A candle in the lab

Stephen Hughes and Andrew Gale

Department of Physical and Chemical Sciences, Queensland University of Technology, Gardens Point, Brisbane, Queensland, Australia. E-mail: sw.hughes@qut.edu.au

Abstract

This article describes some experiments performed to obtain a spectrum of a candle, oil lamp, 60W incandescent lamp and fluorescent tube. A professional spectrometer was used of a type unlikely to be available to schools so the spectral data is provided as a service to the teaching profession. The brightness and rate of fuel consumption of a candle and oil lamp were also measured. The data obtained could provide the starting point for a discussion on green house gas emissions etc.

Introduction

An interesting question is how the emission spectra of historic forms of lighting such as the candle and olive oil lamp compare with those of modern forms of lighting such as the incandescent lamp and fluorescent tube. Olive oil lamps have been around for thousands of years. Candles in various forms have also been used over the millennia, initially made from animal fat (tallow) and then beeswax and also paraffin wax in more recent times (Newman 2000).

Method

A pack of six paraffin candles and a bottle of olive oil were obtained from a local supermarket and a replica oil lamp with a wick obtained from Historic Connections, Shoal Bay, NSW, Australia. The replica oil lamp is of the *Herodian* type, so called as it was widely used in the reign of Herod the Great (c. 37 – 4 BC) and remained in use to c. AD 150 in parts of the Holy Land (probably the type of lamp referred to in the Gospel records in the Bible).

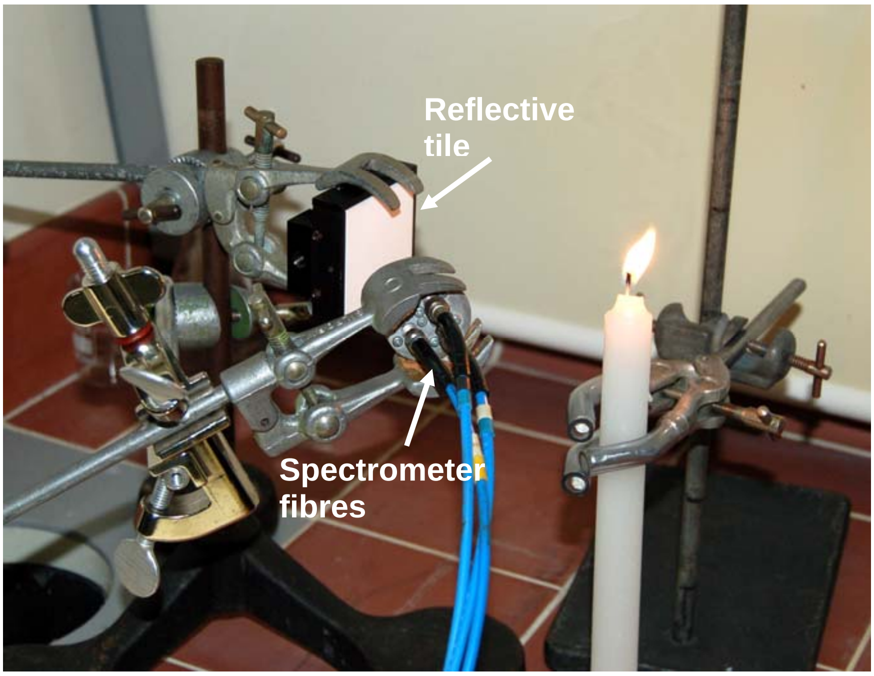

Figure1. A candle placed close to a diffusely reflectance tile to direct light into the fibres of the spectrometer. The spectrometer has three fibres – one each for ultraviolet (UV), visible and infrared (IR) radiation.

An 18W daylight fluorescent tube was also obtained. Experiments were performed in a fume cupboard to reduce the risk of setting the fire alarm off and fees associated with the automatic call out of the fire brigade to the university.

Spectra were obtained using an Ocean Optics ST2000 Fibre Optic Spectrometer (Dunedin, FL, USA) with 3 channels – ultraviolet, visible and near-infrared radiation. The spectrometer was calibrated for wavelength against the persistent lines of sodium and mercury and calibrated for intensity (normalised to 555 nm) against a spectrally calibrated primary standard lamp at the National Measurements Institute (Australia). A diffuse reflectance tile (Labsphere, North Sutton, NH, USA) with a reflectance of 0.976 across the visible region of the electromagnetic spectrum was used to direct light from the sources into the reception fibres of the spectrometer (figure 1).

Figure 2. Oil lamp on an electronic balance, to measure the fuel consumption rate.

The brightnesses[1] of the candle, oil lamp and incandescent lamp were measured using a Topcon IM-3 illuminance meter set to slow integration. The candle, oil lamp and fluorescent tube were placed at 42.5, 39 and 45 cm from the meter respectively. Three readings were taken and the mean and standard deviation calculated A Sartorius BP210S 210 ± 0.1 mg balances was used to measure the rate of fuel consumption for the candle and olive oil lamp. The candle and olive oil lamp were placed on the balance and the reduction in weight over a 10 min period recorded (figure2).

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[1] In reality the illuminance is being measured in this paper rather than brightness. However, brightness is indirectly related to illuminance. The unit of illuminance is the lux. 1 lux = lumens m^{-2} . 1 lumen = 1 candela into 1 steradian. The candela is a measure of the luminous intensity of a source that emits monochromatic radiation at a wavelength of 555 nm with a radiant intensity of 1/683 W per steradian in the direction being measured. The luminous intensity (candela) of a common candle is approxiamtely equal to 1 candela. As these units are unfamiliar to those not working in the field of lighting it was thought better to use the term brightness.

Results

The spectra, normalised to a wavelength of 555 nm (approximately the middle of the visible region of the electromagnetic spectrum which spans 400–700 nm) are shown in figure 3. Table 1 shows brightness measurements. The fuel consumption rates of a candle and olive oil lamp were 6.12 g per hour and 5.46 g h^{-1} for the candle and olive oil lamp respectively.

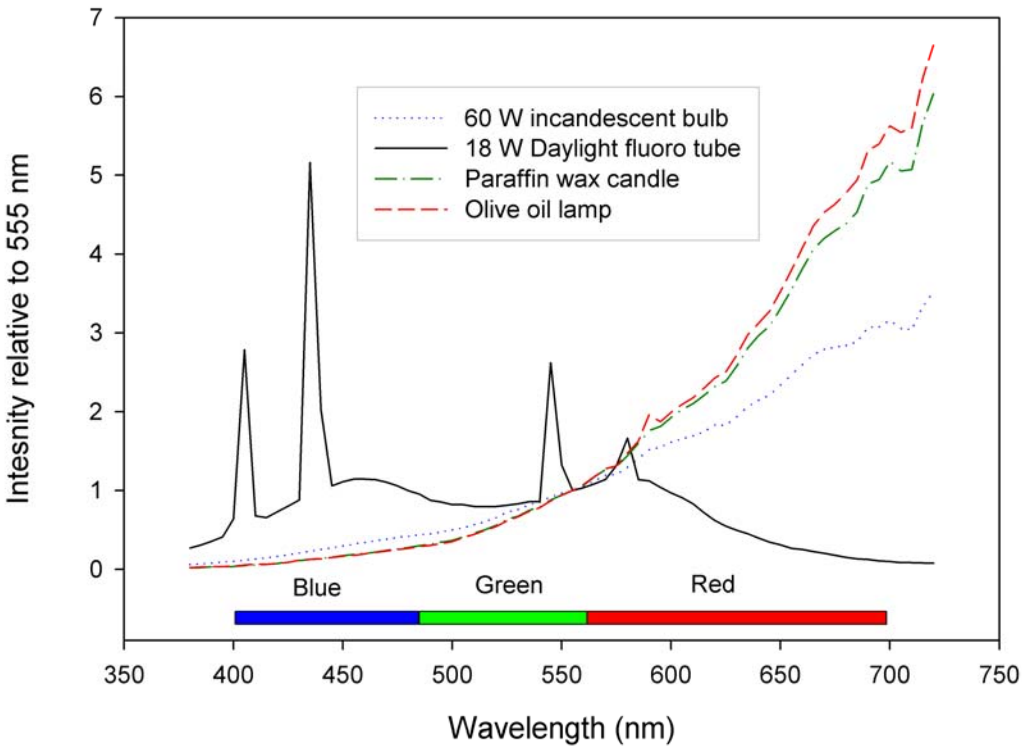

Figure 3. Spectra of a candle, olive oil lamp, 60 W incandescent lamp and 18 W daylight fluorescent tube normalised to emission at 555 nm. The spectra were recorded from 260–950 nm, but only 380-720 nm is shown as this encompasses the visible part of the electromagnetic spectrum. The range of wavelengths that we perceive as red, green and blue are represented by the colour bars. The peaks on the fluorescent tube curve are emission lines from the ionised mercury gas within the tube and phosphor coating.

The data used to produce this graph has been provided as an Excel spreadsheet, available in the online version of the journal at stacks.iop.org/physed/42/271. The brightnesses of the candle, olive oil lamp and 60 W incandescent lamp at 1m were measured as 0.81 ± 0.16, 1.34 ± 0.2 and 62.71 ± 0.42 lux respectively.

Discussion

The spectra of the candle and olive oil lamp are very similar. However significant differences exist between the ancient and modern lights. For example, the candle and oil lamp emit more red light than the incandescent lamp but less visible light, and the daylight fluorescent tube emits much less red light and more visible light than the candle or oil lamp. This is why candles and oil lamps have a softer, i.e. redder light than other forms of lighting. The ratio of the light intensities at 555 nm and 700 nm were calculated from the spectra and compared with those obtained with a black-body radiator at various temperatures. This showed that the equivalent black-body temperatures of the candle, oil lamp and incandescent lamp were 1970, 1910 and 2400 K respectively.

Source	Distance (m)	Brightness (lux)	Variation in brightness as a % of total	Brightness (lux) normalised to 1m	Brightness (lux) normalised to 2m	Distance (m) of source to be as bright as 60W lamp at 2m
Oil lamp	0.39	5.3 ± 1	20	0.81	0.20	0.23
Candle	0.425	7.4 ± 1	14.6	1.34	0.33	0.29
60W lamp	0.45	309.7± 2	0.7	62.71	15.68	

Table 1. Brightness of the oil lamp, candle and 60W incandescent lamp. The brightness measurements were normalised to 1 and 2m. The last column shows the distance that an olive oil lamp and candle need to be placed to an object (e.g. a book) to provide the same level of illumination as a 60W incandescent lamp at 2m.

Oil lamps and candles are obviously much dimmer than modern lights; however this would not have been such a problem to the ancients as the human eye has a dynamic range that stretches across at least 12 orders of magnitude of brightness. (The difference in brightness between the midday sun and the faintest stars that can be seen by the naked eye is a factor of about 10^{13}). Although the level of illumination for required for eating dinner, for example, lies between these two extremes, this serves to demonstrate that our eyes operate across a very wide range of illumination. Many of us have experienced a candle-lit dinners and have not had problems in getting food safely from the table to our mouths!

In the past, people were still able read books using oil lamps and candles. And of course, candles are frequently used throughout the so-called developed world during power cuts. The same level of illumination as a 60 W incandescent lamp placed 2 m away from a table (for example) can be achieved by placing a candle at a distance of 29 cm and an olive oil lamp at 23 cm (assuming a point-source approximation).
The greater variation in the brightness of oil lamps and candles compared with an incandescent lamp accords with common experience. However, we readily accept the fluctuating light from a candle, but noticeable variations in the brightness of electric lights can be disturbing. Another major difference between older and modern forms of lighting is the portability of candles and oil lamps compared to fixed electric lights.

Another interesting point of discussion is the question of carbon emissions from the various forms of lighting. On the basis of the cost of candles, olive oil and electricity in Brisbane, $1 will provide 2, 2.4 and 4.8 days of lighting for candles, olive oil lamps and a 60W incandescent lamp respectively. Different forms of lighting can also be compared in terms of carbon emissions. The efficiency of generating power in a coal-fired power station and transporting it to a domestic house is no better than about 27%, assuming a 70% loss in generating the electricity and 9% in transmission (Lovins 2005); therefore 220 W needs to be generated at the power station to light a 60 W incandescent lamp in the home. The amount of chemical energy stored in coal is 2.9×10^7 J Kg^{-1}; therefore 27.6 g of coal needs to be burnt every hour to light a 60 W incandescent lamp - which is about 4.5 times greater than the fuel consumption rate of a candle. If we assume that weight for weight coal and paraffin wax emit similar amounts of carbon when burnt then we have a similar saving in the emission of carbon.

It could be argued that this is not a fair comparison as a 60W incandescent lamp emits much more than 4.5 times as much light as a candle. However, as we have shown above, the difference in illumination can be compensated by bringing a candle closer to our work area. Olive oil lamps and candles made from beeswax of vegetable oils (e.g. soya) are carbon neutral, i.e. there is no net contribution to carbon emissions as the carbon in the fuel came from the atmosphere anyway. It would be interesting to calculate the annual reduction in carbon emissions that would occur if every once in a while each household in the developed world had a candle-lit dinner in which every light, TV and computer was switched off for the duration of the dinner!

Acknowledgements
We thank Historic Connections, Shoal Bay, NSW, Australia for providing the oil lamp used in these experiments.

Note added in proof. On Saturday 31 March 2007, more than half of Sydney's 4.4 million residents switched off their lights and household appliances between 7.30 and 8.30 pm in an event known as Earth Hour organized by WWF. Some people held candle-lit BBQs and a candle-lit wedding took place. According to reports, power consumption dropped from 22 800 kW h^{-1} to 205 000 kW h^{-1}, a reduction of 10.1%, equivalent to a drop in CO_2 emissions of 25 tonnes. The organizers of Earth Hour hope to expand the event to include other cities in Australia and even the rest of the world. More information, including photos and a video, can be obtained from the website of *The Sydney Morning Herald* (www.smh.com.au); search for the article 'Enlightened city knocks the worlds lights out'. More general information about Earth Hour can be obtained from www.earthhour.com.

References

Newman, J, 2000 *Candles,* (London: PRC)
Lovins A B 2005 More profit with less carbon *Sci. Am.* **293** 74-83