A Transient Experiment to Determine the Heat Transfer Characteristics of a 100 *W* Incandescent Light Bulb, Operating at 48 *W*

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Abstract

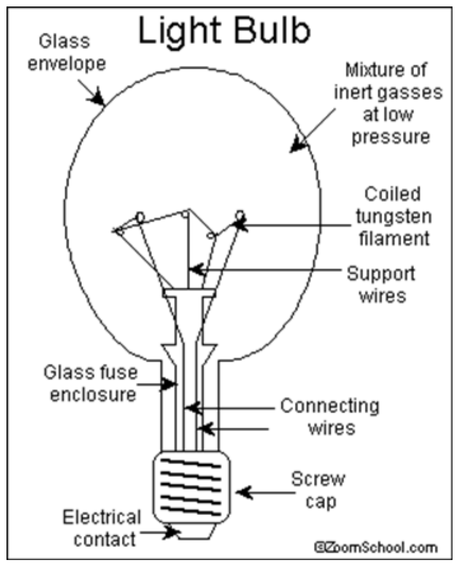
A simple and inexpensive experiment that illustrates a number of heat transfer principles is presented for use in either the laboratory or the classroom. The purpose of this paper is to describe a transient experiment which determined the heat transfer characteristics of a 100 *W* light bulb, operating at 48 *W*. The fraction of the filament power absorbed by the glass envelope was measured and the fractions of the heat transferred from the glass envelope to the surroundings were determined for natural convection, forced convection and radiation. The glass bulb absorbed 26.3% of the filament radiation. At steady state, 64% (8.1 *W*) of the heat transfer from the glass envelope to the classroom surroundings was by convection and 36% (4.5 *W*) was by radiation. The calculated natural convection heat transfer coefficient was 7.1 $\frac{W}{m^2K}$ and the experimentally determined forced convection coefficient was 12.9 $\frac{W}{m^2K}$. The effective classroom air velocity required to produce this coefficient was 0.6 $\frac{m}{s}$ (1.4 *mph*), which is in the upper range of air velocities mandated by ASHRAE Standards to keep classroom occupants comfortable in a 26°*C* (79°*F*) classroom. The experimental results indicated that very little of the heat transfer from the filament to the glass bulb occurred by convection through the argon/nitrogen atmosphere within the bulb; essentially all heat transfer from the filament to the bulb was by radiation.

Introduction

One of the main objectives of engineering education is to effectively transfer subject information to the engineering students. A number of methods have been developed for enhancing student learning including multimedia developments,[1,2] active, problem-based learning,[3] collaborative learning,[4,5] and participation in cooperative education.[6] Several papers have specifically addressed methods for improving or supplementing the teaching of engineering including the use of spreadsheets to solve two-dimensional heat transfer problems,[7] the use of a transport approach in teaching turbulent thermal convection,[8] the use of computers to evaluate view factors in thermal radiation,[9] implementation of a computational method for teaching free convection,[10] and the use of an integrated experimental/analytical/numerical approach that brings the excitement of discovery to the classroom.[11]

Since many students learn best when exposed to hands-on exercises,[12] the importance of developing these types of activities cannot be overemphasized. A number of hands-on activities have been suggested for use in the laboratory or classroom, including rather novel experiments such as racecar-based laboratory exercises,[13] the drying of a towel[14] and the cooking of French fry-shaped potatoes.[15] Several examples for the integration of hands-on engineering material into the laboratory and classroom have been described by Penney and Clausen,[16-24] who presented a number of simple hands-on fluids and heat transfer experiments that can be constructed from materials present in most engineering departments. This cross-course integration of course material has been shown to be a very effective learning tool that causes students to think beyond the content of each individual course.[25]

Heat transfer from a simple light bulb is pertinent in our everyday lives. Every building, every store and every vehicle have light bulbs. Standing on a stage with full lighting overhead, or simply hovering a hand over a lit bulb demonstrates the heat transfer from a light bulb. Incandescent light bulbs only emit about 9% of their radiation in the visible spectrum; the remainder is wasted. A significant portion of the wasted energy is absorbed by the glass envelope surrounding the filament. This absorbed energy is then transferred by convection and radiation to the environment. The experiment described in this paper measures parameters associated with this heat transfer to determine (1) the fraction of the filament radiation absorbed by the glass bulb, (2) the combined heat transfer coefficient for the bulb, (3) the natural convection heat transfer coefficient of the bulb, and (4) the forced convection coefficient for the bulb. This experiment is ideal for use as a laboratory experiment and/or as a classroom demonstration because of its simplicity and coverage of a number of heat transfer principles.



The incandescent light bulb is a marvel of modern technology. Riveros and Oliva[26] present an excellent explanation of the key parts of a light bulb. The accompanying diagram was taken from http://www.enchantedlearning.com/inventors/page/i/incandescentbulb.shtml as an aid in understanding the description. "*The three main components of an incandescent lamp are: the metallic filament (usually tungsten) with a high melting point; the bulb envelope made of glass, which is empty or partially filled with an inert gas, to prevent oxidization of the element; and the base of the lamp, which includes the two separate electrodes (metallic threaded base and the eyelet) and the glass tube (which seals the lead-in wires). The pressure of the gas reduces the evaporation rate but increases the convection losses, so that lamps below 25 W are in a low vacuum. To increase the visible light production, tungsten filaments need to be heated to high temperatures (between 2700 K and 2900 K), producing a small change in colour from yellow to white for illumination. However, infrared radiation is always produced, reducing the efficiency of the visible light emission.*"

The glass bulb for a 100 *W* bulb weighs about 13 *g*, is 6 *cm* in diameter and is about 0.4 *mm* thick. The glass is almost transparent to radiation in the visible spectrum, but is increasingly

opaque to radiation above a 2.5 μm wavelength. A tungsten element operating at 2800 *K* emits a significant fraction of it radiation at wavelengths exceeding 2.5 μm. An excellent video about the complex spiral within a spiral tungsten element is available on Mr. Barlow's Blog.[27]
The glass envelope is filled to about 0.7 *atm* with argon/nitrogen gas to prevent evaporation of the tungsten filament. The filament operates at about 2800 *K* and only produces about 9% of its light in the visible spectrum.[28] Much of the radiation from the filament is in the infrared region, where the glass is practically opaque.[28]

Equipment and Procedures

The following paragraphs describe the equipment and materials, experimental procedures and safety considerations in performing the experiment.

Equipment List

The equipment and supplies used in the experiment were as follows:

- 100 *W*, 115 *V* Sylvania Double Life Clear glass tungsten filament light bulbs, 2
- Omega Precision Fine Wire thermocouple (0.003 *in* (0.008 *mm*) diameter)
- Omega HH12 thermocouple reader
- Stopwatch
- Porcelain ceramic light socket
- EXTECH, Model DW-6060 wattmeter
- Digital caliper
- Laboratory ring stand
- Mettler Toledo AB104-S analytical balance
- STACO Energy Products, 120 *V* variable autotransformer
- Transparent tape

Experimental Apparatus

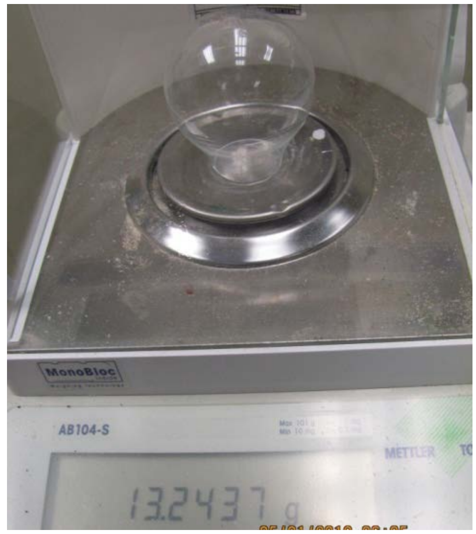
The experimental apparatus (Figure 1) consisted of a light bulb, in its socket, attached horizontally to a standard laboratory ring stand. A thermocouple was taped to the bulb as shown in Figure 1. A variable voltage transformer was used to reduce the power drawn from a standard room outlet from 100 *W* to 48 *W*, as measured by the wattmeter. The reduced power was used to slow the rate at which the bulb heated as it was lit.

An identical second light bulb had its base removed for weighing the glass envelope. Figure 2 is photograph of this bulb, sitting on the analytical balance. The mass of the bulb was 13.24 *g*. Figure 3 shows the caliper used to measure the bulb diameter of 6 *cm*.

Experimental Set-up and Procedure

The following procedure was used in assembling the apparatus and conducting the experiment:

- A glassblower removed the metal cap and the diameter and mass of a bulb was measured.
- The light bulb was attached to the ring stand using a laboratory clamp.



- The thermocouple was taped to

the bulb using transparent tape.

- The voltage toggle switch set to "off" and the voltage control knob was rotated to 30%.
- The ambient temperature was recorded.

Figure 2. Cut-away Bulb being Weighed

Figure 3. Caliper Measuring Bulb Diameter

Figure 1. Photograph of Experimental Apparatus

- The voltage toggle switch was moved to 120 *V*, giving a power output of 48 *W*.
- The time was recorded for each 3°*C* increase in bulb temperature, until the temperature reached 60°*C*; from 60°*C* to 80°*C*, the time was recorded for each 2°*C* rise; and, above 80°*C*, the time was for each 1°*C* rise until the bulb temperature reached steady state, as determined by nearly constant temperature with time.
- The experiment was repeated.

Safety

- Safety glasses, closed toed shoes, and long pants were worn during the experiment.
- Caution was exercised to avoid touching the hot bulb.
- The bulb was allowed to become cool to touching before removing it from the ring stand.

- Care was taken in handling the cutaway light bulb envelope avoid contact with the sharp cutaway edges.

Experimental Results

Table 1 presents the experimental results as incremental times between temperatures. The two incremental times were averaged and an elapsed time was computed and included in Table 1.

Table 1. Raw Experimental Data

Temp (°*C*)	Time Run 1 (*s*)	Time Run 2 (*s*)	Average Time (*s*)	Time Elapsed (*s*)
24	3.4	3.5	3.45	3.45
27	2.2	2.1	2.15	5.60
30	2.3	2.2	2.25	7.85
33	2.4	2.6	2.50	10.35
36	2.3	2.3	2.30	12.65
39	2.5	2.6	2.55	15.20
42	2.3	2.2	2.25	17.45
45	3.3	3.2	3.25	20.70
48	3.1	3.0	3.05	23.75
51	3.3	3.7	3.50	27.25
54	3.6	3.9	3.75	31.00
57	4.0	3.9	3.95	34.95
60	2.1	2.3	2.20	37.15
62	2.0	1.9	1.95	39.10
64	3.5	3.2	3.35	42.45
66	3.8	4.2	4.00	46.45
68	3.1	3.1	3.10	49.55
70	2.3	2.3	2.30	51.85
72	5.4	5.3	5.35	57.20
74	3.1	3.2	3.15	60.35
76	6.5	6.4	6.45	66.80
78	6.6	6.7	6.65	73.45
80	5.4	5.3	5.35	78.80
81	2.8	1.9	2.35	81.15
82	3.4	9.8	6.60	87.75
83	6.0	7.3	6.65	94.40
84	7.0	3.2	5.1	99.50

85	6.0	5.8	5.9	105.80

Data Reduction

The experimental data can be used to determine the heat transfer characteristics of the light bulb, including the fraction of the filament power absorbed by the glass bulb; the fractions of the heat transfer to the environment by convection and radiation and, by using correlations from the literature for natural convection and combined (i.e., natural and forced) convection, the heat transfer coefficients for natural and forced convection.

Glass Envelope Absorption Filament Radiation

To determine the absorptivity of the glass, a transient heat balance was written for the spherical bulb at time zero:

$$Q_i - Q_o + Q_g = Q_a \qquad [1]$$

Because $T_s = T_a$ at $t = 0$, the convection and radiation terms in Q_i and Q_o are zero. Thus,

$$Q_g = Q_a \qquad [2]$$

where Q_g is the heat absorbed by the glass as the thermal radiation from the filament passes through it and Q_a is the accumulation of heat in the glass. Thus,

$$Q_g = mC_p \frac{dT_s}{dt} \qquad [3]$$

where $\frac{dT_s}{dt}$ is the initial rate of bulb temperature rise ($1.27\ \frac{K}{s}$ from Figure 4, in which the experimental data are plotted as T_s vs. t), m is the bulb mass (13.24 g) and C_p is the glass heat capacity, 750 $\frac{J}{kgK}$. Then, $Q_a = Q_g = 12.6\ W$.

The fraction of filament radiation absorbed by the glass envelope at the initial instant of heating is $f = Q_g/Q_e = 12.6/48 = 0.263$. At the initial instant of heating, the heat transfer by convection from the filament to the glass bulb is precisely zero.

Combined Convection Heat Transfer Coefficient

The determination of the combined convection heat transfer coefficient starts with a heat balance over the glass bulb at steady state when, Q_i and Q_a are both zero.

$$Q_g = Q_o = Q_c + Q_r = h_c A_s (T_s - T_a) + \sigma \varepsilon A_s (T_s^4 - T_a^4) \qquad [4]$$

The radiation heat transfer from the bulb to the classroom is 4.6 W, and $Q_g = Q_o = 12.6\ W$, $Q_c = 8.0\ W$, $D = 6\ cm$ and $A_s = \pi D^2 = 0.011 m^2$. As a result, $h_c = 12.9\ \frac{W}{m^2K}$.

Natural Convection Heat Transfer Coefficient

The heat loss by combined convection is by natural and forced convection. The natural convection coefficient can be calculated by a literature correlation[28]

$$Nu_n = \frac{h_n D}{k} = 2 + \frac{2+0.589Ra^{0.25}}{\left[1+\left(\frac{0.469}{Pr}\right)^{0.63}\right]^{0.444}} \qquad [5]$$

With $k = 0.0274\ \frac{W}{mK}$, $\nu = 1.85E\text{-}5\ \frac{m^2}{s}$, $\beta = 1/327\ K^{-1}$, Pr = 0.723, Gr = 1.4E6 and Ra = GrPr, $h_n = 7.6\ \frac{W}{m^2K}$.

Forced Convection Heat Transfer Coefficient

In order to determine the forced convection heat transfer coefficient, a correlation[28] for the combined coefficient as a function of h_n and h_f must be used

$$Nu_c = (Nu_n^{\,n} + Nu_f^{\,n})^{1/n} \rightarrow h_c^{\,n} = h_n^{\,n} + h_f^{\,n} \rightarrow h_f = (h_c^{\,n} - h_n^{\,n})^{1/n} \qquad \text{(Note: used } n = 3\text{)} \qquad [6]$$

With $h_c = 12.9\ \frac{W}{m^2K}$and $h_n = 7.6\ \frac{W}{m^2K}$, $h_f = 11.9\ \frac{W}{m^2K}$.

Thus, the forced convection heat transfer coefficient was not measured. Is the resulting value reasonable for a classroom with an ambient temperature of 26°*C* (79°*F*)? To answer this question, it is essential to know what air velocity would yield this value of h_f. h_f can be determined from a forced convection correlation[28] for spheres

$$Nu_f = 2 + [0.4Re^{1/2}\ 0.06Re^{2/3}]Pr^{0.4}\left(\frac{\mu_b}{\mu_s}\right)^{0.25} \qquad [7]$$

with $Nu_f = \frac{h_f D}{k} = 26$, $Pr = 0.723$ and $\mu_b \approx \mu_s$, $Re = \frac{VD}{\nu} = 2{,}000$ and $V = 0.62\ \frac{m}{s}$ (1.4 *mph*). In the very next section the reasonableness of this value will be discussed.

Discussion of Results

Figure 4 is a plot of the bulb surface temperature, T_s, as a function of time, t. The data are fitted nicely with a second order polynomial in T_s and t. As was noted earlier, the slope of the plot at time zero (i.e., $\frac{dT_s}{dt}$ in Equation 3) is 1.27 $\frac{K}{s}$.

Assuming free convection is negligible as a mode of heat transfer between the filament and the glass bulb, the fraction of heat radiated by the filament which is absorbed by the glass bulb is 0.263. This value could be verified independently by using Figure 12-9 from Cengal and Ghajar[28], which presents the black body emissive power vs. radiation wavelength for various source temperatures from 100 *K* to 5800 *K*, in conjunction with Figure 12-36 from Cengal and Ghajar,[28] which presents spectral transmissivity of low-iron glass as a function of radiation wavelength and glass thickness. These calculations were not carried out because all the other results of this experiment indicate that the measured factional absorption of 26% is reasonable.

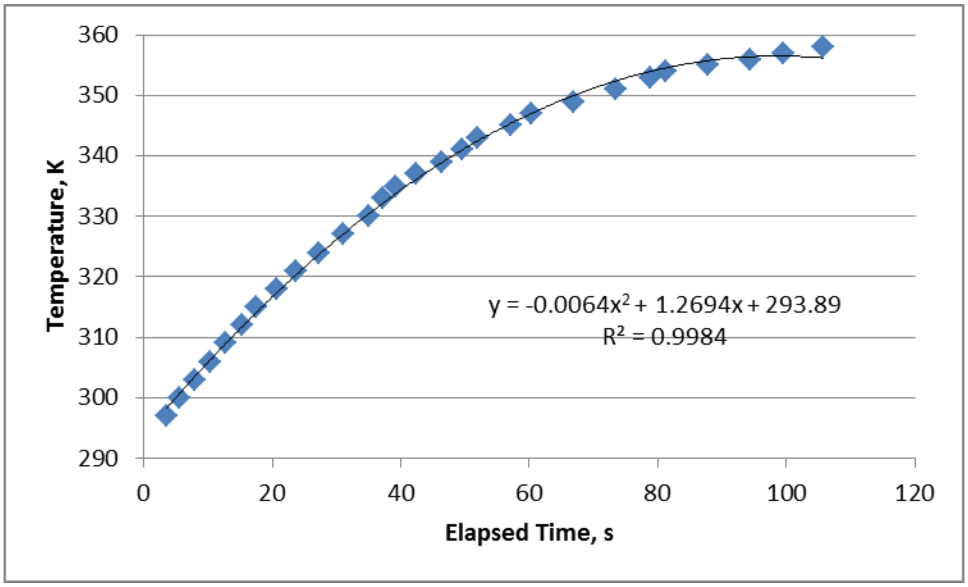


Figure 4. Plot of Experimental Data: Bulb Surface Temperature as a Function of Elapsed Time

Table 2 summarizes the quantitative results of this experiment. The back-calculated forced convection coefficient is 160 % of the natural convection coefficient. Is this reasonable? ASHRAE Standard 55P[29] indicates that this is reasonable because Figure 5.2.3-1 of the proposed standard shows that an air speed of $0.6\ \frac{m}{s}$ (1.4 *mph*) will offset a room temperature increase of $4°F$ above the operative comfort temperature of $75°F$.

Table 2. Summary of Experimental Results

Fractional absorptivity of the glass bulb	0.263
Heat transfer due to …	
Radiation, Q_r	$4.6\ W$
Convection (natural + forced), Q_c	$8.0\ W$
Percent of heat transfer due to . . .	
Radiation	36 %
Convection	64 %
Heat transfer coefficient for . . .	
Combined natural and forced convection, h_c	$12.9\ \frac{W}{m^2K}$
Natural convection, h_n	$7.6\ \frac{W}{m^2K}$
Forced convection, h_f	$11.9\ \frac{W}{m^2K}$
Velocity to produce h_f from correlation	$0.62\ \frac{m}{s}$ (1.4 *mph*)

Conclusions

1. A simple but effective incandescent light bulb experiment, using readily available materials and equipment, was developed for use in the classroom and/or laboratory.
2. The fraction of filament radiation absorbed by the bulb was 26 %. This value is reasonable based on the wavelengths of radiation produced by the element and based on other reasonable results of the experiment.
3. Forced convection in the classroom was greater than natural convection by a ratio of 1.6. From literature correlations, the air velocity required to produce the forced convection coefficient is 0.62 $\frac{m}{s}$ (1.4 *mph*). This value is within the ASHRE guidelines for room air speeds allowed to offset room temperatures above the comfort zone temperature at a lower air speed of 0.4 $\frac{m}{s}$.
4. The experimental results indicate that, at steady state, the convection component of heat transfer from the filament to the bulb is very small relative to the radiation component.

Nomenclature

Latin Symbols

A_s	Surface area of the bulb, m^2
C_p	Specific heat of glass, $\frac{W}{kgK}$
D	Bulb diameter, m
f	Fraction of the filament radiation which is absorbed by the glass envelope
g	Gravitational acceleration, $\frac{m}{s^2}$
h_c	Combined (natural + forced) convection heat transfer coefficient, $\frac{W}{m^2K}$
h_f	Forced convection heat transfer coefficient, $\frac{W}{m^2K}$
h_n	Natural convection heat transfer coefficient, $\frac{W}{m^2K}$
k	Thermal conductivity of air, $\frac{W}{mK}$
m	Mass of the bulb, kg
Q_a	Accumulation term in the heat balance equation, $= mC_p\frac{dT_s}{dt}$, W
Q_c	Heat loss from the glass bulb by combined natural and forced convection, W
Q_e	Measured power input to the light bulb from the electrical source, W
Q_g	Heat generation term in the heat balance equation, W
Q_i	Heat input term in the heat balance equation, W
Q_o	Heat output term in the heat balance equation, W
Q_r	Heat loss from the glass bulb by radiation to the classroom environment, W
t	Time measured from the start of power input to the light bulb, s

T_a Ambient temperature, K; also, steady state surface temperature, K
T_s Bulb surface temperature, K
V Air velocity required to produce h_f, $\frac{m}{s}$

Greek Symbols

β Volume expansion coefficient, K^{-1}
μ Kinematic viscosity, $Pa\ s$
ε Surface emissivity of the tungsten filament
σ Stefan–Boltzmann constant, $\frac{W}{m^2K^4}$
ν Kinematic viscosity of air, $\frac{m^2}{s}$

Dimensionless Parameters

Gr Grashoff number, $\frac{g\beta(T_s-T_a)D^3}{\upsilon^2}$
Nu_c Nusselt number, $\frac{h_cD}{k}$, combined natural and forced convection
Nu_f Nusselt number, forced convection
Nu_n Nusselt number, natural convection
Re Reynolds number, $\frac{VD\rho}{\mu}$, required to produce the forced convection coefficient, h_f
Ra Rayleigh number, $GrPr$

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