University of Salford MANCHESTER

Thermal Energy Storage from a Radiation Source

Heat Transfer Laboratory

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Thermodynamics and
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Summary

The radiation of the sun in which the planet is incessantly plunged, penetrates the air, the earth and the waters; its elements are divided, change direction in every way, and penetrating the mass of the globe would raise its temperature more and more, if the heat aquired were not exactly balanced by that which escapes in rays from all points of the surface and expands through the sky.

- The analytical theory of heat, J.Fourier

This Laboratory will be used to demonstrate methods of obtaining radiated energy from a light source.[1]

Note: All tags that appear as [1..3...x] are referenced excerpts, The table of contents is interactive if viewed as a .pdf, and can be clicked to aid navigation.

1 Introduction

This laboratory experiment was designed to assess the varying ability of materials to absorb heat energy from a controlled source of thermal radiation, i.e. a heat lamp. The course of thermodynamics this year has been focused on using heat sources to produce work, and the transmission, capture, conversion and storage of thermal energy has been highlighted as an important part of mechanical engineering, indeed HVAC and building services engineers strive to produce more thermally efficient buildings, material scientists and aeronautical engineers work together to produce advanced materials for the aerospace industry that are subject to extreme heating and cooling cycles. Mechanical design engineers work on turbomachinery such as jet turbines and turbochargers, engines and rocketry, even cooling systems and heat exchangers in nuclear reactors, all of which require an understanding of heat transfer and methods of controlling it's aspects.

In the laboratory session, the aim was to explore a range of engineering materials, a Ceramic, an Aluminum, an piece of wood, and a piece of hard foam. It is shown in the report the variation in thermal characteristics of each, and in this way material selection can be conducted based on the system requirements.

The over arching subject of this topic and module is the practical topic of thermal and energy systems. This field encompasses such hardware as internal-combustion engines, aircraft propulsion, heating and cooling systems, and electrical power generation through both renewable (solar, wind, hydroelectric, geothermal, and biomass) and nonrenewable (oil, petroleum, natural gas, coal, and nuclear) sources. It will become more and more important for engineers to study and solve energy issues; three of the 14 NAE(National Academy of Engineering United States) grand challenges are directly related to energy issues: making solar energy economical, providing energy from fusion, and developing carbon sequestration methods.[2]

1.1 Aims

Measure the amount of energy radiated to the material, and compare with other materials, then compare these results with a theoretical prediction based on known parameters. Taking into account such parameters as efficiency, power, material properties, heat loss, black body radiation inident on black surfaces.

To explore simple methods of converting the energy radiated from a source directly into heat.[1]

2 Theoretical Background

Thermodynamics: the branch of physics that deals with conversions between heat energy and other forms of energy.

Heat transfer: A discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy and heat between physical systems.
Heat transfer is the tendency of heat or energy to move from a warmer space to a cooler space until both spaces are the same temperature. Obviously the greater the difference in temperatures, the greater will be the heat flow.[6]

2.1 Modes of Heat Transfer

At the very basic level thermal energy is the flow of energy within a substance due to it's molecules impacting, and producing an kinetic energy exchange, and causing the molecules to vibrate, this is measured as a macroscopic change in temperature.

The fundamental modes of heat transfer are:

2.1.1 Conduction or diffusion

The transfer of energy between objects that are in physical contact.

2.1.2 Convection

The transfer of energy between an object and its environment, due to fluid motion.

2.1.3 Advection

The transfer of energy from one location to another as a side effect of physically moving an object containing that energy.

2.1.4 Radiation

The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation.

2.2 Radiation

Radiation - This occurs between a warm object and a colder object when they are separated only by a medium which is transparent to infrared radiation. This is easiest to understand by just standing in the sun: while the sun is very far away, it is also very big and very hot while space and the atmosphere block very little of that incoming radiation. With smaller and much cooler objects, radiation is a much less significant source of heat transfer, although its affects can still easily be noticed.[6]

2.3 Theory of Investigation

For the particular experiment the mode of heat transfer is clearly the infrared light being emmited from the light source and acting incedent on the surface of the material, this high energy interaction of photons causes some of the atoms of the material to undergo energy transitions and then release this energy, simply the molecules vibrate more quickly in there lattice as a result of the imparted energy.

The wavelength of infra red radiation is of the order of magnitude 1 to 100μm, given by

$$\lambda = \frac{c}{v}$$

c being the speed of light, v being wave velocity, lambda being wave length.

The incident energy imparted by one photon of electomagneic radiation is given by

$$e = hv$$

v again being velocity, $h = 6.6256 \times 10^{-34}$ J, planks constant.

Clearly heat transfer by radiation is the macro effect of the microscopic interactions.

2.4 Macro characteristics of thermal radiation

Radiation is due to the described microscopic interations, thermal radiation exists in the wavelenghts of visible light, and infrared, shorter wavelengths lack the energy to cause thermal radiation, and longer wavelengths pervade materials in other ways, for example microwaves carry enough energy to penetrate and no longer be a surface interaction imparting energy internally. The rate of thermal emmision increases with increasing temperature, and is emitted by all materials above 0 kelvin, i.e. all materials constantly emit and absorb some level of thermal radiation.[3]

Radiation is emitted by all of the microscopic bodies (molecules,atoms etc.) that make up the material, and is therefore a volumetric phenomenon, however, since the energy never reaches the surface, radiation is considered to be a surface interaction, and the radiation characteristics can be changed completely by applying thin layers of coatings on them.[3]

2.4.1 Black Body Radiation

A blackbody is defined as as a perfect emitter and absorber of radiation. At a specific temperature and wavelength no surface can emit more energy than a blackbody.[3]

The thermal energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature.[5] Blackbody emissive power is given by the Stefan-boltzmann law:[3]

$$E_b(T) = \sigma T^4$$

Where:

- E_b blackbody emmisive power
- T is Temperature
- σ is the stefan-boltzmann constant ($5.67 \times 10^{-8}\ W/m^2K^4$)

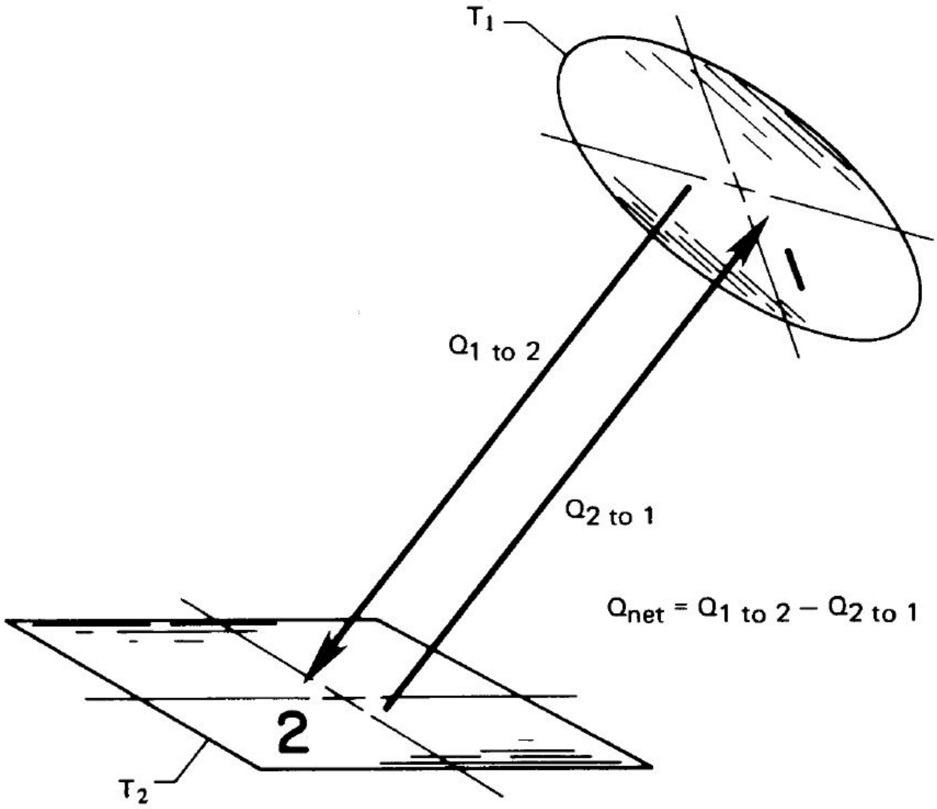
Clearly mimicking the black body by using coatings of black paint then, will amplify the materials abillity to absorb radiation.

For hot objects other than ideal radiators, the law is expressed in the form:

$$P = e\sigma A(T^4 - T_C^4)$$

Where:

- P is net radiation energy loss from source (Power) alternatively gained by absorber.
- T is Temperature
- T_C is temperature of surroundings
- σ is the stefan-boltzmann constant ($5.67 \times 10^{-8}\ W/m^2K^4$)
- A is Area
- e is emissivity of the object (1 for ideal.)



[4]

Figure 1: Thermal radiation between two arbitrary surfaces.

2.4.2 The problem of radiative exchange

- Electromagnetic wave spectrum
- Heat radiation & infrared radiation
- Black body
- Absorptance, α
- Reflectance, ρ
- Transmittance, τ
- $\alpha + \rho + \tau = 1$
- $e(T)$ and $e_\lambda(T)$ for black bodies
- The Stefan-Boltzmann law
- Wien's law & Planck's law
- Radiant heat exchange
- Configuration factor, $F_{1\text{-}2}$
- Emittance, ε
- Transfer factor, $\mathcal{F}_{1\text{-}2}$
- Radiation shielding

[4]

2.5 $Q_{Top.Loss}$ Equation

The $Q_{top.loss}$ Equation is an empirical one provided in the laboratory session[1] The equation descirbes the energy lost through transit between the surface of the radiation source, and the radiation absober, i.e. with the glass cover on detailed in the experiment, the energy lost due to the surface of the sample radiating energy.

$$Q_{top.loss} = \frac{N \times (T_C - T_a) \times A_C}{\frac{365}{T_C} \times \left(\frac{T_C - T_a}{N + 0.5}\right)^{0.13}}$$

Here Qtop.loss is the energy lost at the top of the piece (Watts), Tc is the collector plate temperature (K), Ta is the ambient temperature (K), N is the number of covers on the piece and Ac is the aperture area (meters squared). the efficiency = Qtop.loss/energy in:

$$\left(1 - \frac{Q_{top.loss}}{Power \times Area}\right) \times 100$$

The efficiency from this is calculated as 99.67%

The main concerns of the phenomena have been discussed, and the experiment can now be carried out.

3 Experimental Investigation

3.1 Method

Set up the light such that you measure approximately 1000 Wm^{-2} at the collection point with the solar power meter.

For each of the following four samples determine the absorptivity of each sample when subjected to incident radiative light for five minutes.

Samples :

1. Aluminium
2. Wood
3. Ceramic
4. Foam

Initial prediction: Aluminium will absorb the most, then wood, then ceramic, then foam.
Following this prediction the laboratory session was set up to observe the behaviour of the materials using the following method,

1. Place the sample in the incidence area
2. Ensure the thermocouple is recording
3. Record the pre incident temperature
4. Switch on the lamp and record the temperature after 5 minutes (Measured at 990 Wm^{-2} for a rated 1000 Wm^{-2} lamp)
5. Repeat with alternate material

3.1.1 further investigation of the aluminium sample

The sample is painted black on one side to simulate the effects of blackbody radiation. Within the experiment the samples have four test configurations:

1. Unpainted incidence side
2. Painted incidence side
3. Painted and insulated
4. Painted, insulated, and covered by glass.

Following the procedure for the other material, for the aluminum two more steps were added:

a. Cooling the sample in the cold water for two minutes, dried, and temperature measured using the thermocouple,

and

b. Place the sample under the lamp, at the measuring point with the thermocouple underneath. Then measure the back surface temperature after 10 minutes.

3.2 Initial Results

Sample	Ceramic	Wood	Aluminium	Hard Foam
Ambient Temperature TA K	295.15	295.15	295.15	296.15
Collector Temperature,TC,K	299.15	301.15	302.15	306.15
Specific Heat Capacity, C_P, J/Kg	1085	1700	900	180
Change in Temperature	4	6	7	10
Time, t, s	300	300	300	300
Density, ρ, Kgm^{-3}	2400	750	2700	30
Thermal Capacity	10416	7650	17010	540

Table 1: Results of initial material comparison

From the table we can see the hard foam absorbed the most , followed by aluminum, wood, and ceramic respectively. This is in contrast with the initial predictions, clearly the combined properties of the foam lends itself to greater temperature sensetivity than the other materials, however in terms of energy absorbed is proportional to the specific heat capacity and the temperature change, since the samples are of varying mass, we cannot directly calculate the value Q for

$$Q = mC_p\Delta T$$

However assuming all the samples have the same thickness, and the are is specified, the volume, and therefore the mass can be calculated for each, allowing Q for each material.

Assume a 10mm thick sample size(The value doesn't matter for direct comparison), each sample has voume:

$$V = (55 \times 55 \times 10) \times 10^{-9} m = 3.025 \times 10^{-5} m$$

Mass for each sample is :

$$m = \rho \times V$$

Sample	Density(ρ)	Mass (kg)	Cp	ΔT	Q(J)
Wood	750.00	0.02	1700.00	6.00	231.41
Aluminium	2700.00	0.08	900.00	7.00	514.55
Ceramic	2400.00	0.07	1085.00	4.00	315.08
Hard foam	30.00	0.0009075	180.00	10.00	1.63

Table 2: Calculating energy for a 10mm thick sample

Clearly the aluminium absorbs the most radiated thermal energy, and this is consistent with the aluminium's thermal capacity being the highest.

3.3 Results of the Aluminium experiment

Case	1	2	3	4
Mass, M, Kg	0.051	0.051	0.051	0.051
Specific Heat Capacity, CP, J/Kg	900	900	900	900
Ambient Temperature, TA, K	296.15	296.15	295.15	296.15
Collector Temperature, TC, K	306.15	319.15	326.15	328.15
Thermal Capacity	24300	55900	75300	77800
Change in Temperature	10	23	31	32
Time, t, s	600	600	600	600
Density, ρ, Kg/m3	2700	2700	2700	2700
Thermal Energy, Q, J	459	1055.7	1422.9	1468.8
Q$\times\frac{5}{3}$	0.765	1.7595	2.3715	2.448
Efficiency, %	25.54%	58.75%	79.19%	81.74%

Table 3: Results of the aluminium test cases.

For the cases with the Glass cover on top the λT value for the range of temperatures corresponds to a negligable blackbody radiation function (0) Example: $\lambda T = 0.8 \times 299.15 = 239.32$ The function is only non zero after $\lambda T > 800$

For the values of the stefan boltzman law the calculations have been carried about for each case.

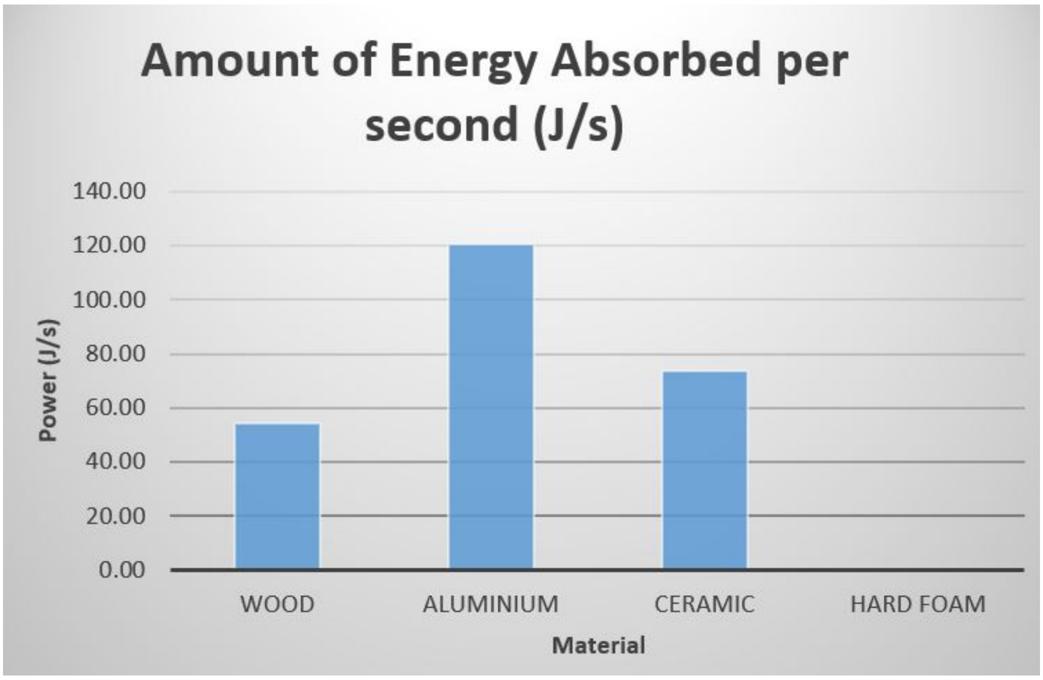


Figure 2: For constant conditions this is both the absorbtion and emission rate.

The Experiment was carried out with some assumptions:
The lamp was not quite the rate 1kw, and instead read 990W/m^2.
Sample Area = 3.025mm^2.
Hard-Foam is assumed to be poly eurethane.
The Ceramic was assumed to be a piece of standard porceline tile.
The wood was oak.
A standard aluminium grade was assumed with minimal alloying.

3.4 Factors affecting the experiment

4 Discussion

Folowing the experiment a number of key observations have been obtained, all other things being equal, the material properties of the samples determine their ability to absorb and emit thermal radiation, with the more dense material being better, this is due on a microscopic level to the fact there are more atoms packed into a tighter space and therefore more atoms to interact with the photons from the electromagnetic radiation initially the efficiency was 25.54%.

Having calculated the theoretical efficiency this value was compared to experimental values, the varying test cases of the aluminium sample show the effects of mimicking a black body radiator, with the black paint able to absorb a wider spectrum of wavelengths than the shiny aluminium surface, this in turn increases the number of photon interations and also the number of higher wavelength, and therefore higher energy photons able to interact with the materials surface, this increased the efficiency to 58.75%, more than double the previous value, clearly the aluminum surface was very reflective.

Placing the sample on an insulated material ensures there is limited heat transfer via conduction between the sample and the surface it was placed on by choosing a poor conductor (good insulator) as a barrier, this increased the efficiency to 79.19%, another sizeable jump in performance, however not double as previous, likely a sign of diminishing returns in improvements.

Covering the system with a glass cover acts to allow the thermal radiation to act incident through the glass and interact with the surface, which is now painted black and absorbing a wide range of wavelengths, the small amount of radiation that is reflected, is reflected back onto the sample by the inside of the glass, further increasing the efficiency to 81.74%

Ssubtracting the efficiency from the theoretical efficiency indicates that: (99.67-81.74) = 17.93% is unnacounted for, this translates in real terms to (0.1793×990 (watts incident on sample)) = 177.507 watts lost to the other components of the system, and the boundary of the system as in reality the system is not a closed one.

This 177.507 watts is likely lost in a number of components, for example the air is presumed still, however a breeze will produce a convection current and take away some thermal energy from the sides, the bottom will always conduct some thermal energy to the table/insulation etc. and the incident thermal radiation has travelled from the lamp source, through atmosphere, some heat is bound to be lost in transit, some will be imparted to the glass cover, and radiation will occur at the surface of the glass also, so by the time the 990 watt incident source has propagated to the surface of the material it is no longer supplying 990 watts.

5 Conclusions

In conclusion the laboratory aims and objectives have been met, the effects of thermal radiation have been observed and their consequences have been quantified in terms of power outputs, levels of radiation, and efficiencies. The techniques used should allow future material selection for thermal radiation applications such as heat exchangers and other applications(see introduction for scope of applications). The physical phenomena has been understood and the explainations given where possible. The methods of improving efficiency have been explored, and the over all iterative method of improvement serves as a reasonable showcase of experimental improvement of a system, gaining an appreciation of improving a system is important for future work, proffesionally and academically.

In conclusion the aluminum was shown to absorb the most energy, however due to the higher specific heat capacity, it did not record the highest temperature change, clearly this is a poor indicator of energy transfer for materials that vary.

Further experimentation was carried out to explore the effects of blackbody radiation theories, by painting the sample black, and further testing to illustrate insulation from heat conduction, and insulation from convection and making use of the green house effect of the glass cover.

5.1 Improvements

The laboratory session could be improved in a number of ways, using higher quality themocouples for more accurate measurements, using a more closed system and controlled environment to specify ambient temperature, humidity, pressure, and ensuring the air is conditioned to be still. Using a more precise heat source and/or allowing for an appropriate warm up period. Using a higher quality cover made from better glass, such as solar glass.

6 References

[1] Notes given in Laboratory session, H.Leonard, University of Salford

[2] An introduction to mechanical engineering 3rd ed. , J.Wickert, K. Lewis (Cengage 2013)

[3] Fundamentals of Thermal-fluid sciences chapter 2nd ed, 21 p.955-960, Cengel, Turner, McGraw-Hill publishing

[4] A heat Transfer Textbook, 3rd ed, J.H.Lienhard IV, J.H. Lienhard V, Part IV, Chapter 10, p.525-540

[5] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/stefan.html#c2, accessed 14/3/14

[6] Heat Loss Calculations and Principles ,Course No: M05-003 ,A. Bhatia ,Continuing Education and Development, Inc.

A Apparatus

The following material was made available (all samples are 55x55 mm)

- Aluminium Sample.
- Wooden Sample.
- Ceramic Sample.
- Hard Foam Sample.
- Insulator: The Polystyrene insulator was used to minimise heat loss through convection to the surface below the sample.
- Glass/Plastic Cover: This casing is used to cover the sample and trap radiation within the case see greenhouse effect.
- Radiation Source: In this case a lamp is used to emit radiation onto the sample.
- Digital Thermometer, thermocouples: Used to take temperature readings of ambient air and of the collectors.
- Solar Power Meter: Used to measure the power that is incident to the sample.
- Water: Water is used to cool samples after testing.

[1]

B Constants related to Thermal Radiation

Symbol	Name	Value
h	Planck's constant	$6.6260693(11) \times 10^{-34} Js$
b	Wien's displacement constant	$2.8977685(51) \times 10^{-3} mK$
k_B	Boltzmann constant	$1.3806505(24) \times 10^{-23} JK^{-1}$
σ	Stefan–Boltzmann constant	$5.670373(21) \times 10^{-8} Wm^{-2}K^{-4}$
c	Speed of light	$299,792,458 ms^{-1}$

Table 4: Important constants

[4]

C Safety Observations:

Do not handle the samples with bare hands.
Do not look directly at the lamp.
Use UV Glasses, and Gloves where applicable
Beware of reflections which could reflect and focus the radiation.
Do not allow prolonged exposure of bare skin to the heat lamp.

D Graphical forms of obtained data

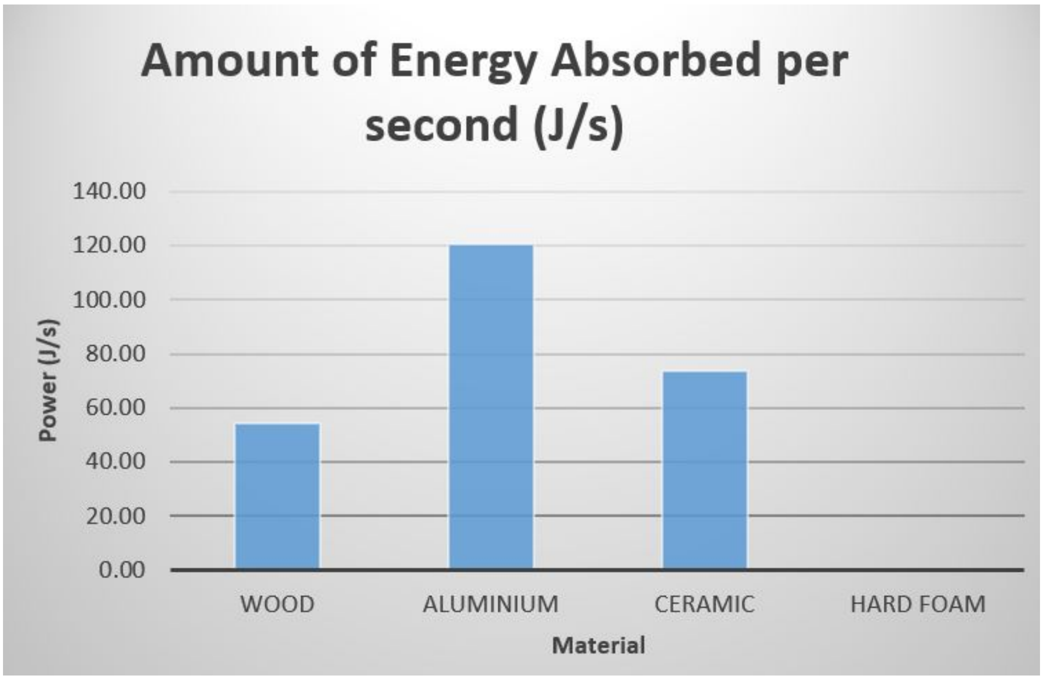


Figure 3: For constant conditions this is both the absorbtion and emission rate.

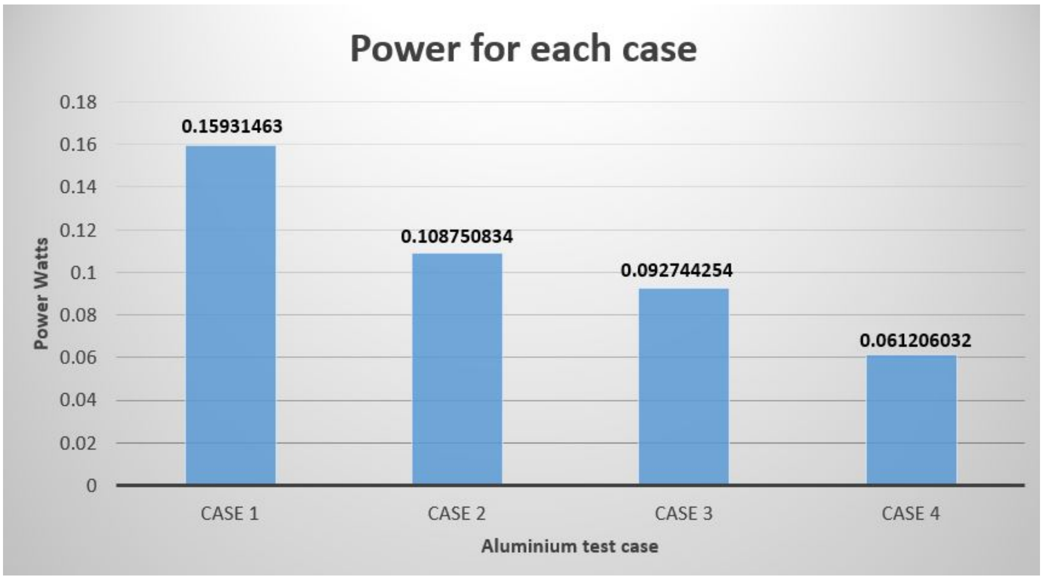


Figure 4: Emission Comparison

Figure 5: Efficiency Comparison

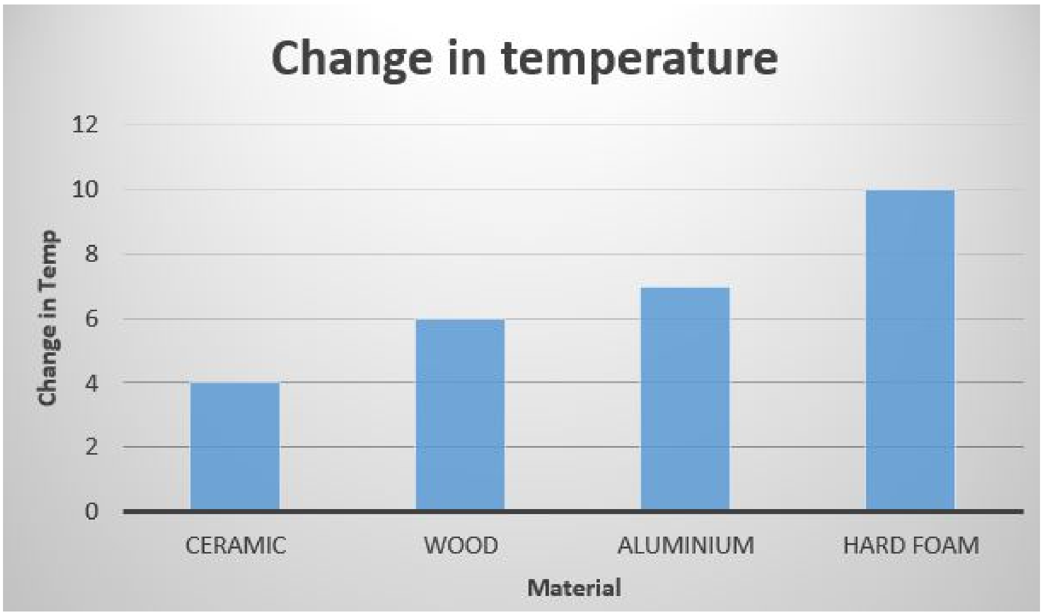


Figure 6: Temperature Comparison