Lab # 3

Experiment # CV1
Stefan-Boltzmann Law

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ME 326, Section B
Heat and Mass Transfer Lab
Group 2

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Abstract

The main purpose of the lab was to verify the accuracy of the Stefan-Boltzmann Law, as well as the Stefan-Boltzmann constant, denoted s. A black plate, connected to a thermocouple, was heated by a radiation source where a nearby radiometer detected the heat flux from the plate. A console that displayed the temperature and heat flux of the plate also controlled the percentage of power to the radiation source. Temperature of the surface, heat flux, and power setting were recorded for two separate trials of which five sub-trials were taken for both of the trials. The radiometer was stationed at 110 mm (trial 1) and 220 mm (trial 2) from the radiation source, while the black plate was held at a constant distance of 50 mm. The power setting was varied from 50%-90% to alter the temperature and heat flux for the trials. For the first trial, the percent error was 11.68% when the experimental and theoretical Stefan-Boltzmann constants were compared. However, for the second trial, the percent error was much higher—60.6%. The calculated Stefan-Boltzmann constants for each trial were never more than a few tenths apart, meaning that the behavior of the experiment was stable and predictable.

Introduction

In applications of radiation, the heat flux generated by a surface is proportional to the fourth power of absolute temperature. The constant that relates to this proportionality is called the Stefan-Boltzmann constant (s) and has been scientifically and experimentally proven to be $5.67*10^{-8}$ W/(m^2K^4). It is similar to conduction and convection coefficients, but differs because the surface or fluid interfaces do not affect the heat flux generated—the coefficient is always constant. The Stefan-Boltzmann Law relates the absolute temperature of the object minus the surrounding temperature with the heat flux. When performing the experiment, a black plate was set in front of the radiation source and the temperature of the plate was recorded as the radiation increased. To note, the radiation recorded by the radiometer was not the actual heat being generated over the face of the plate. Instead, the plate had a geometrical factor as to how the heat was dispersed over the plate. So the heat flux was to be multiplied by a factor of 5.59R. For the entire experiment, the constant of proportionality was calculated and compared to the known value for each trial, while the behavior of the radiation was analyzed in a graphical format [1].

Procedure and Experimental Data

The setup of the Stefan-Boltzmann Law used a radiation source, a mounted adjustable track integrated with a measuring stick, a radiometer, and a black plate. A console that displayed plate temperature and radiation heat flux values had lead wires from a radiometer and a thermocouple connected to the ports of these displays. The black plate was mounted on the track 50 mm away from the radiation source. Thermocouples, which sense temperature, were attached to the plate. Since the plate and air were in thermal equilibrium, the surrounding temperature could be recorded before heating the plate. The surrounding temperature was recorded at $T_{surr}=26^oC$. This value would later be used in determining the Stefan-Boltzmann constant. Positioning the radiometer 110 mm away from the radiation source, it was connected to the console's display and set facing towards the plate to detect heat flux. The console had a knob to adjust the percentage of power being delivered to the radiation source. Using this knob, five trials were done while varying the power to the heat source in increments of 10% beginning at 50% power and ending at 90%. This in turn altered the temperature and heat flux readings of the plate, which were recorded in a tabular format. A second trial was repeated with the black plate at the same distance of 50 mm from the radiation source while the radiometer was moved to 220 mm. Instead of setting the dial back to 50%, the first temperature, heat flux, and setting readings were taken at 90% power and worked backwards to 50% in decrements of 10%. Tables 1 and 2 show the two trials recorded data as well as units to the values.

Table 1. Experimental Data for Trial 1.

Temperature (^oC)	R (W/m^2)	Setting
65	60	50%
81	89	60%
91	109	70%
118	175	80%
142	245	90%

Table 2. Experimental Data for Trial 2.

Temperature (^oC)	R (W/m^2)	Setting
85	54	50%
101	73	60%
112	88	70%
134	122	80%
143	140	90%

Results, Discussion, and Analysis

The results obtained from the radiometer and thermocouples were accurate for the first trial. However, the second trial was less accurate but followed a similar behavior as that of the first. As the radiation source increased its thermal output, the plate increased in temperature thereby increasing the radiation detected by the radiometer. In order to properly calculate the Stefan-Boltzmann constant, the temperature was converted to the absolute scale, or Kelvin, and the recorded radiation was modified by the geometrical factor of the black plate. Equations 1 through 3 show the modification factors and how to calculate the Stefan-Boltzmann constant.

$$Kelvin = 273.15 + Celsius \quad (1)$$

$$q_b" = 5.59 * R \quad (2)$$

$$\sigma = \frac{q_b"}{T_{plate}^4 - T_{surr}^4} \quad (3)$$

Sample Calculations:

Using Trial 1, 50% power setting, the temperature was converted to Kelvin (equation 1) and the detected radiation was modified with the geometric factor (equation 2).

$$273.15 + 65^oC = 338.15\ K \qquad and \qquad 273.15 + 26^oC = 299.15\ K$$

$$5.59 * 60 \frac{W}{m^2} = 335.40 \frac{W}{m^2}$$

Afterwards, using this information and the recorded surrounding temperature (26°C), the Stefan-Boltzmann constant was calculated (equation 3).

$$\sigma = \frac{q_b"}{T_{plate}^4 - T_{surr}^4} = \frac{335.40}{338.15^4 - 299.15^4} = 6.62 * 10^{-8} \frac{W}{m^2K^4}$$

An average value for the constant s was calculated to compare with the known value $5.67*10^{-8}$ $W/(m^2\ K^4)$.[1] Table 3 shows the modified data for this experiment.

Table 3. Modified data for Trials 1 and 2.

Trial 1		Trial 2	
Temperature (K)	q_b" (W/m^2)	Temperature (K)	q_b" (W/m^2)
338.15	335.40	358.15	301.86
354.15	497.51	374.15	408.07
364.15	609.31	385.15	491.92
391.15	978.25	407.15	681.98
415.15	1369.55	416.15	782.60

The calculated Stefan-Boltzmann constant for the first trial was close to the known value of $5.67*10^{-8}$ $W/(m^2\ K^4)$. However, the second trial was not as accurate and provided a high percent error for the experiment. Shown below is Table 4 which has the calculated Stefan-Boltzmann constants for both trials.

Table 4. Calculated Stefan-Boltzmann constants.

Trial 1	Trial 2
s (W/(m^2 K^4))	s (W/(m^2 K^4))
6.62*10^{-8}	3.57*10^{-8}
6.44*10^{-8}	3.52*10^{-8}
6.36*10^{-8}	3.51*10^{-8}
6.35*10^{-8}	3.50*10^{-8}
6.31*10^{-8}	3.56*10^{-8}
Average Value	
6.42*10^{-8}	3.53*10^{-8}

As can be seen from Table 4, Trial 1 is accurate for the Stefan-Boltzmann constant with the percent error being 11.68%; however, the second trial is not as accurate with a percentage of 60.62% error, but there is a legitimate reason as to why the error was so high. The radiometer cannot sense the actual radiation emanating from the plate, but rather it senses the intensity of the radiation. As the radiometer was moved to double the distance, the intensity decreased (due to the inverse square law) and thereby lowered the Stefan-Boltzmann constant. The only way for the constant to be calculated accurately and precisely was to have the radiometer pressed against the black plate to know the real radiation heat flux being generated. Figures 1 and 2 give a graphical representation of how the temperature to the fourth power relates to the emitted radiation.

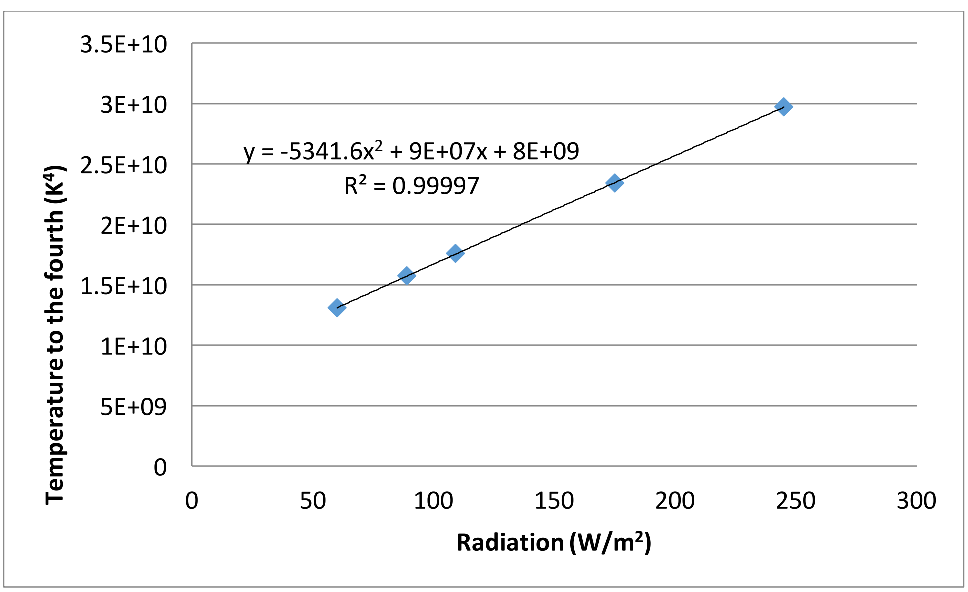

Figure1. Radiation versus Temperature for Trial 1.

The y-value points are very large making the spacing look linear rather than parabolic. The parabola is fitted with a polynomial equation and a statistical R^2 term.

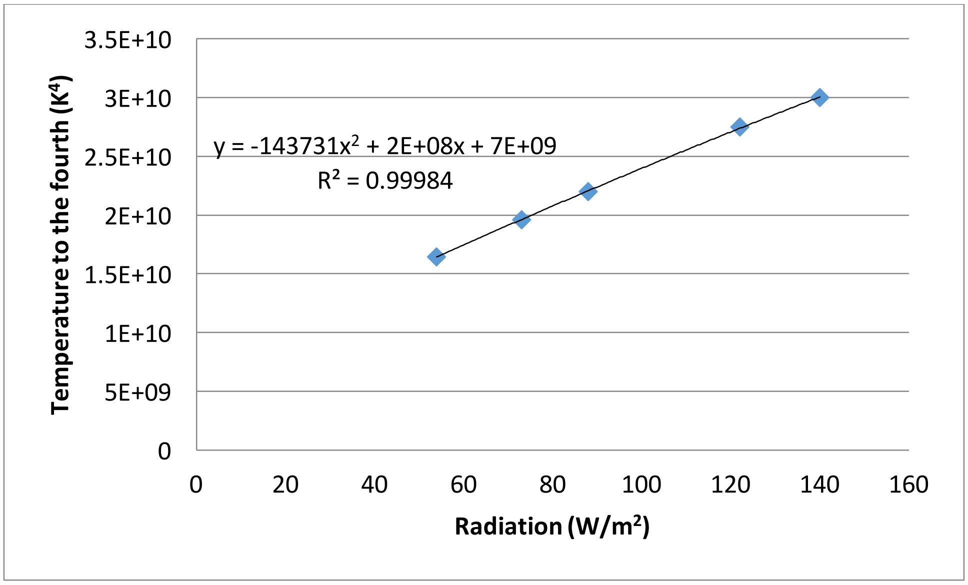

Figure 2. Radiation versus Temperature for Trial 2.

The y-value points are very large making the spacing look linear rather than parabolic. The parabola is fitted with a polynomial equation and a statistical R^2 term.

From both Figures 1 and 2, the R^2 value is one or nearly one. In statistics, the R^2 value is an indicator for the variance of all the points in a model. The farther it is from one, or 100%, the more variability in an experiment [1]. For the first trial, the R^2 term came perfectly to one meaning that there was no variance in the recorded points. The lack of error in this part of the experiment was due to how close the radiometer was to the plate and that it started in equilibrium at the beginning of the experiment. Figure 2 shows that the R^2 term was nearly one, two ten thousandths off, and showed little variance in the recorded points. This value was so close to one that it could be assumed that there is no variance. The error in the second trial was due to starting at 90% power and letting the plate cool as the setting was adjusted downwards. If the plate did not cool enough before each reading, the temperature and radiation would be greater than the equilibrium point. Overall, the Stefan-Boltzmann Law of radiation experiment was accurate numerically, graphically, and behaviorally.

Practical Application

One application of the Stefan-Boltzmann Law is increasing microwave efficiency. A heat retentive plate made from ceramic or other materials that absorb electromagnetic radiation can be used in a microwave [2]. As the plate heats up from microwave bombardment, the microwave's empty space containing air heats from convection with the plate. Over time (within 30 seconds) the air and plate come to almost the same temperature, with only minimal heat loss through the walls of the oven [2]. Using the Stefan-Boltzmann equation to determine the heat loss occurring in the microwave, it can be seen that the plate and surrounding temperature are nearly equal, thus reducing the overall heat loss in the microwave oven.

Conclusion

Both behavioral and numerical data to the Stefan-Boltzmann Law experiment were accurate. As the radiation power source increased the surface temperature of the black plate, the radiation heat flux increased. Moving the radiometer further from the plate lessened the radiation sensed by the radiometer due to the thermal intensity decreasing. After graphing the recorded points for each trial, it was determined that the relationship between the temperature to the fourth power and radiation had significant accuracy. The statistical R^2 term was one or nearly one for both Figures 1 and 2 meaning that the points would not deviate from the equation or trend line. The calculated results were also successful in that the first trial came very close to the known Stefan-Boltzmann constant, $6.42*10^{-8}$ versus $5.67*10^{-8}$ W/(m^2 K^4), yielding a percent error of 11.68%. The second trial result of $3.53*10^{-8}$ versus the actual $5.67*10^{-8}$ W/(m^2 K^4) was not accurate, displaying an error of 60.62%. However, due to the radiometer measuring intensity of radiation and not the actual heat flux from the plate, the constant was expected to decrease. The error could have been further reduced if the radiometer was closer to the plate during the second trial. Overall, the Stefan-Boltzmann Law of radiation was proved successfully by this experiment.

References

[1] Kalim, S.P. (2011). *Heat and Mass Transfer Laboratory Manual*. Division of Engineering and Physics. Wilkes-Barre, PA: Wilkes University.

[2] Ramirez, J. (2006, July 18). A practical application of the Stefan-Boltzmann Law. *Enzine*

Articles. Retrieved from http://ezinearticles.com/?A-Practical-Application-Of-The-Stefan-Boltzmann-Law&id=246054

Comments:

This is a "good report" by a good student. However, improvements that could be made:

1. The abstract is set off by being on its own page. That is good. It also is not serving as the introduction; a separate introduction section follows. It still might have been helpful to set the abstract style off somehow, such as the use of bold type.
2. The informal word "lab", used in the first sentence of the abstract, is better replaced by "laboratory exercise" if it refers to that, or to "laboratory facility," if the room is meant.
3. Needed commas are omitted in several places, notably in the introduction.
4. The introduction paragraph needs to be divides into two separate paragraphs pertaining to two different thoughts. The first paragraph states the hypothesis, the physical principle to be tested in the experiment. The material starting with, "When performing the experiment …" describes the experimental approach, and thus is a different subject and ought to have its own paragraph.
5. The first line of the Procedure section begins with, "The setup of the Stefan-Boltzmann Law used …" I think "setup" must be a favorite word among engineering students. It is so vague it can mean anything. A more explicit term for the laboratory test equipment configuration is needed, if that is what is meant. In addition, the phrase "setup of the Stefan-Boltzmann Law" implies that it is the "setup" of the "Law" itself, rather than some experimental apparatus, that is under discussion. (The vagueness of the term "setup" could mean it applies to the typeface and layout of the equation itself!) Yes, the rest of the sentence allows a reasonably intelligent reader to figure out what is going on, but it is better to use English with precision. "The experiment equipment configuration to test the Stefan-Boltzmann Law …" would be better. "Used" is also an overly vague term that is popular, but wording with greater specificity is preferred. In this case, without a complete rewrite, "included" might be marginally better. The first sentence of any section or paragraph is usually the most important; it's worth investing the effort to convey the intent as clearly as possible.
6. The Procedure section paragraph is too long, and needs to be broken up. The point at which discussion turns from configuration to conducting the exercise and collecting data would be a good place for a break to a new paragraph. A figure showing the experimental configuration would have been most helpful.
7. In equations one, units of "degrees" should have been attached to the constant. In equation two units are also needed. Similarly, in the sample calculations that follow, units need to be attached to all constants and calculated values.
8. Indentation is inconsistent; sometimes paragraphs are indented, at other times not.
9. Figures 1 and 2 have formatting problems. There should be no outer frame. There are no vertical grid lines. The "goodness of fit" information should be in the text rather than as part of the figure. (In this report the author at least makes good use of this information; in some reports it is shown in a figure but never discussed.)
10. The use of scientific notation is customary for expressing the Stefan-Boltzmann constant. The author of this paper does a good job of using unit prefixes like mm as a good alternative for scientific notation throughout the paper where appropriate.