ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #20876

WIP: Exploring Light Bulb Technologies to Teach Conservation of Energy, Numerical Integration, and Consumer Consciousness

Dr. Kaitlin Engle Mallouk, Rowan University

Kaitlin Mallouk has been an Instructor in the Mechanical Engineering and Experiential Engineering Education Departments at Rowan University since 2013. Kaitlin has a BS in Chemical Engineering from Cornell University and an MS and PhD in Environmental Engineering in Civil Engineering from the University of Illinois.

Dr. William T. Riddell, Rowan University

William Riddell is an Associate Professor in the Civil and Environmental Engineering department at Rowan University. His interests include energy, infrastructure, mechanics and materials. Prior to joining Rowan, he worked at the John A. Volpe National Transportation Systems Center, and was a National Research Council postdoctoral fellow in the Mechanics of Materials Branch at NASA Langley.

Mr. Karl Dyer, Rowan University

Karl Dyer is a Mechanical Engineering Technician at Rowan University. He received his B.S. in mechanical engineering and M.S. in electrical engineering from Rowan University.

WIP: Exploring Light Bulb Technologies to Teach Energy Conservation, Numerical Integration, and Consumer Consciousness

Kaitlin E. Mallouk, William T. Riddell, Karl B. Dyer
Rowan University, mallouk@rowan.edu, riddell@rowan.edu, dyerk@rowan.edu

Abstract - **In a freshman engineering course, one objective is to introduce multidisciplinary teams of engineering students to unifying engineering and science principles such as mass, momentum and energy balances; materials; thermodynamics, and electricity and magnetism using a consumer product or engineering process as a test bed. In several of the course sections, the test bed was a Net Zero Energy Building (NZEB). A NZEB is a building that, over the course of a year, produces as much energy as it consumes. One lab activity associated with this project was experimentally determining the most energy efficient of several types of light bulbs. Students measured the visible light output, power consumption, and surface temperature of four different bulb types (incandescent, halogen, compact fluorescent, and LED) and then determined the efficiency of the bulbs and considered the implications for a NZEB and their own home. In the lab, student teams measured illuminance as a function of angle for each bulb, converted that illuminance to a luminous flux using numerical integration, and then converted to radiant flux and power. Students then calculated the fraction of the power consumed by the bulb that was used to produce light. Students' results showed LED bulbs were the most efficient and incandescent bulbs were the least efficient. While this is, perhaps, an obvious finding, the addition of the bulb temperature measurement brought to life the First Law of Thermodynamics. In their reports students commented on the inverse relationship between efficiency and bulb temperature and related their results to NZEBs, indicating that LED bulbs would be preferable not only for their high energy efficiency, but for their low residual heat. This paper will describe the details of the laboratory set up and assignment, highlight the intellectual scaffolding that was provided to students, and present future assessment plans.**

Index Terms - Energy, laboratory project, numerical integration, Excel, measurements, lighting, freshman

INTRODUCTION

At Rowan University, all freshman engineering students take a two-semester engineering clinic course designed to introduce them to many of the topics they will need throughout their engineering careers (*e.g.,* measurements, units and dimensions, statistics, engineering economics, etc.), as well as to develop the professional skills outlined in the ABET A-K outcomes. In the second semester, students from six engineering majors work in interdisciplinary teams on faculty-designed projects that introduce them to unifying engineering science principles such as mass, momentum and energy balances; materials; thermodynamics; and electricity/magnetism using a consumer product or engineering process as a test bed. In Spring 2017, five sections with 19 to 22 students each used a Net Zero Energy Building (NZEB) as the test bed for the project. NZEBs are structures that produce as much energy as they consume over the course of a year. This energy balance is achieved through production via photovoltaic cells and reduction of consumption through insulation, supersealing, highly efficient windows, implementation of overhangs and thermal mass, and using low energy appliances [1]. While "reverse engineering" the NZEB, students conducted experiments related to dissection of a mechanical thermostat, solar power, heat transfer, hot water heater design, and energy consumption of light bulbs.

The goals of the light bulb experiment ("light bulb lab") were to introduce students to principles of lighting, and conservation of energy; give students experience with numerical integration in Excel; and encourage students to consider their energy consumption habits. The basics of the light bulb lab have been described previously [2], but the experiment in its current form will be described in detail here to allow for implementation in other programs.

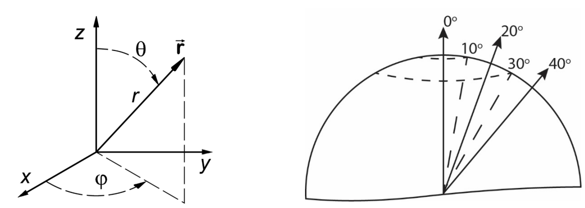
BACKGROUND INSTRUCTION

Throughout the course, topics related to energy consumption and sustainability had been covered in the framework of NZEBs. Students were introduced to the Intergovernmental Panel on Climate Change, the Department of Energy's Zero Energy Ready Home program, typical energy consumers in a home, and worldwide sources of energy (fossil fuels such as coal, natural gas and oil, nuclear, hydro, and sustainable sources such as solar, wind, geothermal, and micro-hydro). This information provided motivation to examine ways to reduce energy consumption in a home, one of which is to use the most energy efficient lighting available.

To deliver relevant scientific principles of the light bulb lab, students were provided with a detailed hand out and lectures. Together, these delivery mechanisms provided information regarding conservation of energy, illuminance, luminous flux, radiant flux, monochromatic light sources, and power spectra density of visible wavelengths for incandescent, halogen, compact fluorescent (CFB), light emitting diode (LED), and High-Color Rendering Index (CRI) LED bulbs. For example, the lab handout includes (1) that converts the illuminance [lx] measured by light meters to luminous flux [lm] using the summation method and the coordinate system shown in Figure 1A.

$$\Phi_v = \sum_{i=1}^{n} SA_i \, E_v(\theta_i) \tag{1}$$

Where SA_i and $E_v(\theta_i)$ are the surface area and illuminance associated with θ_i, respectively, and $\theta_1 = 0°$, $\theta_n = 180°$ and the rest of the θ_i range uniformly between 0 and 180°. Equations for SA_i can be derived from the equation for the surface area of a spherical cap (2, 3) (Figure 1B).



A B

FIGURE 1
A. COORDINATE SYSTEM FOR ANALYSIS. ASSUME THE CENTER OF THE BULB IS AT THE ORIGIN AND THE BULB IS ALIGNED ALONG THE Z-AXIS [3]. B. DIAGRAM OF SPHERICAL CAP SURFACE AREA. THE ARROWS SHOW THE DIRECTION OF E_v MEASUREMENTS FOR THE FIRST THREE θ'S. THE SMALLER DASHED LINES SHOW THE SA_i'S ASSOCIATED WITH θ_1 AND θ_3, RESPECTIVELY.

$$SA_1 = SA_n = 2\pi r^2 \left[1 - cos\left(\frac{\theta_1 + \theta_2}{2}\right)\right] \tag{2}$$

$$SA_i = 2\pi r^2 \left[cos\left(\frac{\theta_{i-1} + \theta_i}{2}\right) - cos\left(\frac{\theta_i + \theta_{i+1}}{2}\right)\right] \quad for\ \mathrm{i = 2\ to\ n - 1} \tag{3}$$

Alternatively, if $E_v(\theta)$, illuminance as a function of θ can be estimated, then (4) can be used to determine luminous flux.

$$\Phi_v = 2\pi r^2 \int_0^{\pi} E_v(\theta) \, sin\theta \, d\theta \tag{4}$$

In addition, students were provided with an Excel document that was populated with the results (but not the equations) of sample calculations for an ideal light source. Students were then challenged to characterize the various bulbs by finding the pattern of emitted light with respect to the angle from the bulb axis, as well as to calculate the total lumens emitted. This required students to determine the appropriate equations to put into Excel, which they could then use with their experimentally generated data. Excel tasks that were required to complete the module included simple arithmetic operations, plotting data in radar and scatter charts, adding trend lines to scatter chart data, using the LINEST function to obtain coefficients from the trend lines fit to data, and using the SUM function.

Finally, students were provided with each bulb's packaging material, which included the rated power and luminous flux for the bulb. Students' measured results would be compared to the manufacturers' specifications as part of the data analysis.

EXPERIMENTAL SET UP

Each experiment was conducted with four 40 W equivalent bulb types: incandescent, halogen, CFB, and LED.

Illuminance Measurements

Figure 2 shows the experimental set up for measuring illuminance from a given bulb. A light socket connected to a clamp was plugged into a Kill-A-Watt meter, which was plugged into a wall receptacle. The bulb was screwed into the light socket and the clamp was attached to a custom stand constructed of a piece of 2x4 with two feet used for stability and positioning a protractor. The stand also included a piece of 1.5 m string with a marking at 1.0 m to indicate where students should hold the light meter.

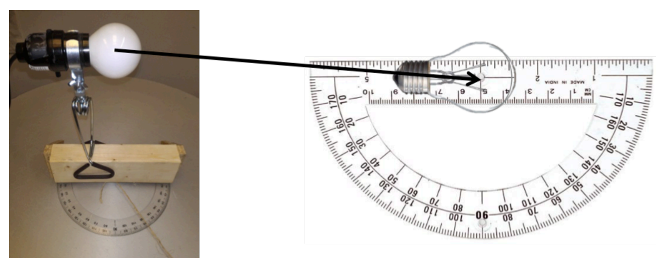


FIGURE 2
ILLUMINANCE TEST RIG CONSISTING OF A CUSTOM BULB STAND AND PROTRACTOR.

Testing was conducted in a dark room and each team was provided with a trifold poster board spray painted flat-black to act as a light shield from other teams' setups. Students used an Omega HHLM1 Lux Meter to measure each bulb's illuminance 1 meter from the center of the bulb in 10° increments from the top of the bulb (0°) to the base of the bulb (180°). They also recorded the power consumption from the Kill-A-Watt meter. These data were entered into the template spreadsheet and analyzed to determine the luminous flux and percentage of power consumed by the bulb that was used for luminous flux.

Temperature Measurements

Energy consumed by the bulb that is not converted to visible light is either converted to heat or non-visible electromagnetic radiation. To observe this, the surface temperature at the top of each bulb was measured with a thermocouple after the bulb had been on for 20 minutes.

DATA ANALYSIS AND INTERPRETATION

Through spreadsheet manipulation, students were able to observe the pattern for luminous flux at 1 meter for each bulb (*e.g.*, Figure 3). They used (1-3) to estimate the luminous flux from the data via the summation method. They also created plots of sin(θ) x $\boldsymbol{E_v}$ as a function of angle (*e.g.*, Figure 4) and subsequently used the line fit of the plotted values to calculate the luminous flux using the trapezoid rule via (4). Finally, students determined the estimated efficiency of the bulb assuming that the bulb was monochromatic at 555 nm.

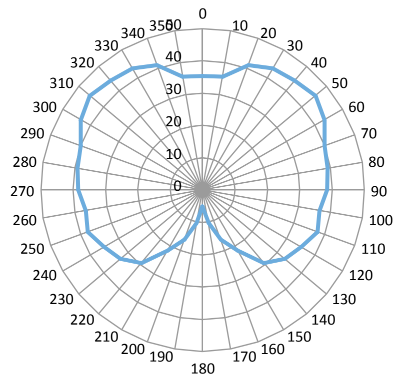


FIGURE 3
ILLUMINANCE IN LUX OF A SYLVANIA 26957 CFB MEASURED AT 1 M.

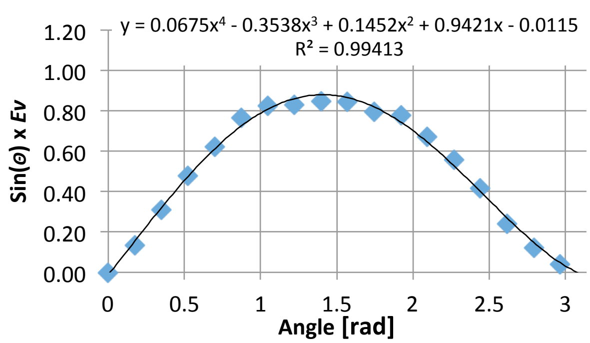


FIGURE 4
ROTATED ANGLE X OBSERVED LUX OF A SYLVANIA 26957 CFB MEASURED AT 1 M. THE ANGLE REPRESENTS ONE-HALF OF THE BULB AND SYMMETRY IS ASSUMED FOR THE COMPLEMENTARY DATA.

The luminous flux measurements that were calculated using the summation and trapezoid methods were compared to understand the relative advantages of each method. The values were also compared to the manufacturers' specifications from the product packaging. The results were then converted to an equivalent radiant flux assuming a monochromatic light source with a wavelength of 555 nm. This assumption of a monochromatic light source was a conscious simplification – including the standard luminosity function, which provides the relative sensitivity of the human eye for each wavelength of light would have added several more columns to an already complicated Excel file without much additional learning.

Once students had determined the radiant flux for each bulb, they were able to determine what fraction of the total power consumed by the bulb went to radiant flux. This experimentally determined value ranged from 4% for incandescent bulbs to 30% for LED bulbs. The temperature data students collected supported this finding, with LED bulbs having surface temperatures of approximately 35°C and incandescent bulbs having surface temperatures >150°C. From these data students could see that energy that was not being used to produce light was instead being used to produce heat. The lower efficiency bulbs are detrimental for net zero houses for two reasons: they consume more energy to produce the equivalent light, but they also produce heat, which in a well-insulated, air-tight space would require additional energy to mitigate.

DELIVERABLE

Students submit team-written lab reports to document their efforts. In the report students are required to include the equivalent of Figures 3 and 4 for each of the four types of bulbs they tested as well as an explicit comparison of their findings to the manufacturers' specifications.

FUTURE WORK

While this lab has been run successfully in several sections of the second-semester freshman engineering course, data regarding its learning outcomes and student perceptions has not been collected. In the future we plan to give students a pre- and post-test to assess how their knowledge of the relevant topics (conservation of energy, illuminance, luminous flux, etc. changes as a result of completing this lab.

ACKNOWLEDGMENT

Paris Von Lockette for idea generation in the early stages of the development of this laboratory.

REFERENCES

[1] Newell, T, Newell B, "Net Zero Energy Project", *ASHRAE Journal,* 2010, 88.

[2] Riddell, W.T., VonLockette, P.R., "Freshman Engineering Projects Related to Home Energy Use", *2013 ASEE Northeast Section Conference,* Norwich University, March 14-16, 2013.

[3] P. Wormer, "Citizendium Website," 2008. [Online]. Available: http://en.citizendium.org/wiki/File:Spherical_polar.png. [Accessed 2 Feb 2016].

AUTHOR INFORMATION

Kaitlin E Mallouk, Tenure-Track Instructor, Rowan University, mallouk@rowan.edu

William T. Riddell, Associate Professor, Rowan University, riddell@rowan.edu

Karl B. Dyer, Technician, Rowan University, dyerk@rowan.edu