Verifying the Sun's Power

Introduction

I used to have a science kit which had a number of small plastic lenses of different aperture areas. Having watched Garfield's Pet Force, I wished to recreate the scene where John's rope is burnt with a monocle (single eye lens). Obviously, instead of a rope, I attempted to burn a piece of paper. Conducting my little experiment, I realized that the lens with the largest aperture caused the paper to burn in the least amount of time. Intuitively, this made sense to my young mind. Studying Energy Production, I was introduced to the concepts of Intensity and the Solar Constant. Such a high intensity value, (and a power value with an order of magnitude of 10^{26} W) even though the Sun is so far away from us, left me awe-struck.

Although I was amazed by the greatness of the Sun, I was also sorrowful of the damage the large power of the Sun caused. Melting of glaciers, in particular, grabbed my attention and I wondered whether, along with global warming, an increase in the power of the Sun was also a factor which led to such adverse consequences.

Inspired by my childish experiment and the concepts learnt in class, I wished to determine the relation between aperture area and temperature change. This led to my research question, "**How does the aperture area of a convex lens affect the temperature change of water?**" Based on my findings, I then wished to calculate the power emitted by the Sun. Determining the accuracy of the investigation and verifying whether there has been a change in the value of the power of the Sun led me to calculate its power.

Figure 1:- Melting of glaciers[1]

Background Information

Specific Heat Formula and Power of the Sun

Specific heat formula provides a relationship between heat energy and the mass,

$$Q = mc\Delta T \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 1}$$

(where Q is heat energy in joules $\{J\}$, m is mass in kilograms $\{kg\}$, c is specific heat capacity in joules per kilogram and celsius $\{J.kg^{-1}.°C^{-1}\}$, water has a specific heat capacity of $4200\ J.kg^{-1}.°C^{-1}$, and ΔT is temperature change in celsius $\{°C\}$)

[1] Wehner, Mike. "Melting Glaciers Are Pushing Down The Bottom Of The Ocean". *Nypost.Com*, 2018, https://nypost.com/2018/01/09/melting-glaciers-are-pushing-down-the-bottom-of-the-ocean/. Accessed 3 Nov 2019.

Intensity of sunlight passing through the convex lens is given as,

$$I = \frac{P}{a} \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 2}$$

(where I is intensity in watts per meter-squared $\{W.m^{-2}\}$, P is power in watts $\{W\}$, and a is aperture area in meter-squared $\{m^2\}$)

Now, the aperture area of the convex lens can be determined by,

$$a = 2\pi r^2 \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 3}$$

(where r is radius of convex lens in meters $\{m\}$)

Power can be written as,

$$P = \frac{W}{t} = \frac{Q}{t} \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 4}$$

(where W is work done in J, and t is time in seconds $\{s\}$)

Using *equation 4* and *2* and after rearrangement,

$$I.a.t = Q \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 5}$$

Now, the intensity of the Sun is,

$$I = \frac{P}{A} \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 6}$$

(where A is the area over which the power of the Sun is spread on Earth in m^2)

A is calculated as,

$$A = 4\pi R^2$$

(where $R \approx 1.5 \times 10^{11}$ m [2] and is the separation between the Sun and the Earth)

Using *equation 5* and *6*,

$$Q = \frac{P}{A} \times at \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 7}$$

Using *equation 1* and *7*,

$$\frac{P}{4\pi R^2} \times at = mc\Delta T \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 8}$$

After rearrangement of *equation 8*

$$\Delta T = \frac{Pt}{4\pi R^2 mc} \times a$$

[2] Nnm Pitjeva, E. V., and E. M. Standish. "Proposals For The Masses Of The Three Largest Asteroids, The Moon-Earth Mass Ratio And The Astronomical Unit". *Celestial Mechanics And Dynamical Astronomy*, vol 103, no. 4, 2009, pp. 365-372. *Springer Science And Business Media LLC*, doi:10.1007/s10569-009-9203-8. Accessed 7 Nov 2019.

Stefan-Boltzmann's Law and Power of the Sun

Stefan-Boltzmann's Law states that the energy radiated from a black body is proportional to the fourth power of the absolute temperature.[3]

$$P = e\sigma AT^4 \ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 9}$$

(where e is surface emissivity, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W.m^{-2}.K^{-4}}$ [4] and is the Stefan-Boltzmann's constant, A is the surface area in $\mathrm{m^2}$, and T is surface temperature in kelvin $\{K\}$[5])

Using *equation 9*, the power of the Sun can be calculated,

$$P = 1 \times 5.67 \times 10^{-8} \times 6.08 \times 10^{18} \times 5772^4$$

(where $e = 1$ as the Sun is a black body, $A = 6.08 \times 10^{18}\ \mathrm{m^2}$ [6], and $T = 5772\ K$ [7] is the average temperature of the Sun as the temperature of the Sun continuously varies)

$$P = 3.83 \times 10^{26}\ W$$

Therefore, solving the above equation, the literature value for the power of the Sun can be approximated to 3.83×10^{26} W.

Hypothesis

I hypothesize that a directly proportional relationship would exist between the aperture area of the convex lens and the temperature change of the water. This is because a larger aperture would allow more Sunlight to pass through the lens and would ultimately result in a larger increase in the temperature of water. This hypothesis is further backed up by,

$$T = \frac{Pt}{4\pi R^2 mc} \times a$$

(where $T \propto a$, $\frac{Pt}{4\pi R^2 mc}$ is the constant, and T, a are the variables)

Methodology

To fulfill the objective of the investigation, water will be placed in a test tube in the Sun with a convex lens focusing the Sunlight on the test tube. For each trial, the aperture area of the lens will be reduced by covering the aperture with circular paper cutouts of varying sizes. The water is placed in the Sun for a fixed duration, and the temperature change of the water will be measured for each trial.

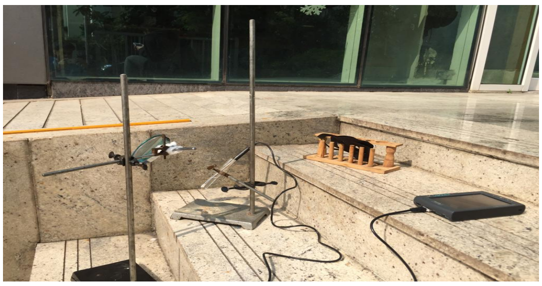

Figure 2:- Experimental setup

[3] "Stefan-Boltzmann Law". *Warwick.Ac.Uk*, 2010, https://warwick.ac.uk/fac/sci/physics/intranet/pendulum/stefan/. Accessed 8 Nov 2019.
[4] K.A. Tsokos Sixth Edition, 2014
[5] Kim, Jongyoun, and Terri S. Hogue. "Evaluation Of A MODIS-Based Potential Evapotranspiration Product At The Point Scale". *Journal Of Hydrometeorology*, vol 9, no. 3, 2008. *American Meteorological Society*, doi:10.1175/2007jhm902.1. Accessed 8 Nov 2019.
[6] "By The Numbers | Sun – NASA Solar System Exploration". *NASA Solar System Exploration*, https://solarsystem.nasa.gov/solar-system/Sun/by-the-numbers/. Accessed 8 Nov 2019.

[7] "Sun Fact Sheet". *Nssdc.Gsfc.Nasa.Gov*, 2018, https://nssdc.gsfc.nasa.gov/planetary/factsheet/Sunfact.html. Accessed 6 Nov 2019.

Variables

Independent Variable

Aperture area of convex lens (a/m^2): The aperture area is measured in meter-squared (m^2) and is changed by covering the same lens by different circular paper cutouts of different sizes. Covering the surface of the lens with paper cutouts changes its radius and ultimately changes the aperture area. The following aperture areas are investigated: $0.0157m^2$, $0.0127m^2$, $0.0100m^2$, $0.0077m^2$, $0.0056m^2$, $0.0039m^2$.

Dependent Variable

Temperature change ($\Delta T/°C$): The temperature change is measured in celsius (°C). A temperature probe connected to a data logger with an uncertainty of $\pm 0.1°C$ is used to measure the initial and final temperature of water in the test tube. Temperature change is calculated as,

$$\Delta T = T_f - T_i$$

(where T_f is final temperature and T_i is initial temperature)[8]

Control Variables

1. Duration of each trial: As the amount of time for which the water is kept in the Sun increases, the temperature and, ultimately, the temperature change would increase. Hence, to ensure the calculation of a precise value of power, the time for each trial ought to remain the same. The duration of each trial was taken as 180 seconds.
2. Mass of water: Varying mass of water in the test tube for each trial would result in differing amounts of heat energy required to raise the temperature. Given that the duration of each trial is held constant, different quantities of water for each trial would make it unfeasible to calculate the power. For each trial, the mass of water in the test tube was taken as 15 g.
3. Separation between lens and test tube: The Sun rays are concentrated on a particular point on the test tube when the focal point of the convex lens is adjusted on to the test tube. The concentration of the Sun rays and the point on the test tube where they are concentrated have an effect on the temperature change. This makes it necessary to ensure a constant separation between the lens and test tube. Upon adjusting the position of the lens with respect to the test tube, the focal point of the convex lens was determined (21 cm), and therefore, a constant separation of 21 cm was kept between the two.
4. Color of circular paper cutouts: Certain colors absorb light (the colors red, black, etc) while others do not (the color white). Furthermore, certain colors, especially light colors, allow some amount of light to pass through them. Therefore, ensuring consistency in color choice for all trials and choosing a color for the paper cutouts which allows passing of little to no light becomes necessary. To this end, circular cutouts from black paper were used for all trials.

List of Apparatus

i. Black Colored A2 Paper
ii. Clamp Stand × 2
iii. Compass
iv. Cutter
v. Glass Convex Lens (21 cm Focal Length)
vi. Stopwatch (± 0.01 s)
vii. Tape
viii. Temperature Probe attached to Data Logger (LabQuest2) ($\pm 0.1°C$)

[8] "Thermochemistry". Documents.mx, 2014, http://documents.mx/documents/thermo-55845cf5df90c.html?cv=1. Accessed 8 Nov 2019.

ix. Test Tube
x. Water (450 ml)
xi. Wooden Ruler ($\pm$0.0005 m)

Figure 3:- Apparatus used in the experiment

Safety Precautions

The data collection process requires spending few hours in the Sun and focusing the Sun rays on the test tube. Therefore, the following measures ought to be taken to protect oneself:

i. Apply Sunscreen with a SPF of 30 or higher to protect yourself from Sunburns.
ii. Wear long-sleeved shirts and shorts to keep yourself cool.
iii. Wear Sunglasses with UV protection and wide-brimmed hats to protect your eyes and head from the Sun.
iv. Drink plenty of water to prevent dehydration.
v. Do not stare at the point on the test tube where the Sun rays converge so as to prevent damage to the eyes.
vi. Do not place your hand or come in front of the convex lens as the converged Sun rays cause burns on the skin.

Procedure

i. Making circular paper cutouts
   a. To reduce the radius of the convex lens from 0.05 m to 0.0045 m, the compass is stretched to 0.05 m on the wooden ruler and a circle with a radius of 0.05 m is drawn with a pencil on a black A2 paper.
   b. Inside the circle, another circle with a radius of 0.045 m is drawn using the compass.
   c. With the help of a cutter, the larger circle from the A2 paper is cut, and then the outline of the smaller circle is cut.
   d. The obtained circular paper width is then stuck to the lens with tape so as to reduce the aperture area of the lens.
   e. Steps *a-d* are then repeated to further reduce the aperture area of the lens by creating circular paper cutouts of larger sizes. For example, to reduce the radius to 0.04 m, a circle with a radius of 0.04 m would be drawn in a circle of 0.05 m radius and cut with a cutter.

ii. Measuring temperature change
   a. 15 cm^3 of tap water is taken in a test tube.
   b. The temperature probe, connected to the data logger, is then inserted in the test tube such that the probe's tip is submerged in water.
   c. The temperature displayed on the data logger, immediately after the probe is submerged in the test tube, is noted as the initial temperature (T_i).
   d. The two clamp stands are setup: one holding the convex lens while other holding the test tube with the immersed temperature probe.

e. To ensure that the focal point of the convex lens falls on the test tube, the distance between the two clamp stands is set as 21 cm and the two are appropriately adjusted such that the light converges on the test tube.

f. The test tube is then placed in the Sun for 300 s.

g. After 300 s, the temperature indicated on the data logger is then noted as the final temperature (T_f).

h. Steps *a-g* are then repeated for different aperture areas by covering the convex lens with larger circular paper cutouts each time (reducing the aperture area). For a single aperture area, five trials are conducted to reduce the effect of random error on the result of the investigation.

Data Collection and Processing

Raw Data

Radius of Convex Lens r/m (± 0.0005 m)	Temperature of water $T/°C$ ($\pm 0.1°C$)									
	Trial 1		Trial 2		Trial 3		Trial 4		Trial 5	
	Initial (T_i)	Final (T_f)	Initial (T_i)	Final (T_f)	Initial (T_i)	Final (T_f)	Initial (T_i)	Final (T_f)	Initial (T_i)	Final (T_f)
0.0500	30.2	50.1	29.5	51.7	29.2	49.5	29.4	54.1	29.8	52.7
0.0450	30.1	47.1	30.9	48.8	29.6	51.2	30.2	47.5	29.6	46.8
0.0400	30.3	40.9	30.7	49.6	30.2	43.9	30.9	44.7	30.2	44.2
0.0350	29.8	40.4	30.5	39.3	30.1	40.8	30.6	41.5	30.9	46.2
0.0300	30.5	38.2	30.3	36.6	30.8	38.7	29.9	35.8	30.0	43.1
0.0250	30.2	36.5	29.7	36.9	30.3	39.1	29.6	33.2	30.6	35.8

Table 1:- Raw data table displaying temperature change for five trials

Data Processing

Apparatus Uncertainty

Apparatus	Uncertainty
Temperature Probe connected to Data Logger (LabQuest2)	$\pm 0.1°C$
Wooden Ruler	± 0.0005 m

Table 2:- Uncertainties of used apparatus

Temperature Change

Trial 1 of radius 0.0500 m has been used as an example.

The temperature change of water (ΔT),

$$(T_f) - (T_i)$$

$$\Delta T = 50.1 - 30.2 = 19.9°C$$

The uncertainty of ΔT can be found by summing the uncertainties of the two temperature values used to calculate ΔT. Therefore, given that the uncertainty of the two temperatures is ± 0.1°C (as collected by the digital data logger), the uncertainty of ΔT is,

$$\pm\Delta T = 0.1 + 0.1 = 0.2°C$$

$$\therefore\ \Delta T = 19.9 \pm 0.2°C$$

Since the temperature change is calculated for five trials, we can calculate average temperature change (ΔT_{avg}) by summing the five temperature change values and dividing them by five,

$$\Delta T_2 = 22.2 \pm 0.2\ °C$$
$$\Delta T_3 = 20.3 \pm 0.2\ °C$$
$$\Delta T_4 = 24.7 \pm 0.2\ °C$$
$$\Delta T_5 = 22.9 \pm 0.2\ °C$$

The average then is,

$$\frac{19.9 + 22.2 + 20.3 + 24.7 + 22.9}{5} = 22.0\ °C$$

Using the maximum and minimum value of the temperature changes out of the five values, we can calculate the uncertainty in ΔT_{avg},

$$\pm\Delta T_{avg} = \frac{24.7 - 19.9}{2} = 2.40°C \approx 2°C$$

$$\therefore \Delta T_{avg} = 22 \pm 2\ °C$$

We can calculate the percentage uncertainty of the average temperature change using the average temperature change and its uncertainty,

$$\pm\%\Delta T_{avg} = \frac{2}{22} \times 100 = \pm 9.09\% \approx \pm 9.1\%$$

Aperture Area

Trial 1 of radius 0.0500 m has been used as an example.

The aperture area of convex lens (a),

$$a = 2\pi r^2$$

Using the value for radius,

$$a = 2.\pi.(0.0500)^2 = 0.0157\ m^2$$

Processed Data

Radius of Convex Lens $r/m\ (\pm 0.0005m)$	Aperture Area a/m^2	Average Temperature Change $\Delta T_{avg}/°C$	Average Temperature Change Uncertainty $\pm\Delta T_{avg}/°C$	Average Temperature Change Percent Uncertainty $\pm\Delta T_{avg}/\%$
0.0500	0.0157	22	2	9.01
0.0450	0.0127	18	2	11
0.0400	0.0100	14	4	29
0.0350	0.0077	11	3	27
0.0300	0.0056	8	4	50
0.0250	0.0039	6	3	50

Table 3:- Processed data table displaying temperature change of five trials and the average temperature change

Graphing Data

From *table 3*, the graph of aperture area and its respective average temperature change can be plotted.

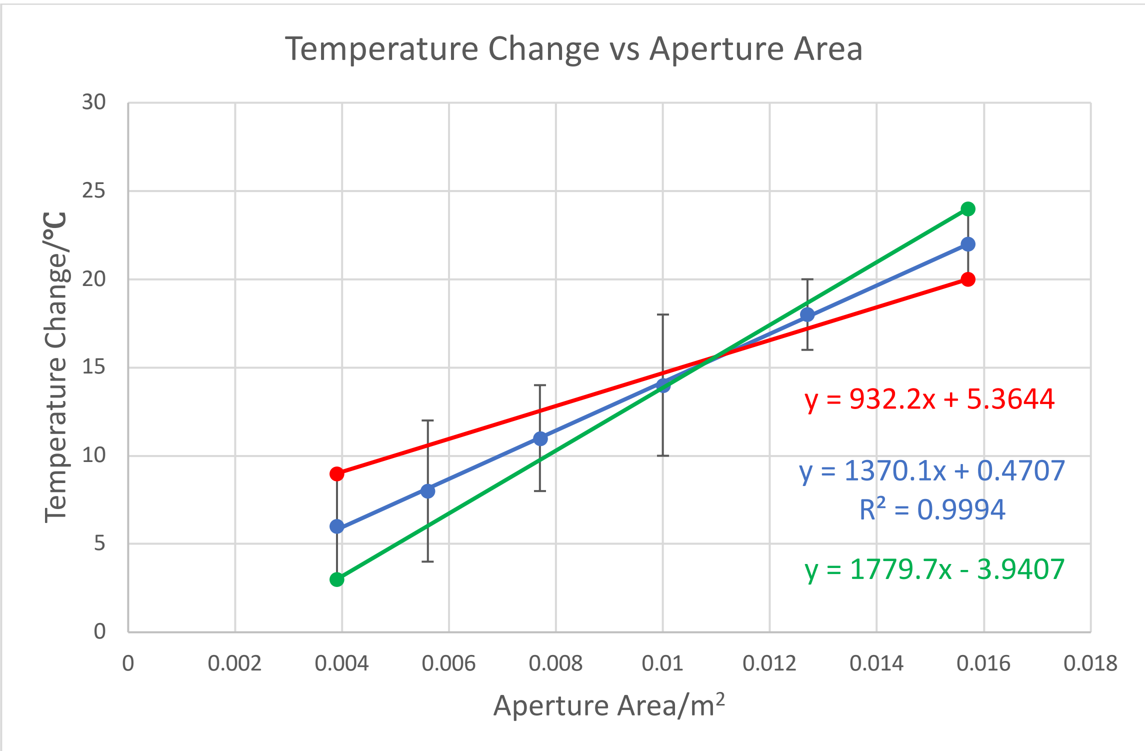

Figure 4: - Graph displaying squared average temperature change vs aperture area where blue represents the best-fit line, red represents the max-slope, and green indicates the min-slope

Error Calculation from Graph

Slope Uncertainty:

$$\text{Slope Uncertainty } (\pm s) = \frac{|\text{Max Slope} - \text{Min Slope}|}{2}$$

$$\pm s = \frac{|932.2 - 1779.7)|}{2} = \pm 423.75\ ℃.\mathrm{m}^{-2} \approx \pm 400\ ℃.\mathrm{m}^{-2}$$

Accuracy:

Using,

$$\Delta T = \frac{Pt}{4\pi R^2 mc} \times a$$

We can calculate the power of the Sun after rearrangement,

$$P = \frac{\Delta T.\,4\pi R^2 mc}{a.\,t}$$

(where ${}^{\Delta T}/_{a}$ is the slope of the graph displayed in *figure 4*)

Substituting the appropriate values,

$$P = 1370.1 \times \frac{4 \times \pi \times (1.5 \times 10^{11})^2 \times 0.015 \times 4200}{180} = 1.36 \times 10^{26}\ \mathrm{W}$$

Since the slope (${}^{\Delta T}/_{a}$) calculated from the graph in *figure 4* has an uncertainty ($400\ ℃.\mathrm{m}^{-2}$), we can use this uncertainty to calculate the uncertainty in the obtained value for the power of the Sun,

$$\frac{\pm P}{P} = \frac{\pm s}{s}$$

$$\frac{\pm P}{1.36 \times 10^{26}} = \frac{400}{1370}$$

(as $s = 1370 \pm 400\ ℃.\mathrm{m}^{-2}$)

$$\pm P = \pm 0.39 \times 10^{24}\ \mathrm{W} \approx \pm 0.4 \times 10^{24}\ \mathrm{W}$$

Using the literature value for power of the Sun obtained in the Background Information, we calculate the percentage error for the value obtained from experimentation,

$$\text{Percent Error} = \frac{|Experimental\ value - Literature\ value\ |}{Literature\ Value} \times 100$$

$$\text{Percent Error} = \frac{|1.36 \times 10^{26} - (3.83 \times 10^{26})|}{3.83 \times 10^{26}} \times 100 = 64.49\% = 64\%$$

Conclusion and Evaluation

Conclusion

From the data which has been gathered and processed, it can be seen that the hypothesis is supported to a certain extent. The graph displayed in *figure 4* shows that as the aperture area of the convex lens (independent variable) increases, the average temperature change of the water (dependent variable) increases. That is, there exists a positive correlation between the independent and dependent variables. Using the graph displayed in *figure 4,* we can calculate the average temperature change for a corresponding change of $0.001\ \mathrm{m}^2$ in the area of the convex lens as follows,

$$\frac{\Delta y}{\Delta x} = 1370.1 \text{ (as slope of the best fit line in } \textit{figure 4} \text{ is } 1370.1\ ℃.m^{-2}\text{)}$$

$$\frac{\Delta y}{0.001} = 1370.1 \text{ (as calculating for an increase in area by } 0.001\ m^2\text{)}$$

$$\Delta y = 1.37℃$$

Hence, the temperature change for a corresponding change of $0.001\ \mathrm{m}^2$ in the area of the convex lens is 1.37℃. However, as the graph fails to pass through the origin, the possibility of a directly proportional relationship existing between the two variables is dismissed. The existence of a high correlation between the independent and dependent variables ($R^2 = 0.9994$) acts as evidence regarding the effectiveness of the investigation in determining a relation between aperture area and the average temperature change.

Along with appropriately deducing a relation between the two variables, the objective of the investigation was partially fulfilled as well: determination of the power emitted by the Sun per second. The obtained power value was less than the literature value for the power of the Sun and contradicts the assumption made earlier that an increase in the power of the Sun has increased and contributes to the recent rise in temperatures. However, the large discrepancy in the value of the obtained power (64% error) points to the presence of a number of systematic and random errors in the investigation which are detailed in the next section. Furthermore, since the literature value of the power itself is an approximate (meaning it too is prone to numerous errors), the question whether the power of the Sun has actually increased still remains.

Evaluation

Although the high correlation value acts as evidence for the precision of the experiment, there were a number of errors which affected the outcome of the investigation. The vertical error bars displayed in *figure 4* exhibits errors in the value of the average temperature change as a result of a number of random errors. Similarly, the graph is not seen passing the origin due to the presence of systematic errors. The presence of such random and systematic errors in the data collected is also verified by the power value obtained which is far off from the literature value and has a large uncertainty.

Random Errors

1. Number of trials: Due to the paucity of time, the investigation involved the collection of only five trials for each aperture area. Less number of trials result in the outliers present in the data having a larger impact on the outcome on the investigation. The vertical error bars displayed in *figure 4* are a consequence of this error. The precision of the average temperature change could have been increased by conducting a larger number of trials for each aperture area.
2. Ambient temperature: The investigation was carried out on a sunny windy day. Therefore, although the experiment was conducted when the Sun was strong, the breeze could have affected the temperature increase of the water differently for each trial and, in some cases, may have affected the initial temperature of water by slightly reducing the temperature of the water.

The ability to control temperature by possibly covering the opening of the test tube with a test tube cap would reduce the effect of ambient temperature on the results. The effect of this error on the investigation was explored by placing $15\ \text{cm}^3$ of distilled water with a temperature of 30.2°C (typical temperature of water in the investigation) in the open for 100 s. Due to the transfer of heat energy from the surroundings to the water, the final temperature was recorded to be 30.4°C. As the obtained temperature change was quite less change compared to what was obtained in the investigation the effect of this error on the investigation was deemed to be minuscule.

Systematic Errors

1. Amount of data: Only six different aperture areas were tested as part of the investigation. Testing a smaller number of aperture areas amplifies the effect outliers could possibly have on the outcome and relation between aperture area and average temperature change. This might result in the prediction of an inaccurate correlation between the two variables. Testing a larger number of aperture areas would result in the prediction or further investigation of a more accurate correlation.
2. Temperature Probe: A major contributor to the uncertainties obtained in the investigation was the temperature probe. Although the probe recorded temperature to an uncertainty of ± 0.1°C, the method by which uncertainties are propagated led to an increase in the temperature change's uncertainty and, ultimately, the average temperature change's uncertainty. To place this in context, the typical average temperature change and its uncertainty was 13°C and 3°C respectively. Therefore,

   $$\text{Percentage Uncertainty} = \frac{3}{13} \times 100 = \pm 23.08\% \approx \pm 23\%$$

   The considerable percentage uncertainty value shows that the effect of this error on the outcome is quite significant. Therefore, using a temperature probe which reports values with much higher precision is required to decrease the effect of such uncertainty on the outcome of the investigation.
3. Earth's shape: The spheroidal shape of the Earth results in the Earth being close to the Sun during a certain time in its orbit. Theoretically, at this point, we would attain a higher power value. However, since the aperture areas of the lens being investigated are tiny compared to the size of the Earth, the shape of the Earth would have little to no effect on the obtained results. Furthermore, the location where the experiment would be conducted would have an insignificant effect on the rectification of this error. Therefore, this can be considered as a shortcoming of the investigation.
4. Aperture Area: Aperture area was calculated using the formula,

   $$a = 2\pi r^2$$

   However, this formula does not take into consideration the thickness concentrated at the center of the convex lens. Neglection of this thickness results in an inaccuracy in the calculated aperture area values. By modelling the different radii convex lenses in Solid Works, it would be possible to calculate the aperture areas to a higher accuracy.

Random and Systematic Errors

1. Earth's atmosphere: When the energy emitted from the Sun reaches the Earth's atmosphere, some of the energy is absorbed by it. This results in less and varying amounts of energy reaching the water, affecting accuracy and precision. The effect of this error on the investigation can be explored by calculating the percentage uncertainty in the obtained value of the power of the Sun. This percentage uncertainty is calculated using the obtained power value and its uncertainty as follows,

$$\pm\%P = \frac{0.4 \times 10^{24}}{1.4 \times 10^{26}} \times 100 = \pm 0.28\%$$
$$(\text{as } P = 1.4 \times 10^{26} \pm 0.4 \times 10^{24} \text{ W})$$

Such a small value for the percentage uncertainty indicates that the effect of this error on the investigation is insignificant. However, this is one of the reasons why the obtained power value deviated from the literature value of power of the Sun. Taking into account the absorbed energy in the calculations would potentially decrease the effect of this error.

2. Refraction: The light is able to pass through the convex lens and reach the test tube via the phenomenon of refraction. Therefore, if the incident ray were to approach the aperture of the lens at an angle which is equivalent to or larger than the critical angle, then light would be reflected instead of being refracted. That is, the light would not pass through the lens. A similar situation would occur when the light rays approach the glass test tube. Furthermore, depending on the point where the Sun rays would fall on the test tube, refraction would further affect the temperature change of the water due to light bending at different degrees. The effect of this error could be reduced by using a convex lens with a lower refractive index to ensure that maximum amount of light passes through the lens and by ensuring that the light is converged by the lens at a fixed point on the test tube.
3. Weather conditions: The large error bars shown in *figure 4* act as evidence for the presence of this error. This error arises because as the experiment was carried outside, cloud cover had an impact on the obtained temperature change as the values decreased when a cloud came in the line of sight of the lens. Although the experiment was conducted when the Sun was strong, the possibility of the high uncertainty being obtained due to this error source shows that there was a limited window for the experiment to be conducted and acts as evidence for the limitation of the experimental location. A possible solution could be to conduct the experiment during a time or at a location where cloud cover does not exist, and the Sun is strong.

Further scope of the investigation

Numerous factors responsible for the systematic and random errors in the investigation could be accounted for such as using a temperature probe which measures temperature with higher precision, a convex lens with a lower refractive index, modelling the convex lens in Solid Works, etc. This would contribute to furthering the scope of the investigation.

Furthermore, since location and the time when the experiment was conducted were one of the few limitations of the investigation, the investigation could be carried out at different locations and times to obtain different values of power. The investigation could be carried out at the equatorial regions as these regions receive sun rays which are almost perpendicular (90°) to the Earth's surface and result in the accumulation of the sun rays across smaller surface areas, resulting in warmer temperatures. Similarly, the investigation could also be carried out at regions of lower latitude as these regions receive sun rays which approach the Earth's surface at larger angles, resulting in increased heating. Lastly, the investigation could be conducted at different times such as 8 am, 12 pm, etc. The rationale behind this is that as the angle of sun rays approaching a particular location change with time, carrying out the investigation at different times would provide a wide range of power values depending on the angle of incidence of the sun rays. The obtained power values for the different locations and time could then be averaged out to reduce the percentage uncertainty and obtain a more accurate value for the power of the Sun.

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