Experiment 6: Physics with a car headlamp

Introduction:

In this experiment, you will try to answer some real-life questions on the tungsten filament of a car headlamp, such as

- How efficient is the halogen gas-filled lamp with a tungsten filament?
- What temperature does the filament reach?
- In what part of the electromagnetic spectrum is most of the radiation emitted from the hot lamp?

In order to answer the above questions, one needs to do a lot of data analysis, and hence in this experiment, you will realise why a spreadsheet program such as Microsoft Excel, is indispensable for a large amount of data manipulation.

Theory:

When a lamp has reached a steady state, the electrical power dissipated in the filament must be equal to the total rate of heat lost from the filament, due to conduction, convention and radiation. However, when the lamp is glowing, we can safely assume that most of the energy is lost by radiation and so the electrical power dissipated in the filament, $P_{el} = VI$, is effectively equal to the power lost by radiation, P_{rad}.

In the first part of the experiment you will check whether the empirical formula

$$T = T_s\left(R / R_s\right)^m \tag{1}$$

is valid, where R is the resistance at the temperature T and R_s is the resistance at the room temperature T_s. Thus, using equation (1), one can estimate the temperature T of a halogen lamp at a given resistance R. Incidentally, m is a constant whose value can be found from the experimental results as explained below:

…. to find m

If we assume that the hot tungsten filament behaves as a greybody the net power radiated, to a good approximation, is described by the Stefan-Boltzmann law:

$$P_{rad} = \varepsilon A \sigma\left(T^4 - T_s^4\right) \tag{2}$$

where the filament is at a temperature T and the surrounding room temperature is $T_s \varepsilon$ is the emissivity of the filament's surface, A is the area of the surface from which the radiation is emitted and σ is the Stefan-Boltzmann constant. For a blackbody surface, $\varepsilon = 1$; for other surfaces, the emissivity is a complicated function of temperature, environment and fabrication (Incropera and De Witt,1990). However, to simplify the analysis the following assumptions are made about the filament: its emissivity is constant and independent of the temperature, it has a uniform surface temperature and all the radiation is emitted from its surface.

For the filament, the constants A and ε are unknown. However, these two unknown quantities can be eliminated by taking a ratio. If P_1 is the power when the filament just starts to glow brightly at a temperature T_1 $\left(T_1^4 >> T_s^4\right)$ and P_i is the power at a higher temperature T_i then,

$$\frac{P_i}{P_1} = \left(\frac{T_i}{T_1}\right)^4 \tag{3}$$

Combining equations (1) and (3), it is possible to relate the power radiated to the resistance of the filament:

$$\log\left(\frac{P_i}{P_1}\right) = m\left[4\log\left(\frac{R_i}{R_1}\right)\right] \tag{4}$$

If the predictions given by equations (1) and (2) are valid, a plot of log (P_i/P_1) against 4log(R_i/R_1) will yield a straight line with slope m through the origin. In this way we can calculate the temperature the filament reaches. But what about the efficiency of the car headlamp? We will try to answer these questions in the second part of the experiment.

Assuming that the tungsten filament radiates as a greybody, then the spectrum of the emitted radiation will be given by the Planck distribution function (Eisberg and Resnick 1985):

$$p(\lambda)d\lambda = \frac{N}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}d\lambda \tag{5}$$

where $p(\lambda)d\lambda$ is the radiant power emitted in the wavelength interval λ and $\lambda + d\lambda$ with $p(\lambda)$ being the power emitted per unit wavelength in this interval, N is a normalising factor, λ is the wavelength of the emitted radiation, h is the Planck constant, c is the speed of light and k is the Boltzmann constant. The integral over all wavelengths of the function $p(\lambda)$ given by equation (5) equals the total power radiated by the hot filament at a temperature T, i.e.

$$P_{rad} = \int p(\lambda)d\lambda \tag{6}$$

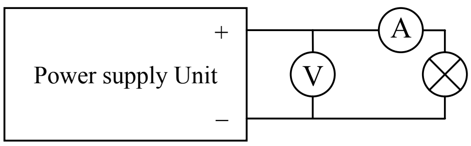
With a spreadsheet this integral can be evaluated numerically and the value of N adjusted so that the integral is equal to the input power, $P_{el.}$ The luminous efficiency of the lamp is defined as the ratio of the power radiated in the visible part of the spectrum to the input power. Thus, the efficiency of the lamp can be found by comparing the ratio of areas under the Planck distribution curve.

Procedure:

For this experiment, the following apparatus is required:

- a digital power supply unit (p.s.u.)
- 12V, 60/50 W car headlamp
- a thermometer

First note the room temperature T_s and then set up the following simple circuit. Using a digital power supply unit one can vary the voltage across the lamp and then read the corresponding current.



- Start increasing slowly the voltage across the lamp until the filament lamp just starts to glow brightly. Note the voltage V_1 (approximately about 1V) and the corresponding current I_1.
- Afterwards, take about 60 current readings for voltages between 0.2V-12V, i.e. in 0.2V steps. As the voltage is increased it is necessary to wait before the readings are recorded so that an equilibrium is established.
- Finally, take 3 more readings in the range 13V-15V, (i.e. in 1V steps)

Data Analysis:

1. Input the data in an Excel Worksheet and hence plot the I-V characteristic of the lamp.

2. For each pair of values, calculate the resistance R $(=V/I)$ of the filament and the dissipated power P $(=VI)$. Plot an R-I graph.

3. The room temperature resistance R_s can now be found by extrapolating the R-I graph to find the resistance at zero current. Note you might notice some deviation from linearity for small values of the resistance. In order to handle this situation the points that deviate from linearity will have to be ignored. These points should be clearly marked on the graph (tip: make two data series and use a legend). State the reason(s) that caused the deviation from linearity that has been observed in the discussion.

4. The next step is to calculate the constant *m*. Verify the relationship: $\log\left(\frac{P}{P_1}\right) = 4m\log\left(\frac{R}{R_1}\right)$ and hence calculate the value of m using the linear regression analysis tools of Microsoft Excel.

5. Now, the temperature *T* (in Kelvin) of the filament is related to its resistance *R* by

$$T = T_s\left(\frac{R}{R_S}\right)^m$$

Since T_s, R_s and m are now known, plot a graph of *R* vs. *T* and comment.

6. In the final part of this experiment you will try to calculate the luminous efficiency of the lamp. Recall, that if we assume that the Tungsten filament lamp radiates as a grey body, the spectrum of the emitted radiation is given by Equation 5, i.e.

$$p(\lambda)d\lambda = \frac{N}{\lambda^5\left(e^{hc/\lambda kT} - 1\right)}d\lambda$$

(i) Set up a column of about 500 wavelength values ranging from 200nm to 9200nm, i.e. ($d\lambda = 18nm$).

(ii) Let T be the maximum temperature of the filament (i.e. at 15V). For each value of λ, calculate the right hand side of Equation 5. The value of the normalising constant *N* should be adjusted to make the area under the graph equal to the power dissipated at that temperature. (Tip: Find the area of the rectangle subtended by each $d\lambda$ and sum.)

(iii) Plot a graph of Power / wavelength interval (W/nm) vs. wavelength (nm)

(iv) Sum the values of $p(\lambda)d\lambda$ for λ values in the range 400nm – 700nm (visible range).

Sum all the values of $p(\lambda)d\lambda$ (i.e. from 200 – 9200nm)

Express these two sums as a % ratio. This % ratio is the luminous efficiency of the car headlamp.

Comment on your result.

Useful Constants:

Planck's constant *h*:	6.62608×10^{-34} Js
Boltzmann's constant *k*:	1.38066×10^{-23} JK^{-1}
Speed of light *c*:	2.99792×10^{8}ms^{-1}