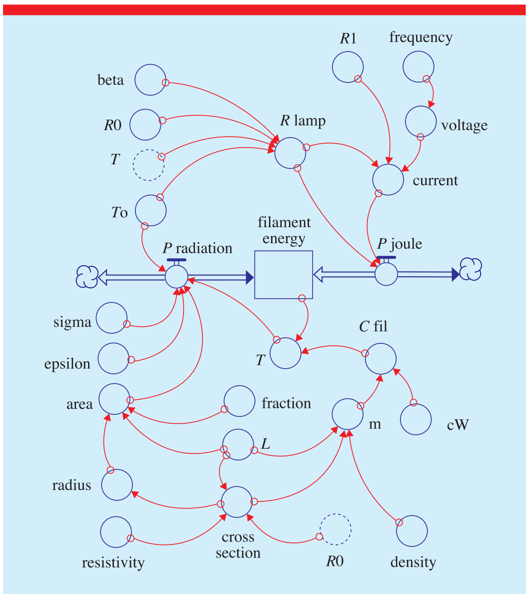

Figure A3. *STELLA* diagram for lamp fed by triangular wave.

```
filament energy(t) = filament energy(t - dt) + (Pjoule – Pradiation) * dt
INIT filament energy = To*Cfil
INFLOWS:
P joule = (current^2)*Rlamp
OUTFLOWS:
Pradiation = epsilon*sigma*area*(T fil^4-To^4)

current = voltage/(R1+Rlamp)
cross section = resistivity*L/R0
D = 2*SQRT(cross section/PI)
area = PI*D*L*fraction
m = density*L*cross section
Cfil = m*cW
Rlamp = R0*((T fil/To)^(1/beta))
T fil = filament energy/Cfil
frequency = 0.3*2*PI {rad/s}
voltage = 8.39*(SIN(frequency*TIME) - SIN(frequency*3*TIME)/3^2 +
          + SIN(frequency*5*TIME)/5^2-SIN(frequency*7*TIME)/7^2+
          + SIN(frequency*9*TIME)/9^2-+SIN(frequency*11*TIME)/11^2)  {V}
beta = 0.833
cW = 0.13e3 {J/(kg K)}
density = 1.935e4 {kg/m^3}
epsilon = 0.35
L = 0.045 {m}
R0 = 1.7 {ohm}
R1 = 10 {ohm}
resistivity = 5.2e-8 {ohm m}
sigma = 5.67e-8{W/(m^2 K^4}
To = 300 {K}
fraction = 0.85
```

Figure A4. Source code for the diagram of figure A3.

In the filament we take into account the exchanges due to the Joule effect (P_{joule}), to radiation following the Stefan–Boltzmann law ($P_{\mathrm{radiation\ filament}}$) and to thermal conduction ($P_{\mathrm{conduction}}$) following the usual Newton law with a linear *thermal coupling*.

In the strip we consider the thermal conduction (from the filament), the cooling effect to the ambient (*strip cooling*), as well an incoming energy flow associated to the incident radiation ($P_{\mathrm{radiation\ strip}}$), the latter being determined by a *radiation coupling factor* whose value is chosen by fitting the model previsions with the measured data.

The intermittent behaviour is obtained by introducing an ON/OFF switch for the electrical current, driven by the strip temperature (T_{strip}), by means of a double trigger with suitable: an upper (T_H) threshold (switch OFF, when temperature is increasing) and a lower (T_L) threshold (switch ON, when temperature is decreasing); both thresholds are validated by detecting the proper time derivative of the variable T_{strip}.

The code lines used to model the intermittent bulb-lamp are shown in figure A2. With respect to the code generated by *STELLA* we suppressed the underscore symbols and rearranged some lines to facilitate understanding the physical model.

Figure A3 shows the flow-diagram used to model the behaviour of the lamp powered by triangular signal. As in the previous case, the heart of the model still is the balance equation for the energy of the filament. Here, two energy exchanges are taken into account: the input power originated by the Joule effect (P_{joule}) and the output flow consisting in the power emitted by radiation (P_{rad}); as discussed in this paper, in fact, even in this situation the conductive and convective contributions can be neglected.

The triangular voltage signal (*voltage*) is generated taking into account the first 6 terms of the Fourier series, and choosing the amplitude so that the signal oscillates between -10V and $+10$V, like the measured output of the generator. Note that in this model, in order to match the model results with the measured data, we use only *one* parameter (the *fraction* that relates the effective radiating length of the filament with geometrical length, since the conductive coupling keeps the filament ends cooler). The best fitting value *fraction* $= 0.85$, seams to be reasonable.

The filament diameter D is calculated from its resistance R_0 and length $L = (45 \pm 5)$ mm, and the result (40 μm) is compatible with the standard value ($D = 35$ μm).

The code lines used to model the lamp fed by the triangular wave are shown in figure A4.

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