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SHORT COMMUNICATION

Light output versus cooling-time of coiled tungsten filament lamp

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ABSTRACT

During steady-state operation filaments of incandescent lamps are considerably hot and provide luminous flux for illumination but when it is switched off the temperature as well as the light output drops quite fast. The cooling-time of a lamp is defined as the time needed for the temperature to drop to the point where the light output of lamp falls to 10% from the steady-state operation magnitude. The operating temperatures of coiled-wire filament lamps of 6, 10, 25, 40, 60, 100, 200, 300, and 500 watts are borrowed from a previous publication and the lumen outputs are estimated here. The lumen output for each degree Kelvin fall of the temperature is calculated to locate the temperature at which lumen output has dropped to 10% as per definition of the cooling time. Lastly the expression for the cooling-time has been derived and estimated for each lamp. The numbers so obtained do match satisfactorily.

Keywords**:** Tungsten filament lamps, coiled-wire, 6-500 watts, steady-state operation, lumen output, cooling time

1. INTRODUCTION

The switching off a hot tungsten filament lamp, operating at steady-state, leads to fall in its temperature and the associated lumen output quite rapidly. The cooling-time of it is

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defined [1] as the time required for the hot filament to cool down to the point where the light output drops to 10 per cent after the circuit has been opened compared to its value when it was closed. The light output data as well as cooling times for coiled filament lamps of 6, 10, 25, 40, 60, 100, 200, 300 and 500 W are reported by General Electric in their catalogue [1].

The objective of this paper will be to evaluate these numbers from the point of view of students and teachers of physics. The required steps would be as follows.

- Firstly the operating temperature $T_{Operating}$ of the coiled tungsten filament should be known. This has been worked out by the author in a separate publication [2] "The Coiling Factor in the Tungsten Filament Lamps". The results will be borrowed for the specified wattages of lamps mentioned above.
- Another publication [3] "Solar luminous constant versus lunar luminous constant" will be followed to determine the light output from the lamps at operating temperatures described in the previous step; the numbers so estimated will be compared with the observed ones.
- In the third step the lamp would be presumed to be switched off to cool down and the fall in the filament temperature will be monitored to ascertain the temperature T_{Cold} at which the luminous flux from the lamp will have diminished to 10% from the steady-state operation.
- Lastly the expression for cooling-time from temperature $T_{Operating}$ to T_{Cold} will be worked out and the evaluated numbers will be compared with the corresponding listed values from the General Electric Catalogue [1].

2. THEORY

A. Operating temperature of the coiled tungsten filament

A detailed theory for coiled tungsten filament lamps have been developed in the paper [2] "The Coiling Factor in the Tungsten Filament Lamps"; it will not be duplicated here and the associated numbers for $6-500$ wattages lamps will be borrowed. These are reproduced in Table I where the first column lists the wattage followed by uncoiled length of the filament L_0, diameter D_0 of the filament at room temperature T_0, heat losses via convection owing to the presence of the gas, through the ends of filament due to conduction, and via the base and case of the bulb. Table II provides operating temperature $T_{Operating}$ of the coiled filament and the fraction of the surface area δ, known as shadow factor arising due to coiling. The value of shadow factor δ is equal to one for a straight wire and it is less than one for coiled filament. The next section will be devoted to estimation of luminous flux from the coiled filaments of the lamps under discussion.

B. Luminous flux from the coiled tungsten filament

A detailed theory for the luminous flux from an object operating at temperature $T\ Kelvin$ having emissivity ε and area $A\ square\ meters$ has been developed in a publication [3] "Solar luminous constant versus lunar luminous constant". The basic expressions will be borrowed to avoid duplication. This expression for the luminous flux $Q\ lumen$ is

$$Q(\lambda_i \to \lambda_f) = \int_{\lambda_f}^{\lambda_i} \frac{683V(\lambda)\cdot\varepsilon\cdot A\cdot 2\pi hc^2\cdot d\lambda}{\lambda^5[exp(\mathrm{hc}/\lambda\mathrm{kT})-1]} \qquad (1)$$

here: h and k are Planck's constant and Boltzmann's constant, respectively. The factor $\boldsymbol{V(\lambda)}$ [4] takes care of the fact that the electromagnetic waves in the wavelengths region $\boldsymbol{\lambda_i} =$ 380 nm to $\boldsymbol{\lambda_f} =$ 760 nm are visible to our eyes; it is optimum at $\boldsymbol{\lambda_m} =$ 555 nm and becomes vanishingly small outside this interval. This fact is represented by

$$V(\lambda) \approx \exp(-\mathrm{az}^2 + \mathrm{bz}^3); \mathrm{z} \equiv \lambda/\lambda_\mathrm{m}; \lambda_\mathrm{m} = 555 \text{ nm} \qquad (2)$$
$$a = 88.90, b = 112.95$$

The factor 683 occurs because at $\boldsymbol{\lambda_m} =$ 555 nm the electromagnetic radiation of one watt provides a luminous flux of 683 lumens. For coiled tungsten filaments having uncoiled length L_0 and radius r_0 at room temperature T_0 the effective surface area would be

$$A = 2\pi \cdot r_0 \cdot L_0 \cdot \delta \qquad (3)$$

and the expressions (1) gets modified to

$$Q(\lambda_i \to \lambda_f) = \int_{\lambda_f}^{\lambda_i} \frac{683V(\lambda)\cdot\varepsilon\cdot 2\pi\cdot r_0\cdot L_0\cdot\delta\cdot 2\pi hc^2\cdot d\lambda}{\lambda^5\cdot[exp(\mathrm{hc}/\lambda\mathrm{kT})-1]} \qquad (4)$$

The above integral was evaluated through Simpson rule and for simplicity thermal expansion of filament [5] was ignored. It is well known that emissivity of tungsten is substantially large in the visible wavelength region [6] and decreases with rise in the temperature of the filament. In contrast, the average value of emissivity over the entire wavelength spectrum is rather small and increases with the rise of temperature of the filament; in view of the pedagogic nature of this article $\varepsilon_{Visible} = 0.44$ [6] and $\varepsilon_{Overall} = 0.0000664T^{1.0796}$ [7] would be adopted. The estimated luminous fluxes for $6 - 500\ W$ lamps at the corresponding operating temperatures are listed in Table II. In the next section the cold temperature at which the light output drops to 10% will be estimated.

C. The fall of temperature during cooling

As soon as the circuit is opened the hot filament starts cooling quickly largely by Stefan-Boltzmann radiation law. This is accompanied by the diminishing light output and as per definition of the cooling time the cold temperature at which it falls to 10% of closed circuit light output has to be ascertained. A program was developed in GW-BASIC to evaluate the integral (4) by Simpson rule for each one degree Kelvin fall in temperature of the coiled filament. This process was carried out for each lamp. The temperature T_{Cold} of the filament at which the drop comes down to 10% that of closed circuit light output was recorded and it is mentioned in Table II. The next section will be devoted to estimation of cooling-time from temperature $T_{Operating}$ to T_{Cold}.

D. Estimation of cooling-time as per definition

The Stefan-Boltzmann law states that the thermal power P radiated from a body having thermal energy $H\,Joule$, uniform hot temperature $T\ Kelvin$, surface area $A\ square\ meters$, and averaged emissivity over the entire spectrum $\varepsilon_{Overall}$ is proportional to the fourth power of the absolute temperature and is represented as

$$P = dH/dt = -\sigma \cdot A \cdot \varepsilon_{Overall} \cdot (T^4 - T_W^4) \qquad (5)$$

here: σ is the Stefan-Boltzmann constant and T_W is the temperature of the walls of the enclosure; the term T_W^4 will not be considered for making calculation simple. Putting the expression for H one gets

$$MC\frac{dT}{dt} = -\sigma \cdot A \cdot \varepsilon_{Overall} \cdot T^4 \qquad (6)$$

here: M is the mass of the filament in kilogram, C is the specific heat in Joule per kilogram per degree Kelvin and t is the time variable in seconds. The specific heat of tungsten metal as reported by metallurgists [8] in the range $0 - 3000\ °\mathrm{C}$ has the following expression

$$C = 3R_g(1 - \theta_D^2/20\,T^2) + 2aT + 4bT^3\ J\ kg^{-1}K^{-1}. \qquad (7)$$

here: T is in Kelvin, $R_g = 45.2268\,J\ kg^{-1}K^{-1}$ is gas constant for tungsten, $\theta_D = 310\ K$ is a constant called the Debye temperature for tungsten at room temperature, $a = 4.5549 \cdot 10^{-3}\,J\ kg^{-1}K^{-2}$ and $b = 5.77874 \cdot 10^{-10}\,J\ kg^{-1}K^{-4}$. The emissivity $\varepsilon_{Overall}$ is also not constant for tungsten, and its value has been parameterized [7] in the temperature range $0 - 3000\ °C$ giving

$$\varepsilon_{Overall} = 0.0000664T^{1.0796}. \qquad (8)$$

Mass of the filament can be written

$$\begin{aligned} M &= Volune\ of\ filament \cdot Density\ of\ tungsten \\ &= \pi \cdot r_0^2 \cdot L_0 \cdot 1.93 \cdot 10^4\ Kg. \end{aligned} \qquad (9)$$

The heat equation (6) can be rewritten as

$$dt = -\frac{\pi \cdot r_0^2 \cdot L_0 \cdot 1.93 \cdot 10^4 \cdot \left[3R_g\left(1 - \theta_D^2/20T^2\right) + 2aT + 4bT^3\right]}{\sigma \cdot 2\pi \cdot r_0 \cdot L_0 \cdot \delta \cdot 0.0000664 \cdot T^{1.0796} \cdot T^4} \cdot dT. \qquad (10)$$

Integration of this and taking the limits from $T_{Operation}$ to T_{Cold} yields the cooling time

$$t_{Cooling} = \frac{r_0 \cdot 1.93 \cdot 10^4}{\sigma \cdot 2 \cdot \delta \cdot 0.0000664} \left\{ \frac{3R_g}{(-4.0796)} \left(\frac{1}{T_{Operation}^{4.0796}} - \frac{1}{T_{Cold}^{4.0796}} \right) - \frac{3R_g \cdot \theta_D^2}{20 \cdot (-6.0796)} \left(\frac{1}{T_{Operation}^{6.0796}} - \frac{1}{T_{Cold}^{6.0796}} \right) + \frac{2a}{(-3.0796)} \left(\frac{1}{T_{Operation}^{3.0796}} - \frac{1}{T_{Cold}^{3.0796}} \right) + \frac{4b}{(-1.0796)} \left(\frac{1}{T_{Operation}^{1.0796}} - \frac{1}{T_{Cold}^{1.0796}} \right) \right\}. \qquad (11)$$

This expression has been used to estimate cooling-times for $6 - 500\ W$ lamps and the corresponding values are listed in Table III and compared with those observed ones [1]. They match each other showing the success of the model adopted in this paper and the papers cited.

3. DISCUSSION & CONCLUSIONS

The incandescent coiled tungsten filament lamps are in the process of being phased out because of their poor efficiency but they will continue to be source of illumination to the minds of physics students as evident from a large number of publications on this subject in the last three decades; the topics covered therein are the historical perspective [9-11], temperature and colour of the filament [12], efficiency and efficacy of the lamp [4], switching time [13], mortality statistics and life of the bulb [14-17], thermal expansion of the filament [5], exponent – rules [18-19], cooling and heating times of uncoiled filaments, etc. However, no attempt was made so far to estimate the cooling times of the filament lamps having coiled structure and this has been accomplished here.

In the first step the operating temperatures of coiled filaments were borrowed from another publication [2] "The Coiling Factor in the Tungsten Filament Lamps" by the author for 6, 10, 25, 40, 60, 100, 200, 300, and 500 W lamps. Next, the theory developed in another publication [3] "Solar luminous flux versus lunar luminous flux" was adopted to estimate the luminous flux output from these lamps at steady-state operation. In the next step through a program in GW-BASIC the luminous flux output for each degree fall in temperature of cooling filament was evaluated. This ascertained the cold temperature at which light output had dropped to 10% of the steady-state operation value. Lastly the expression which was derived for cooling time from temperature $T_{Operating}$ to T_{Cold} estimated the cooling time for each case. The salient findings may be concluded as follows.

- The luminous flux estimated for each lamp is somewhat on the lower side compared to the observed ones (vide columns 4 and 5 in Table II). This may be arising due to the shadow factor δ which may be dependent on the wavelength radiating from the filament in the visible region.
- The expression for the cooling-time appears to be independent of the length of the filament (vide Eq. (11)). However, this is indirectly built-in in the expression through the wattage of the lamp.
- The cooling-times estimated here are somewhat on higher side vis-à-vis those observed ones (vide columns 3 and 4 in Table III). This may be understood on the ground that there are other modes of cooling apart from Stefan-Boltzmann radiation, such as end loss and bulb and base loss via conduction in the case of vacuum bulbs and additional mode convection for bulbs having gas inside.

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