Characteristics of Heat Transfer in a Vacuum: A Demonstration Experiment

by
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Objective:

The objectives of this experiment were to explore the heat transfer characteristics of an object in a vacuum and to fully examine the Stefan-Boltzmann law. In the course of this experiment, the students will be able to experimentally measure the Stefan-Boltzmann constant as well as the emissivities of a wide variety of engineered materials. This experiment will also emphasize the fact that the emissivity of an object is largely controlled by the surface of the object and is not a bulk property of the material.

Background:

The study of heat transfer is of great importance to nearly every field of science and engineering. Heat transfer can be broken down into three processes: conduction, convection and radiation. By utilizing the properties of a vacuum, it is possible to eliminate (or at least greatly reduce in a laboratory setting) the heat transfer by conduction and convection so that one can study the properties of radiant heat transfer. (See the appendix for calculations of mean free path for the air molecules in this experiment.)

The Stefan-Boltzmann Law (equation 1) describes the heat radiated from an object into space. However, since the surroundings of an object are also radiating heat back to the object, the net heat transfer from the object must take into account the heat being radiated back to the object from the surroundings (equation 2). From this we get equation 3 which describes the net heat flow from an object. Simplifying this equation, we end up with equation 4. [1]

$$H = e\sigma A T^4 \qquad (1)$$

$$H_{net} = H_{Radiated\_Away} - H_{Absorbed\_From\_Surrounding} \qquad (2)$$

$$H_{net} = e\sigma A T_{Rod}^4 - e\sigma A T_{Surrounding}^4 \qquad (3)$$

$$H_{net} = e\sigma A (T_{Rod}^4 - T_{Surroundings}^4) \qquad (4)$$

In this experiment, the source of the power that will ultimately be emitted by the object will be electrical, so we have an equilibrium heat balance where:

$$\text{Heat}_{\text{Input}}\ (\text{Electrical}) = \text{Heat}_{\text{Output}}\ (\text{Radiation}) \qquad (5)$$

The heat input to the system can be calculated by using Ohm's Power Law (equation 6). By performing the heat balance and equating the heat terms in equation 4 and equation 6, it is then possible to solve for the desired quantity which, is either emissivity or the Stefan-Boltzmann constant, depending on the goal of the particular experiment (equation 7). Since the emissivity is typically not a strong function of temperature over a small temperature range and since the range of temperature in this experiment is less than 50°C (rod is between 240° and 290° C during experiments), it is safe to assume for purposes of this experiment that emissivity will be independent of temperature and is a constant for a given experimental rod.

$$H = P = IE \qquad (6)$$

$$e = \frac{IE}{\sigma A(T_{Rod}^4 - T_{Surroundings}^4)} \qquad (7)$$

Where:

H= P = Heat (Watts)

σ = Stefan-Boltzmann Constant

T = Absolute Temperature (K)

E = Electrical Potential (V)

e = emissivity of the material

A = Area of object (m^2)

I = Current (A)

Experimental Procedure:

The basic experimental set-up consists of a 35 cm long, 6.3 mm diameter hollow rod of stainless steel, copper or aluminum oxide with a 1 mm-diameter nichrome wire fed through the center of the experimental rod. In the case of the copper and stainless steel tubes, a thin walled glass tube is inserted inside the metal tube to serve as an electrical insulator, between the nichrome heating wire and the outside metal rod. The experimental rod is connected to the electrical leads, which provide the electricity for heating the rod. In addition, a thermocouple is attached to the surface of the rod to measure the rod's temperature. This assembly is then suspended on supports in a large glass tube (5 cm outer diameter, 4.5 cm inner diameter and 60 cm long), which serves as the vacuum chamber for the experiment. A second thermocouple is attached to the wall of the vacuum assembly to measure the temperature of the "surroundings". All of the power leads and thermocouple wires are fed through ports on the glass tube. The wire ports are sealed airtight by applying epoxy to all of the points of connection.

Once all of these attachments are made to the rod, the rod is loaded into the glass tube and the tube is sealed and evacuated to a pressure of about 1 Pa. The vacuum pump is allowed to run for at least 10 minutes before the power is supplied to the rod for heating. Electrical current is passed through the nichrome wire and at this point the data logger is turned on to record the temperature of the rod and the surrounding wall as a function of time. The experimental set-up is shown schematically in Figure 1.

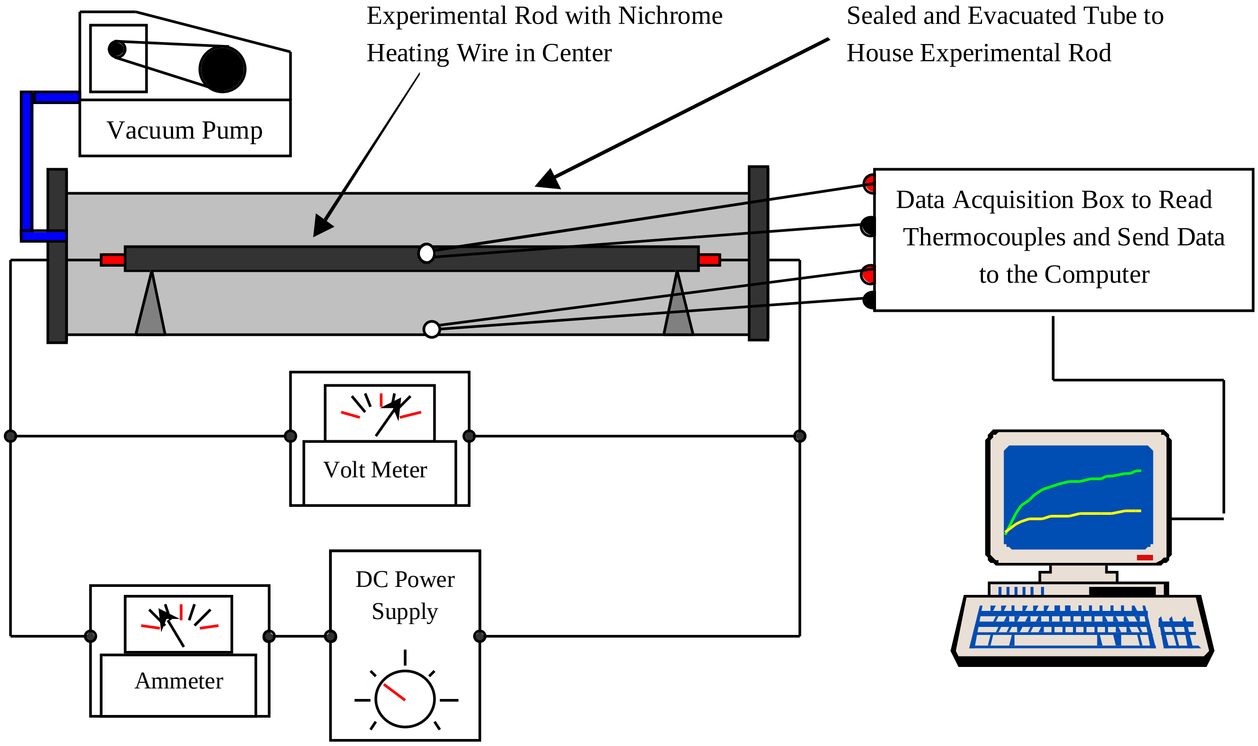

Figure 1: Schematic of experimental set-up.

In the course of the experiment, the experimental rod is heated to a maximum temperature of about 290° C and the wall of the experimental tube experiences a maximum temperature of only about 80° C. The DC power input for the nichrome wire reaches a maximum power of about 30 watts, with a current of approximately 5 A and a voltage of 6 V.

Note: Caution should be used when pulling a vacuum on any vessel. If the tube does not have adequate strength, implosion can result in flying debris and in the case of glass can be extremely dangerous. Appropriate measures should be taken to contain the vessel so that if implosion does occur, the experimenters will be protected. In this experiment, the glass tube was coated with a clear polymer coating to contain the glass in event of failure of the tube. As in most experimental conditions, eye protection is strongly recommended.

After the power has been applied for about 30 minutes, the temperature of the rod and the surrounding material should reach steady state. At this point, the values for the current and voltage supplied to the system are recorded every five minutes. The temperature of the rod and surroundings are measured continuously throughout the experiment. Since the rod is suspended in the vacuum and heat transfer via conduction and convection are effectively eliminated, all of the power which is being supplied by the electricity is being radiated from the rod to the surroundings. Therefore, it is possible to calculate the emissivity of the rod by using equation 7. The experiment is then repeated for the other materials. The results will show that the oxidized surface has a much higher emissivity than the same metals with a polished or shiny surface.

By running this experiment with an aluminum oxide rod that has been coated with carbon, it is possible to approximate a black body object (or a material with an emissivity of 1.) Since the emissivity is known (assumed to be 1), it is possible to solve for the Stefan-Boltzmann constant, instead of emissivity. Experiments can also be run with stainless steel or copper that has an oxidized surface.

Experimental Results:

Once the experimental set-up was complete, several trials were run on each sample. Table 1 shows the results for each of the samples.

Material and Treatment	Emissivity Trial 1	Emissivity Trial 2	Emissivity Trial 3	Average Emissivity Measured	Literature Emissivity
Polished S Steel	0.21	0.32	0.34	0.29	0.35
Oxidized S Steel	0.91	1.03	1.00	0.98	0.80-0.94
Polished Copper	0.16	0.15	0.15	0.15	0.2
Oxidized Copper	0.42	0.58	0.62	0.54	0.6-0.7
Alumina	0.52	0.52	0.53	0.52	0.22-0.40
Soot Covered Alumina	1.51	0.76	0.84	1.04	0.96

Table 1: Experimental Results for the Heat Transfer in a Vacuum Demonstration Experiment. Literature emissivities obtained from the 68th edition of the *CRC Handbook of Chemistry and Physics*.

Equation 8 is a sample calculation of the polished stainless steel rod:

$$\varepsilon = \frac{IE}{A\sigma\left(T_R^4 - T_S^4\right)} = \frac{2.78*3.63}{7.09E^{-3} * 5.67E^{-8}\left[(533.8)^4 - (338.7)^4\right]} = 0.323 \qquad (8)$$

The graphical representations of the polished and oxidized stainless steel rod data are shown in Figure 2 and Figure 3, respectively. The results show that that the oxidized surface of the stainless steel has a higher emissivity than the unoxidized surface of the other stainless rod. These results are consistent with theory since the oxidized surface is darker in color than the shiny stainless finish.

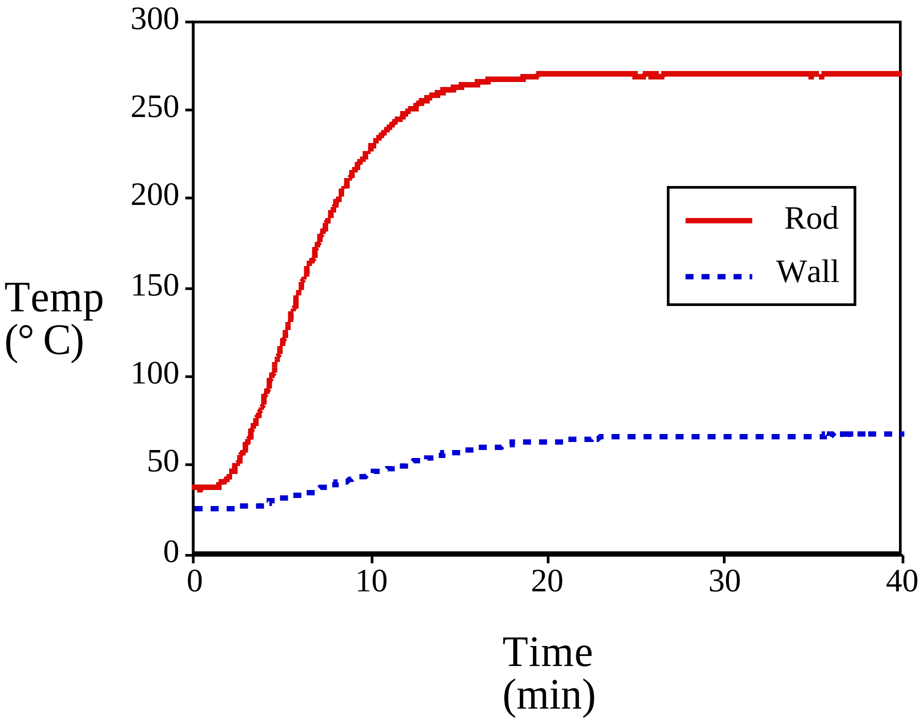

Figure 2: Temperature profile generated during a polished stainless steel experiment. The temperatures reached steady state within about 30 minutes.

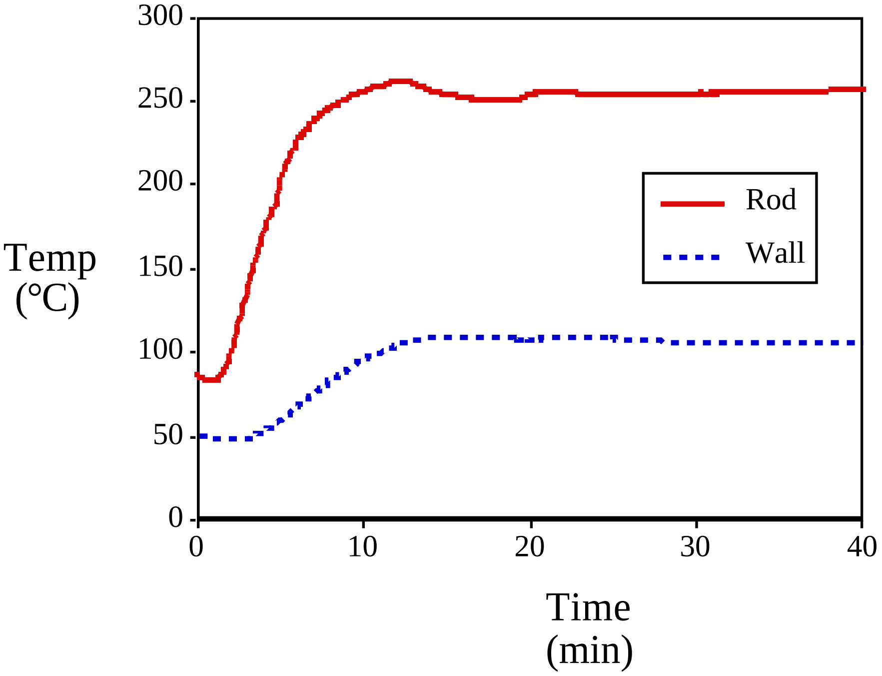

Figure 3: Temperature profile generated during an oxidized stainless steel experiment.

The results of this experiment show very good agreement with the emissivity values stated in the literature.

In an attempt to experimentally measure the Stefan-Boltzman constant, the data of the oxidized stainless steel sample has been substituted into the Stefan-Boltzman equation and algebraically manipulated to solve for σ. Table 2 assumes an emissivity of unity for the oxidized stainless steel rod and compares the calculated Stefan-Boltzman Constant to the established value.

Material and Surface Treatment	**Current (A)**	**Voltage (V)**	**T_{rod} (K)**	**T_{surr} (K)**	**Calculated Stefan-Boltzman Constant (Wm^{-2} K^{-4})**
Oxidized S Steel 1	4.505	5.59	532.6	376.9	5.15 x 10^{-8}
Oxidized S Steel 2	4.525	5.795	524.8	379.5	5.87 x 10^{-8}
Oxidized S Steel 3	4.53	5.83	529.0	379.5	5.66 x 10^{-8}
				Average	5.56 x 10^{-8}
				Accepted Value	5.67 x 10^{-8}
				Percent Error	1.96 %

These experiments should prove to be a very effective tool in demonstrating the various aspects of the Stefan-Boltzman Law and material emissivity in a high school setting. Some possible sources of error that should be considered when performing the demonstration are:

1. Ensure that the thermocouple that is measuring the temperature of the rod is in good thermal contact with the rod. If not, the emissivity would be higher than normal.
2. An insufficient vacuum would allow for convection and thus result in a higher than expected emissivity.
3. If the proper vacuum pressure was not obtained, conduction of heat by gas phase may occur and again result in higher than expected emissivity. See the calculation of mean free path for air molecules in equation 9.

The mean free path for a gas molecule is given by equation 9:

$$\lambda = \frac{kT}{4\pi\sqrt{2}r^2 P} \qquad (9)$$

Where the variables are defined as:

λ = Mean Free Path (in m)
k = Boltzman Constant (1.38 x 10^{-23} J/K)
T = Absolute Temperature (K)
r = Radius of Molecule (in m)
P = Pressure of Gas (in Pa or J/m^3)

In order to perform these calculations, a few experimental parameters must be identified. In the current experimental conditions, the maximum temperature of the rod during experimentation is approximately 290° C or about 563 K. In addition, according to the literature included with the Leybold Trivac B vacuum pump, it is possible to achieve vacuum levels of about 0.1 Pa. Next, to approximate the radius of the gas molecules in the system, it will be assumed that they are spherical and that an average molecule would have the radius which is between that of a nitrogen molecule and an oxygen molecule. Using a weighted average of the two molecules (80 percent nitrogen and 20 percent oxygen to approximate the atmosphere) the radius for the average molecule would be 1.49 Å. Using these values and solving equation 9, the value for the mean free path of the molecule was found to be about 19 cm. Since this is much larger than the diameter of the vessel, it can be assumed that conduction through the gas phase did not effect these measurements.

$$\lambda = \frac{1.38x10^{-23}\left({}^{J}\!/\!{}_{K}\right)*550(K)}{17.77*(1.49x10^{-10})^2(m^2)*0.1Pa} \qquad (10)$$

$$\lambda \approx 19cm$$

However, since the assumption was made that the molecule was spherical for these calculations, the mean free path may have been over estimated because molecules are actually more of ellipsoid with a long axis of 1.49 Å and a short axis of 0.74 Å. Had the radius of 0.74 Å been used, the mean free path of the particle would be 78 cm. Therefore the actual mean free path of the gas molecules in this experiment will lie somewhere between 19 and 78 cm.

References

1. Young, H. D. and R. A. Freedman (1996). University Physics. New York, Addison-Wesley Publishing Company, Inc.
2. West, R. C., M. J. Astle, et al., Eds. (1987). CRC Handbook of Chemistry and Physics. Boca Raton, Florida, CRC Press, Inc.
3. Eshbach, O. W., Ed. (1936). Handbook of Engineering Fundamentals. New York, John Weley & Sons, Inc.
4. Shackelford, J. F. and W. Alexander, Eds. (1992). The CRC Materials Science and Engineering Handbook. Ann Arbor, CRC Press.

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