Nanyang Technological University

School of Mechanical and Aerospace Engineering

P3.27 Thermal Radiation Lab Report

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1. Abstract

This report covers three experiments regarding the principles of thermal radiation in heat transfer. The experiments were conducted at Nanyang Technological University's Heat Transfer Laboratory, in a controlled environment. The first and second experiments require students to verify two laws in thermal radiation, the Stefan-Boltzmann law, and the Inverse Square law respectively. The third experiment requires students to analyse the effects of thermal radiation on different surface conditions, known as emissivity of a surface.

Additionally, the report covers the methodology of each experiment and discusses the validity of the results.

2. Introduction

Thermal radiation is one of the three basic principles of modes of heat transfer, with convection and conduction as the other two principles. Consider the sun, a hot object that exists in the vacuum of space, heat from the sun warms a part of the earth that is approximately 149 million kilometres away [2]. Heat transfer from the sun to the earth can neither occur by conduction nor convection as these two principles do not work in a vacuum [3]. Thus, only one mechanism of heat transfer is possible in a vacuum, this mechanism is known as thermal radiation.

Thermal radiation is a form of radiation that exists within the electromagnetic spectrum. Part of thermal radiation can be observed with the naked eye as it also exists in visible light. Figure 1 shows the range of its existence.

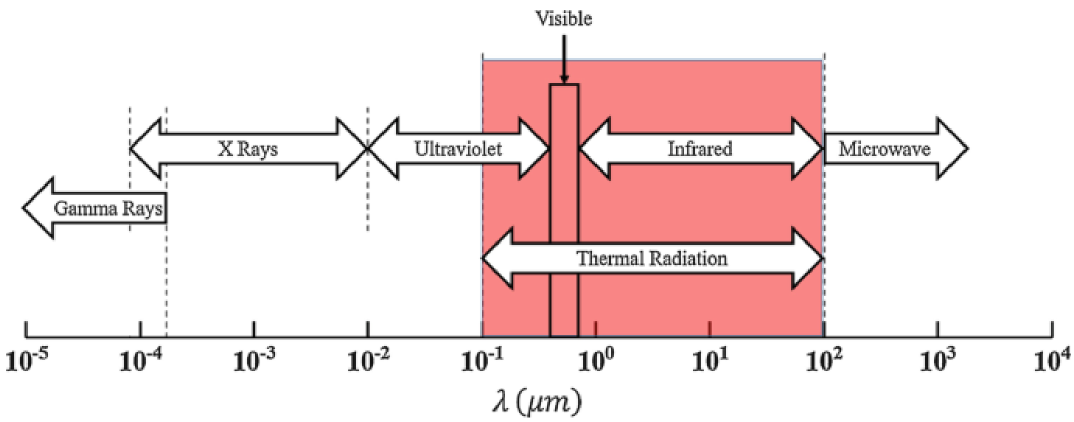

Figure 1. The electromagnetic wave spectrum. Adapted from [3]

3. Theory

3.1 Blackbody Radiation

A blackbody is defined as an object that behaves as a perfect emitter and absorber of radiation. It emits radiation energy uniformly in all directions per unit area normal to the direction emission [1]. The blackbody emissive power over all wavelengths and directions of a blackbody per unit surface area is given by the equation below, known as the Stefan-Boltzmann law.

$$E_b = \sigma T^4 \quad \left(\frac{\text{W}}{\text{m2}}\right)$$

Where T = absolute temperature (K)

σ = 5.67 x 10^{-8} (W/$m^2 \cdot K^4$) (Stefan-Boltzmann constant)

3.2 Planck's law

The Stefan-Boltzmann law gives the total blackbody emissive power of an object, which is the sum of the radiation emitted over all wavelengths. However, to know the spectral blackbody emissive power, which is defined by the emissive power over a specific wavelength in a specific area of the electromagnetic spectrum, the relation, known as Planck's law, is given by:

$$E_b(\lambda, \mathrm{T}) = \frac{C_1}{\lambda^5 \left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]} \quad \left(\frac{\text{W}}{m^2} . \mu\text{m}\right)$$

Where $C_1 = 2\pi h c_0^2$ = 3.74177 x 10^8 W·μm^4/m^2

$C_2 = hc_0/k$ = 1.43878 x 10^4 μm·K

In addition, it should be noted that the Stefan-Boltzmann law can be derived from Planck's law by integrating the spectral blackbody emissive power, $E_{b\lambda}$ with respect to λ, and over all wavelengths to get total emissive blackbody power, shown in the expression below:

$$E_b(T) = \int_0^{\infty} E_{b\lambda}(\lambda, T) d\lambda = \sigma T^4 \quad (\text{W/m}^2)$$

The graphical representation of the relation between Planck's law and Stefan-Boltzmann law is shown below in figure 2:

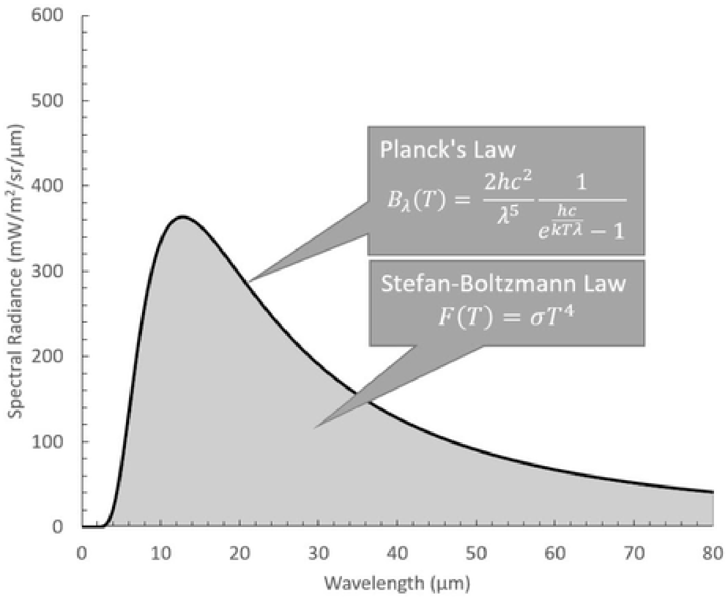

Figure 2. Graphical representation of Stefan-Boltzmann and Planck's law. Adapted from [4]

It is important to understand that a real body can never achieve the ideal properties of the blackbody since it is an idealisation of the perfect emitter and absorber. Therefore, the total emissive power of a real body will be less than a blackbody. Figure 3 shows an example of the spectral emissive power profile of a real body against a blackbody.

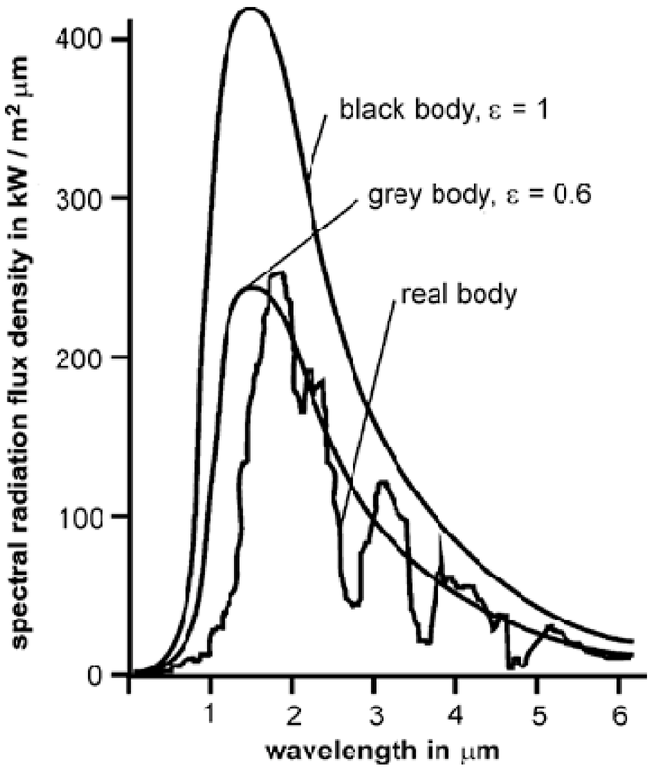

Figure 3. Spectral emissive power profile of a real body. Adapted from [5]

3.3 Solid angle and the inverse square law

The amount of radiation emitted, incident from a point of a diffuse surface, dA_n, normal to the line joining the two surfaces and at a distance r away, is proportional to the solid angle, $d\omega$, subtended by dA_n, at the point on the emitting surface, is given by:

$$d\omega = \frac{dA_n}{r^2} \quad \text{(steradian)}$$

In essence, when the distance between the two surfaces increases by a factor of two, the emissive power is quartered. An example of the solid angle in relation to the inverse square is shown below in figure 4 and figure 5:

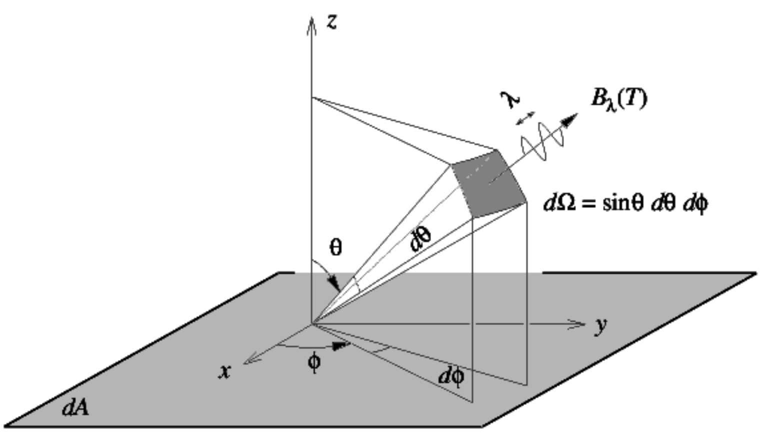

Figure 4. A visual representation of the solid angle. Adapted from [6]

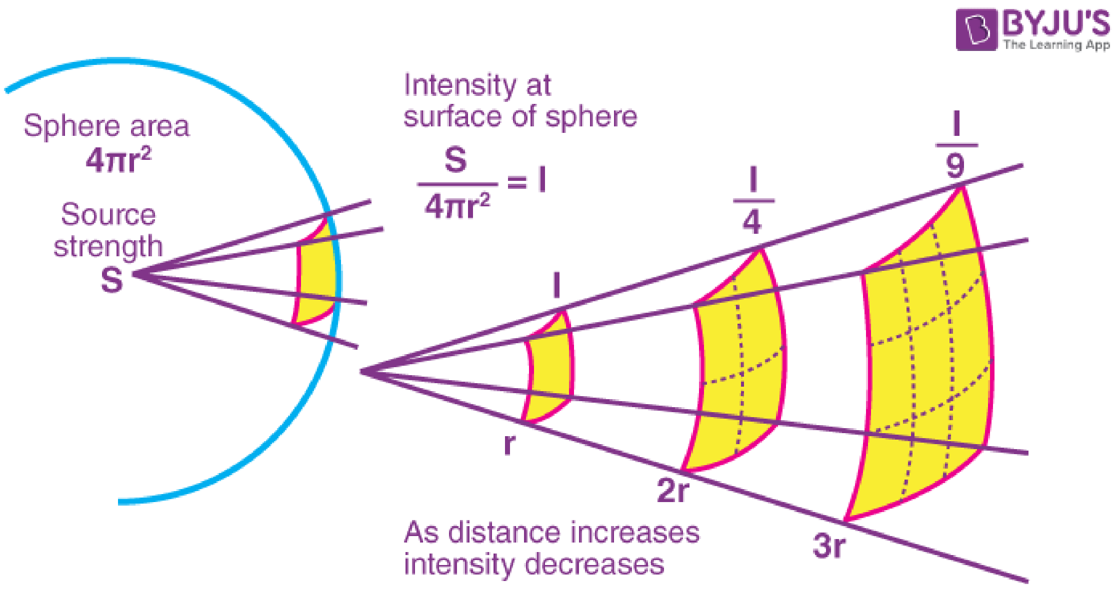

Figure 5. An illustration of the inverse square law. Adapted from [7]

3.4 Net emissive power

The orientation of surfaces relative to each other will affect radiation heat transfer, their radiative properties and temperature. For a black surface with an area *A* at temperature *T* exchanging heat with large surroundings (which behaves like a blackbody) at a temperature of T_o, the net emissive power can be expressed as:

$$\dot{Q} = \sigma \mathrm{A}(T^4 - T_o^4)$$

3.5 Emissivity and Kirchhoff's law

The emissivity of a surface is defined by the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature [1]. The range for emissivity is between zero and one, $0 \leq \varepsilon \leq 1$, where $\varepsilon = 1$ is the emissivity of a blackbody.

Consider a small body of surface A_s, emissivity ε, and absorptivity α at temperature T contained in a large isothermal enclosure. A large isothermal enclosure forms a blackbody cavity regardless of the radiative properties of the enclosure surface, and the body in the enclosure is too small to interfere with the blackbody nature of the cavity [1]. Therefore, the radiation incident on any part of the surface of the small body is equal to the radiation emitted by a blackbody at temperature T [1].

With the explanation referenced from the textbook, it can be deduced that, $G = E_b(T) = \sigma T^4$, and the radiation absorbed the small body will be given by:

$$G_{abs} = \alpha \sigma T^4$$

The radiation emitted by the small body is given by:

$$E_{emit} = \varepsilon \sigma T^4$$

Since the small body would be in thermal equilibrium with the large enclosure, the net rate of heat transfer to the body would be zero. Therefore, the radiation emitted by the body must be equal to the radiation absorbed by it and is given by:

$$A_s \alpha \sigma T^4 = A_s \varepsilon \sigma T^4$$

Thus, the emissivity of a real body can be determined by taking the ratio of the emissive power radiated by the real body and the blackbody at a given temperature.

$$\frac{E_2}{E_1} = \frac{\varepsilon_2 T_2^4}{\varepsilon_1 T_1^4} \rightarrow \frac{\varepsilon_2}{\varepsilon_1} = \frac{E_2 T_2^4}{E_1 T_1^4}$$

Where E_1 = emissive power of a blackbody at a given temperature
E_2 = emissive power of a real body at a given temperature
$T_1 = T_2$

3.6 View factor

The orientation of the surfaces directly affects the amount of radiation that is absorbed. Consider two surfaces facing each other, and surface 1 is emitting radiation while surface 2 is not. The view factor can thus be defined as the fraction of radiation energy leaving surface 1 that reaches surface 2 directly, as shown in figure 6.

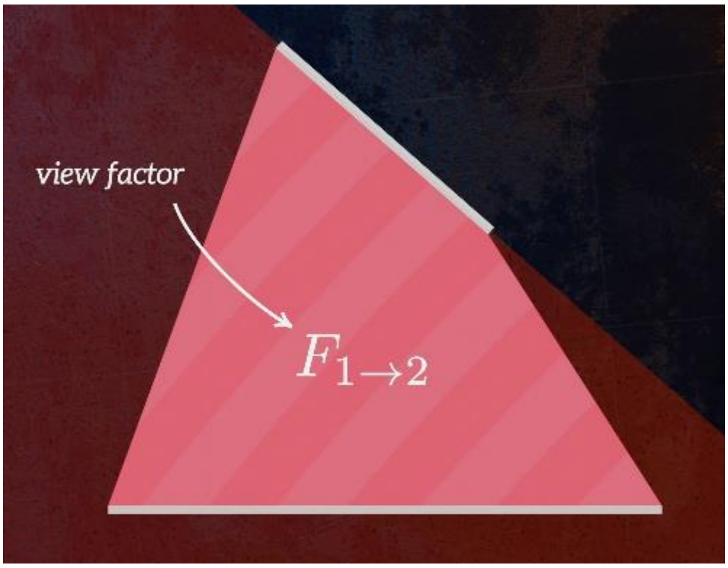

Figure 6. Visualisation of view factor. Adapted from [8]

Therefore, view factor can be summarised as the ratio of radiation reaching the absorber to the total radiation leaving the emitter and is affected by the solid angle.

4. Experiment equipment and objectives

4.1 Experiment equipment and setup

The equipment used in the experiments is a H112C Thermal Radiation Unit manufactured by PA Hilton Pte Ltd. This self-contained apparatus set is configured for the three experiments to demonstrate the basic principles of heat transfer. Figure 7 below shows a picture of the labelled apparatus.

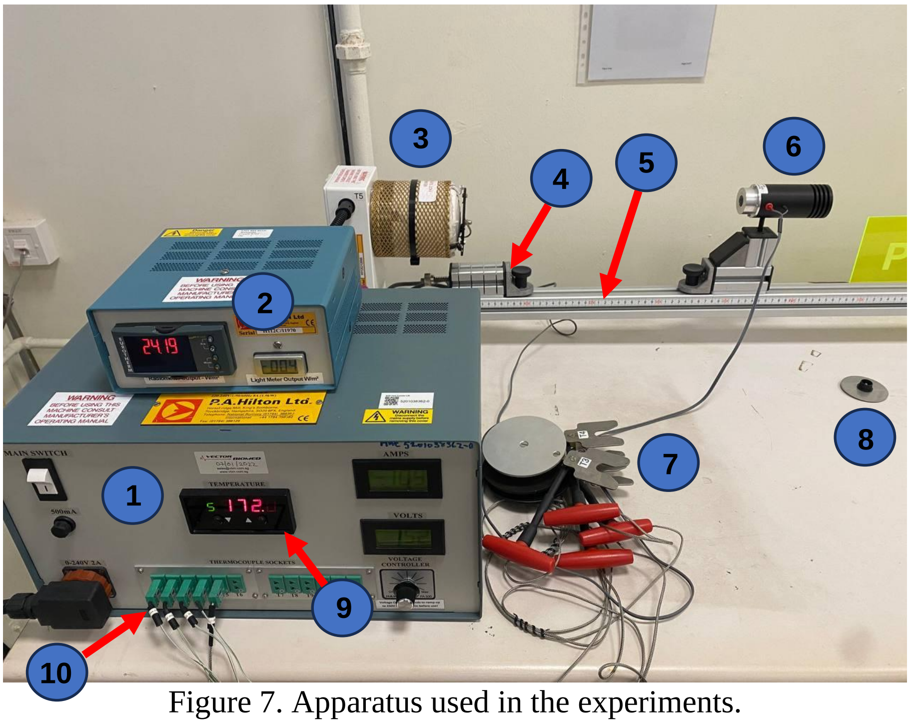

Figure 7. Apparatus used in the experiments.

The equipment list is as follows:

1. **Control Unit:** Supplies user variable voltages up to 240V for the heat source and displays temperature readings.

2. **Radiometer Console:** Measures the radiant flux from the heat source and displays it in W/m^2. During manufacture, it was set to a calibration factor of 30.12 $W/m^2/mV$.

3. **Heat Source:** Ceramic heater on a 100mm diameter black aluminium plate that is coated with a heat resistant matte black paint with an emissivity close to 1. It is rated to produce approximately 200 Watts at 230V AC and reach more than 300^{o}C at maximum voltage.

4. **Frame Carriage:** allows mounting of the metal plates with different finishings.

5. **Frame and Scale:** Allows the radiometer sensor to be adjusted at distances up to 1000mm from the heat source.

6. **Radiometer Sensor:** Measures the emissive power of the heat source or any objected mounted, facing towards it.

7. **Metal Plates:** Comes in dull grey, matte black, and polished. The plates are connected to the control unit via a thermocouple. Each plate is named, T1 and T2 are matte black, T3 is grey, and T4 is polished.

8. **Radiometer Sensor Shield:** Round reflective shield to be fitted onto the radiometer sensor when not in use to minimise heating of the detector body by the heat source.

9. **Selector Panel:** Allows the user to monitor temperature for the heat source and the metal plates by using the arrow keys at the panel to cycle through the options.

10. **Thermocouple Connecting Points:** Thermocouple connection points for the metal plates.

4.2 Objectives

The objectives for each of the three experiments are as follows:

- **Experiment 1:** Given the Stefan-Boltzmann law for a real body, $E = \varepsilon\sigma T^4$ (W/m2), students are to prove that the total emissive power is proportional to fourth power of its absolute temperature by verifying the gradient of the graph, a value is expected to be estimated at 4. The steps to arrive at expression 1 for the experiment is shown below:

$$E = \varepsilon\sigma T^4 \quad \left(\frac{\mathrm{W}}{m^2}\right)$$
$$\log(E) = \log(\sigma\varepsilon) + 4\log(T)$$
$$\therefore \log(E) \propto 4\log(T) \rightarrow (1)$$

- **Experiment 2:** The radiation received by a surface from a point heat source is determined by the solid angle that the surface covers from the perspective of the point heat source. Students will need to verify the inverse square law for the thermal radiation between surfaces by verifying the gradient of the graph, a value is expected to be estimated at -2. The steps to arrive at expression 2 is shown below:

$$\Delta E \propto \frac{1}{r^2}$$
$$\therefore \log(\Delta E) \propto -2\log(\mathrm{r}) \rightarrow (2)$$

- **Experiment 3:** Students will verify the theory of emissivity using three plates varying in surface conditions. An ideal object, known as a blackbody, is a perfect emitter and absorber of radiation and is given an emissivity value of 1, however, real surfaces can never achieve perfect emissivity and absorptivity. The emissivity of a real body can be determined by ratio of the emissive power between it and a blackbody. The expression is shown again below as derived from the theory section previously:

$$\frac{E_2}{E_1} = \frac{\varepsilon_2 T_2^4}{\varepsilon_1 T_1^4} \rightarrow \frac{\varepsilon_2}{\varepsilon_1} = \frac{E_2 T_2^4}{E_1 T_1^4} \rightarrow (3)$$

It should be noted that the setup of the experiment is not conducted in a vacuum environment, therefore, natural convection will still occur between the hot plate and the surrounding air, as well as the conduction from the heated surface to its supports. Students are required to analyse the results of the experiments, determine the impact of these effects on said results, and improve on the methodology of the estimation of radiation performance under such effects.

5. Experiment procedures, results, and discussions

5.1 Experiment 1

<u>Procedure and results</u>

To conduct experiment 1, the radiometer sensor was adjusted 400mm away from the heat source and the control unit was set to an initial voltage value of approximately 90V and a temperature stabilised to approximately 382.19K. Fluctuations in temperature and power were observed throughout the experiment. While minor fluctuations in temperature were considered normal, those in the radiometer readings tended to be more significant due to its sensitivity. Therefore, it was decided to take five readings for both temperature and emissive power, and then calculate the average to account for potential errors in the readings.

After recording the first measurements, the voltage was increased to 110V and a waiting time of approximately 10 minutes was observed to allow the temperature of the heat source, and the radiometer readings to stabilise, these steps were repeated for 130V and so forth. Overall, a set of recordings for temperature and radiometer readings was recorded, it is shown in Table 1. The setup for the experiment using r_1 = 400mm is shown in figure 8.

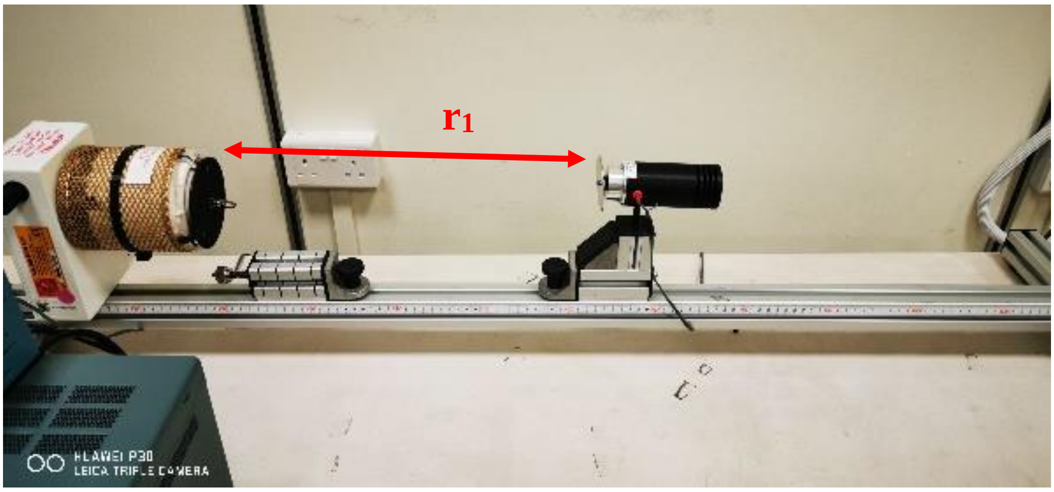

Figure 8. Experiment 1 at r = 400mm

The steps to conduct experiment 1 are:

1. Switch on the apparatus and observe a waiting time of approximately 60 minutes.

2. Set the voltage at the control unit to approximately 90V and adjust the mount for the radiometer sensor to a distance of 400mm at the frame and scale.

3. Allow the apparatus to stabilise the temperature and radiometer readings.

4. Remove the radiometer shield and record the temperature and radiometer readings.

5. Increase the voltage by 20V at the control unit and observe a waiting time of approximately 10 minutes to stabilise the apparatus.

6. Record the temperature and radiometer readings.

7. Repeat **steps 2 to 6** until **210V**.

8. Repeat **steps 2 to 6** until **210V** but shift the radiometer sensor to **600mm** away from the heat source at **step 2**.

Table 1. Recordings for radiometer distance of 400mm away from heat source.

Input Voltage (V)	Average Temperature T (K)	Average Power E (W/m^2)	Log(E)	Log(T)
91	382.19	33.41	1.52	2.58
110	410.07	51.12	1.71	2.61
130	441.81	76.23	1.88	2.64
150	475.73	111.49	2.05	2.68
169	508.49	150.20	2.18	2.71
190	542.89	202.33	2.31	2.73
209	575.09	260.33	2.41	2.76

Another set of seven of recordings was taken while the radiometer was fixed at 600mm away from the heat source to act as a comparison point for this experiment, figure 9 shows the setup for experiment using r_2 = 600mm and the data is shown in Table 2.

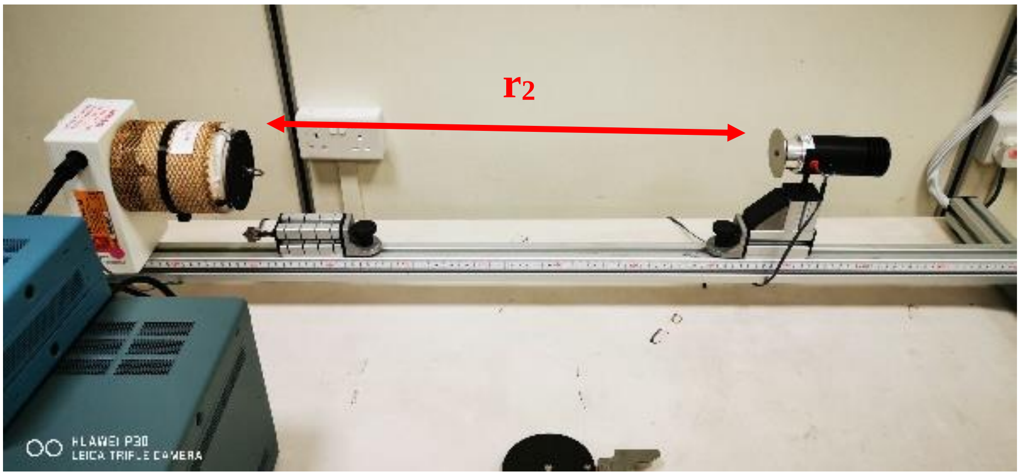

Figure 9. Experiment 1 at r = 600mm

Table 2. Recordings for radiometer distance of 600mm away from heat source.

Input Voltage (V)	Average Temperature T (K)	Average Power E (W/m^2)	Log(E)	Log(T)
90	375.67	7.92	0.89	2.57
110	394.27	11.64	1.06	2.59
130	428.71	19.22	1.28	2.63
150	462.01	29.268	1.47	2.66
170	494.83	42.19	1.62	2.69
190	531.91	59.62	1.77	2.72
210	565.41	78.88	1.89	2.75

The graphs and the gradient values are shown in figure 10 below. A logarithmic graph with linear relation was used for this experiment because plotting E against T would result in an exponential graph, which would have been difficult to analyse.

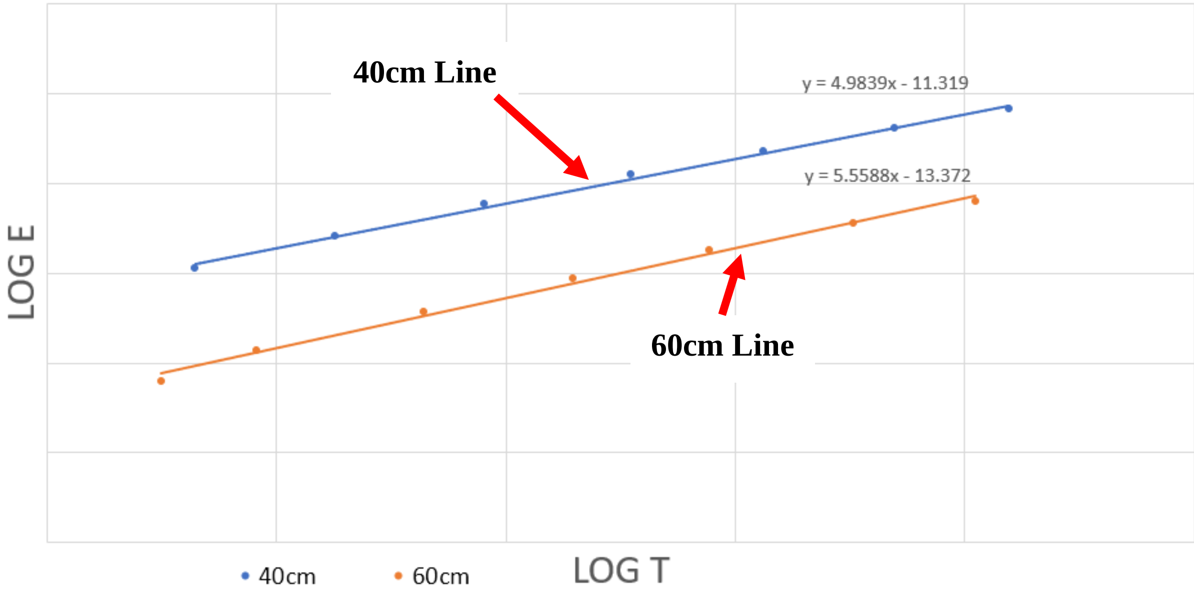

Figure 10. Graph of the results for experiment 1.

Discussion

From the results, a discrepancy was observed between the observed data and the predictions of the Stefan-Boltzmann law, the gradient values are more than the theoretical value of 4 and have an error of $\frac{4.98-4}{4} \times 100\% = +24.5\%$ and $\frac{5.56-4}{4} \times 100\% = +39\%$ for both graphs. Having the power of temperature exceed 4 would indicate a disproportionately larger increase in the radiated power as the temperature rises.

Consider the blackbody at a temperature of 5K, it will emit $5^4 = 625$ while the real body will emit $5^{4.98} = 3026$. As demonstrated from calculations, it suggests that there is an object that is more ideal than the idealised representation of the perfect emitter and absorber. Thus, this situation is not physically possible within the framework of the Stefan-Boltzmann law. Therefore, there were several possible factors that would have compounded to the discrepancies in the results.

Firstly, environmental factors can be considered. The experiment was conducted during a sunny day and a bit of indirect sunlight was penetrating the lab. While this light did not impact the radiometer directly, it could have added to the total radiant flux received by the radiometer, as well as increasing the ambient temperature at the experiment site. Therefore, contributing to compounding measurement errors in the results.

In addition, when the experiment was conducted, a laptop was used to record all the readings in the experiments. The laptop was placed at an empty space on the table relatively close to the radiometer. Laptops emit a wide range of electromagnetic radiation as well as generate electromagnetic fields during operation [10], thus, it can be assumed that the close proximity of the device had resulted in the radiometer measuring more radiant flux, which contributed to the background noise and distorted its readings.

Another consideration point was the stabilisation process for the temperature at the control unit and the readings displayed on the radiometer. Each increment in voltage applied at the control unit led to a rise in temperature, as well as changing the readings on the radiometer console. Achieving stability took time, requiring a waiting period of approximately 10 minutes until the temperature stabilised before collecting data to avoid inaccuracies. It can be assumed that a waiting period exceeding 10 minutes may be necessary to ensure proper stabilisation of the temperature and radiometer, potentially affecting some of the readings.

Finally, the probable factor that contributed to the discrepancies in the results can be attributed to the calibration of the experimental equipment, specifically the control unit and the radiometer. While the other factors mentioned previously can affect and skew the readings, it does not offer a convincing explanation for the larger percentages in errors. In addition, the experiment was conducted accordingly to the instructions given; thus, improper execution of the experiment can be ruled out.

Overall, despite the errors observed in the results, the power increase measured in the radiometer when voltage was increased was correct since the heat source would emit more energy with increasing power supplied to it.

5.2 Experiment 2

Procedure and results

For experiment 2, the control unit was set to a voltage of 190V, and the distance between the radiometer sensor and the heat source was set to 400mm. The temperature of the heat source was allowed to stabilise to approximately 358.58^{o}K, and the initial conditions would be the first reading to be taken. Overall, a set of seven readings will be recorded, the voltage and temperature will remain constant, the only variable in this experiment is the distance of the radiometer sensor from the heat source, which will increase to 1000mm over the course of the experiment. The temperature was allowed to stabilise for approximately 10 minutes before recording at every distance set. The setup for experiment 2 is shown in figure 11.

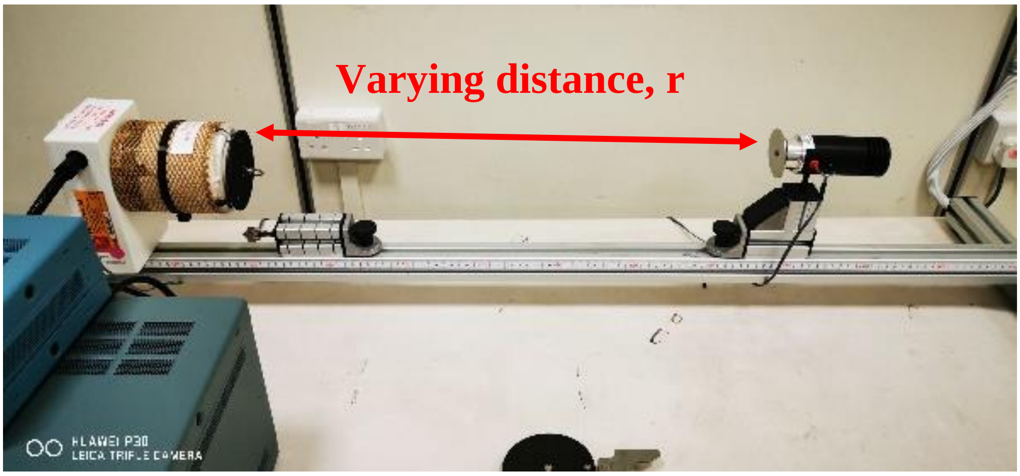

Figure 11. Experiment 2 setup

The steps to conduct experiment 2 are:

1. Switch on the apparatus and observe a waiting time of approximately 60 minutes.
2. Set the voltage at the control unit to 190V and adjust the mount for the radiometer sensor to a distance of 400mm at the frame and scale.
3. Allow the apparatus to stabilise the temperature and radiometer readings.
4. Remove the radiometer shield and record the temperature and radiometer readings.
5. Move the radiometer sensor by 100mm and observe a waiting time of approximately 10 minutes to stabilise the apparatus.
6. Record the temperature and radiometer readings.
7. Repeat **steps 2 to 6** until the radiometer sensor is at the 1000mm mark on the frame and scale.
8. Repeat **steps 2 to 6** until the radiometer sensor is at the 1000mm mark on the frame and scale but adjust **voltage to 230V** at step 2.

Similarly, to the methodology in experiment 1, another set of seven readings was recorded at a voltage of 230V to act as a comparison for the 190V dataset. The results for are shown below in Table 3.

Table 3. Recordings for experiment 2.

Distance (r) mm	190V Power readings E (W/m^2)	230V Power readings E (W/m^2)	Log(r)	190V Log(E)	230V Log(E)
400	200.53	339.5	-0.397	2.30	2.53
500	96.67	171.07	-0.301	1.98	2.23
600	59.33	104.74	-0.222	1.77	2.02
700	39.86	53.28	-0.155	1.60	1.73
800	29.78	75.13	-0.097	1.47	1.87
900	20.32	43.89	-0.046	1.31	1.64
1000	16.10	31.42	0	1.21	1.50

The graphs and the gradient values are shown in figure 12 below. Similarly, to experiment 1, a logarithmic graph with linear relation was used for this experiment because plotting E against *r* would result in an exponential graph, which would have been difficult to analyse.

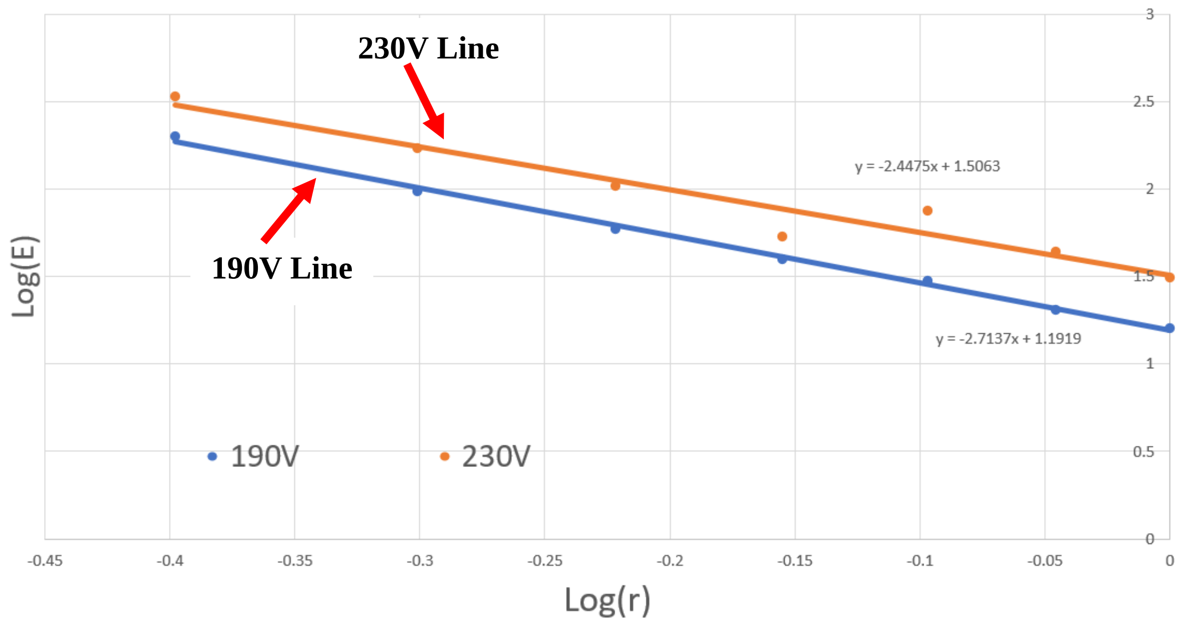

Figure 12. Graph of experiment 2.

Discussion

From the results, it was observed that the gradient values deviate from the expected value of -2. The errors of the gradient values are calculated to be $\frac{2.4475-2}{2} \times 100\% = +22.4\%$ and $\frac{2.7137-2}{2} \times 100\% = +35.7\%$ respectively. Having the power exceed -2 suggests that the results do not adhere to the inverse square law as assumed.

In addition, from Table 3, a spike in readings can be observed in the 230V power readings at 800mm. The abnormality could be attributed to the environmental factors, as well as the calibration of the apparatus as mentioned in the discussion section of experiment 1.

Another possible factor that would have affected the readings could be attributed to the view factor for this experiment. View factor is the ratio of radiation reaching the absorber to the total radiation leaving the emitter and is affected by the solid angle. In figure 7, it can be observed that the black aluminium plate that is attached to the heat source does not align directly to face the radiometer.

Following the concept of view factor and solid angle, it offers a possible explanation for the larger difference for the power drop in the readings and thus, causing the gradient to be steeper. This error can be corrected by ensuring that the aluminium plate is perpendicular to the radial lines from the heat source.

5.3 Experiment 3

Procedure and results

For experiment 3, three of the four the metal plates of different finishings were used in the experiment, specifically, T2, T3, and T4. Since T2 was a matte black plate, it was suited to serve as a reference blackbody for the calculations. Any surface that absorbs light, which is the visible portion of radiation to humans, while any surface that reflects light, would appear white or shiny [1].

The voltage was set to a constant 110V throughout the experiment, and the temperature of T2 was allowed to stabilise before the readings were recorded. The power displayed by the radiometer for T2 was recorded three times and the average value of it was calculated to account for the variations in readings.

The setup for experiment 3 is shown below in figure 13.

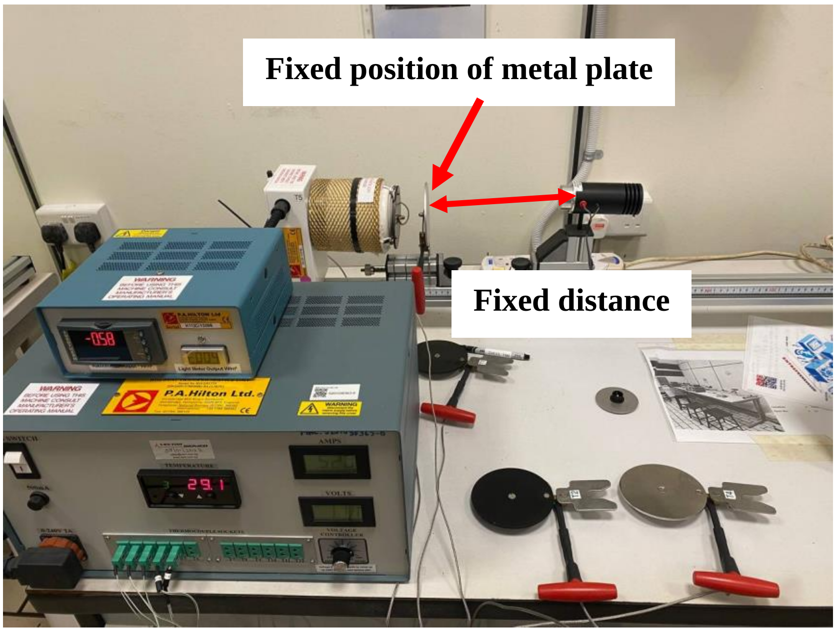

Figure 13. Experiment 3 setup

The steps for experiment 3 are:

1. Switch on the apparatus and set the voltage to 110V at the control unit.
2. Allow the stabilisation of the apparatus, a required waiting time of approximately 60 minutes is needed.
3. Connect T3 and T4 via the thermocouples to the control unit and place them away from the heat source.
4. Position the frame carriage 50mm away from the heat source, and 200mm away from the radiometer sensor. Mount plate T2 and connect the thermocouple of T2 to the corresponding terminal on the control unit.
5. Monitor the temperature of T2 by cycling through the selector panel on the control unit.
6. Remove the radiometer shield.
7. Wait for the radiometer to stabilise, a required waiting time of approximately 10 minutes.
8. Record the radiometer and temperature readings.
9. Re-mount the radiometer shield and shift it back to 900mm on the frame and scale. Repeat **steps 4 to 8** for T3 and T4.

The procedure to record the power for T3 and T4 are the same as T2 and Table 4 shows the results of experiment 3.

Table 4. Recordings for experiment 3.

Plate	Temperature (K)	Power (W/m^2)
T2, Matte black	311.65	3.2
T3, Grey	311.65	3.16
T4, Polished	304.45	1.1

After the readings were recorded, calculations were done to verify the emissivity for each plate.

The calculations are:

$$\frac{E_2}{E_1} = \frac{\varepsilon_2 T_2^4}{\varepsilon_1 T_1^4} \rightarrow \frac{\varepsilon_2}{\varepsilon_1} = \frac{E_2 T_2^4}{E_1 T_1^4}$$

$$\therefore \frac{\varepsilon_3}{\varepsilon_2} = \frac{3.16 \times 311.65}{3.2 \times 311.65} = 0.9875 \rightarrow (1)$$

$$\therefore \frac{\varepsilon_4}{\varepsilon_2} = \frac{1.1 \times 304.45}{3.2 \times 311.65} = 0.3358 \rightarrow (2)$$

$$\therefore \varepsilon_3 = 0.9875, \varepsilon_4 = 0.3358$$

Discussion

From the calculations, the emissivity for plates T3 and T4 are below 1, which follows the principles of emissivity where it varies between zero and one, $0 \leq \varepsilon \leq 1$, where $\varepsilon = 1$ is the emissivity of a blackbody. It can be observed that the emissivity value of plate T3, despite having a lighter finish compared to T2 which was matte black, had an emissivity value of 0.9875, which was close to the reference blackbody of T2.

Possible explanations for this result can be attributed to environmental factors. During experiment 3, sunlight was penetrating indirectly into the laboratory and the laptop that was used to record the readings from experiments 1 and 2 was present as well. Radiation from the laptop may have reflected off T3 and resulted in a higher radiant flux received by the radiometer, skewing the readings.

Another reason resulting in T3 having an emissivity close to the reference blackbody is that visible light lies between 0.40 and 0.76 µm, which is a minute portion of the electromagnetic wave spectrum where thermal radiation is emitted. Therefore, judging the expected emissivity through the visible spectrum of radiation is a false methodology, and the colour of an object is not due to emission. Instead, it depends on the adsorption and reflection characteristics of the surface and is due to selective absorption and reflection of the incident visible radiation [1].

Overall, the results from experiment 3 are consistent with the theory that surfaces with different properties vary in emissivity and are not more ideal than the theoretical properties of the blackbody.

6. Conclusion

Of the three experiments, only experiment 3 yielded results that were consistent to the theoretical concepts of thermal radiation in heat transfer. However, majority of the discrepancies can be attributed to a compounding of factors mentioned in the discussions of the three experiments, leading to inaccuracies in the recording of data and the calculations.

Procedures to ensure accurate readings can be done by proper calibration of the experimental apparatus before use, as well as accounting for potential objects and environmental factors that may contribute to additional background radiation, skewing the readings.

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