Investigation of Solar Radiation Absorbance and Emittance for some Coloured Surfaces

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Abstract: Practical application and interpretations of basic physics laws look, to many, more of mirage than achievable realities within local context and content. In a geographical region of intense heat and radiation, such as Nigeria, these laws are more practicable and verifiable for application toward achieving the comfort of inhabitants of these high temperature zones. This work investigates the absorbance and emittance rates of differently coloured surfaces, in the demonstration of commonly expressed radiation laws, using five (5) 157 ml (170g) tins, of dimensions h = 6.0 cm, and r = 3.1 cm, each separately painted in black, blue, red, green, and white. These were placed in cubicles made in a wooden box and then exposed to solar radiation for about 7 hours daily for 5 days in each of two trials. Results show that solar radiant energy associated with black and white coloured surfaces are 729.866 Wm^{-2}, and 384.450 Wm^{-2} respectively with that of other colours lying in-between these two values. This confirms that while black coloured enclosures may provide warmth when ambient temperature is low, white coloured enclosures may be the colour of choice where low temperature, absorbance and emittance are desired.

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1. Introduction

The Sun, which is the largest member of the solar system, is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9m; it is at an average distance of 1.5×10^{11}m from the earth. With an effective black body temperature T_s of 5777K, the sun is, effectively, a continuous fusion reactor. Several thermonuclear reactions have been suggested to supply the energy radiated by the sun; the most important being the one in which hydrogen atoms combine to form helium in the reaction: $4_1H^1 \rightarrow {}_2He^4 + 26.7$ MeV. This energy is produced in the interior of the solar sphere (Tiwari, 2002).

A simplified description of the sun indicates that the sun does not function as a blackbody radiator at a fixed temperature. Rather, the emitted solar radiation is the composite result of the several layers that emit and absorb radiation of various wavelengths; the photosphere being the source of most solar radiation.

Radiation is known to be a mode of transport of heat energy through vacuum and the empty space between molecules (Bueche, 1988). It is an electromagnetic phenomenon. A black body is also known to be one that absorbs all the radiant energy falling on it. At thermal equilibrium, a body emits as much energy as it absorbs. Hence a good absorber of radiation is also a good emitter of radiation (Halliday and Resnick, 1982).

Bodies, both natural and artificial, come in different shades of colours or are painted in different colurs based on aesthetic views, values, and needs. Primary colours, namely red, blue, and green are known to be complementary in that their combination yields the white colour (Ravi, George, and Hui, 1987). Different combinations of primary colours yield much different colours to meet the diverse tastes of people. These different colours reflect and absorb light by different amounts. They also absorb and, or emit radiant energy by different amounts. The black colour on its own, it is believed, does not reflect much light but absorbs almost all light incident on it; and that in the same vein, absorbs almost all radiant energy that fall on it.

In this work, the absorbance, and hence emittance of radiant energy by the different primary colours, their complementary product, and the black colour were investigated. This was achieved by using non-absorbent wood, plywood, sandpaper, transparent glass sheets, five medium sized cylindrical tins, little quantities of gloss paints in five different colours namely: Black, Blue, Red, Green, and White manufactured by De Meyer Paints Nigeria Limited; and synchronized thermometers. The non-absorbent wood was made into a rectangular box of about 65 cm × 20 cm × 10 cm to serve as the hosting box for the five medium sized cylindrical tins, which are the samples of the investigation. The plywood was used to divide the box into five equal compartments within which each of the tins were centrally placed to allow free air displacement around each of the tins. These enclosures were put in place to prevent or minimize radiation exchange between the five tins. The inside of the enclosures was not painted but left in its natural state. Holes were drilled at appropriate places in the enclosure to permit insertion of thermometers into each of the observation cubicles. The entire system was left opened to free air with each of the thermometers shielded from direct heating by sunlight.

2. Theory

The solar irradiance from the black body is governed by Planck's law of radiation given by:

$$E_{\lambda,b} = \frac{C_1}{\lambda^5[\{\exp(C_2/\lambda T)\}-1]} \quad \ldots\ldots\ldots \quad (1)$$

where, $E_{\lambda,b}$ represents the energy emitted per unit area per unit time per unit wavelength interval at a given wavelength; and, $C_1 = 3.3742 \times 10^9 \mathrm{W\mu m^4/m^2}$ (= $3.3405 \times 10^{-16} \mathrm{m^2W}$); $C_2 = 14387.9\ \mathrm{\mu mK}$ (= 0.0143879 mK) (Young et al., 2008).

Suppose a surface of area A at absolute temperature T radiates a fraction ε as much energy as would a blackbody surface, then ε is called the emissivity of the surface; the energy per second, called the power, radiated by the surface is given by the Stefan-Boltzmann law (Marion and Hornyak, 1984) as:

$$P = \frac{\Delta Q}{\Delta t} = \epsilon\sigma A T^4 \quad \ldots\ldots\ldots \quad (2)$$

where $\sigma = 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^4}$ is called the Stefan-Boltzmann constant.

For a black body, $\varepsilon = 1$ (Bueche, 1988).

For bodies with colours other than black, $0 < \varepsilon < 1$

Noted is that the emissivity of material surfaces vary as a function of temperature and surface finish (www.omega.com, 2013).

All objects whose temperature is above absolute zero radiate energy. According to Orear (1978), when an object at absolute temperature T is located within a region or environment whose temperature is T_0, the net energy radiated per second by the object is

$$P = \frac{\Delta Q}{\Delta t} = \epsilon\sigma A(T^4 - T_0^4) \qquad (3)$$

The orientation of the earth's orbit around the sun is such that the sun-earth distance varies only by 1.7%, and since the solar radiation outside the earth's atmosphere is nearly of fixed intensities, the radiant energy flux received per second by a surface of unit area held normal to the direction of the sun's ray at the mean earth-sun distance, outside the atmosphere, is practically constant throughout the year. This is termed as the solar constant l_{sc}; its value is now adopted to be 1367 $\mathrm{Wm^{-2}}$ (Tiwari, 2006). However, this extraterrestrial radiation suffers variation due to the fact that the earth revolves around the sun in an elliptical orbit with the sun at one focus. Duffie and Beckman (1991) gave the intensity of extraterrestrial radiation l_{ext} measured on a plane normal to the radiation on the nth day of the year as

$$l_{ext} = l_{sc}\,\{1.0 + 0.033\cos(\tfrac{360n}{365})\}. \quad (4)$$

Hence for say, November 12, 2011 in Nigeria, l_{ext} = 1396.9923 $\mathrm{Wm^{-2}}$; and for December 12, 2011 in Nigeria, l_{ext} = 1409.7196 $\mathrm{Wm^{-2}}$.

For major works in solar radiation, it may be necessary to calculate this and other parameters such as angle of incidence of beam radiation on a surface, and solar time, among others. However, for a study such as is being handled in this work, such corrections make no difference to the result obtained, and therefore, unnecessary. Equation 4 is thus sufficient for evaluation of the extraterrestrial radiation, and equation 2 is sufficient to evaluate the radiant energy flux. Furthermore, solar radiation while passing through the earth's atmosphere, are subjected to the mechanism of atmospheric absorption and scattering. The atmospheric absorption is due to ozone (O_3), oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), and water vapour (H_2O). The scattering is due to air molecules, dust, and water droplets (Tiwari, 2006). All these affect the actual insolation, ensuring that only a fraction of the expected/calculated solar radiation for a particular day actually reaches the earth surface.

For a body in radiative exchange equilibrium with its surroundings, the rate at which it emits radiant energy is equal to the rate at which it absorbs it. Then,

$$P_{\mathrm{absorbed}} = P_{\mathrm{emitted}} \quad (5) \quad \text{(Wikipedia)}$$

3. Materials and Methods

According to Duffie and Beckman (1974), most of the measurements of surface radiation parameters are based on a method devised by Gier et al. (1954) in which a sample is created as a *hohlraum* (blackbody) and exposed to blackbody radiation from a hot source. The effect of this blackbody is then observed in order to investigate surface radiation properties such as reflectance, absorbance, and emittance of the covered body.

According to Taylor (1990), by willingly bending a piece of metal, there is the tendency to greatly increase its radiant emissivity. This is because by forming such a bend we allow incident radiation to undergo multiple reflections within the body, hence increasing its rate of absorption. In this way, the metal greatly approaches hohlraum. Other ways of creating enhanced emissivity in various bodies include the use of semi-circular shaped metal, slotted metal cylinder, and metal cone. In this work, the method of enhancing emissivity of radiation was tried through the use of circular-shaped cylindrical metal. To achieve this, five identical cylindrical tins, each having a surface area of about 354.50 $\mathrm{cm^2}$ and volume 181.144 $\mathrm{cm^3}$, were used as the metal surfaces. The original coatings in each tin were removed by etching the coatings using sandpaper after which the outer surface of the tins were painted with black, blue, red, green, and white gloss paints respectively and left to dry in an open space for about 72 hours. They were thereafter arranged in the racks within the box enclosure, opened to free air, and then exposed to solar radiation. The experimental set-up of this work is as shown in fig. 1. The outer surface and inner surface (cavity) temperatures of each of the tins were observed hourly between 10.00 hour (10 a.m.) and 17.00 hour (5 p.m.) on five clear and favourable days (12th – 16th November 2011 at the first trial; and 12th - 16th December 2011) at the second trial; using carefully placed thermometers. The observations were carried out by placing the wooden box on an open terrace at about 1m above the ground. The cavity temperature measurements were considered to be a measure, thus a representative, of the absorbed solar radiant energy with the observed surface temperatures being representative of the emitted solar radiant energy by a sampled body.

4. Results and Discussion

Tables 1 and 2 show the average surface and cavity temperature values of the observed readings, while tables 3 and 4 show the computed average surface and cavity values of for the reported period of observation. From the values of tables 1 and 2, it is clear that maximum insolation occur between 1 p.m. and 3 p.m. Comparison of values show that between the hours of 10.00 and 17.00, the cavity temperature, and thus the absorbed energy, increases in the same order with the surface temperature for the five coloured tins with the black coloured tin having the highest observed temperature value for each hour of observation, and the white coloured tin having the least. This pattern of observation is a confirmation of the theory of heat exchanges that a good absorber of radiation is also a good emitter of radiation, and vice versa. Furthermore, these results are representative of most solar energy measurements as has been reported by Chigbundu (1986), Babatunde and Aro (2000), and, Udo and Aro (2000).

The observed cavity temperature/absorbed radiant energy values are comparable with the surface temperature/emitted radiant energy values for all the coloured bodies for the hours of 10.00 to 12.00. Between the hours of 13.00 to 17.00, there are large variations between the two values. This may be due to the enhancement effect of the cylindrical shaped tin that was used.

According to Bueche (1988), for a black body, $\varepsilon = 1$. However, this may not be true for different shades of black colours as the emissivity of shades of black was found to vary between 0.92 and 0.98 (www.omega.com, 2013); this is also true for different shades of other colours. Computation of results for the data collected showed that the value of the solar radiant energy obtained varied from 702.918 Wm^{-2} to 729.866 Wm^{-2} for the black-coloured surface; 515.303 Wm^{-2} to 521.836 Wm^{-2} for the blue-coloured surface; 412.719 Wm^{-2} to 429.680 Wm^{-2} for the red-coloured surface; 463.602 Wm^{-2} to 486.675 Wm^{-2} for the green-coloured surface; and 374.810 Wm^{-2} to 384.450 Wm^{-2} for the white-coloured surface. These results are comparable with standard values (www.webachieve.com, 2006) showing the validity of this experimentation. Results obtained also follow the pattern of the order of refractive indices for the colours of the visible spectrum, which is also closely tracked by the order of emissivity of these colours.

5. Conclusion

Measurement of the solar radiant energy absorbed and/or emitted by different coloured surfaces had been carried out in this work. Data obtained show an average highest cavity temperatures of 54.17^{0}C for Black, 47.33^{0}C for Blue, 46.67^{0}C for Red, 50.33^{0}C for Green, and 44.17^{0}C for White. It also showed that black coloured surface has the highest radiant solar energy absorbance/emittance while white coloured surface has the least. Similarly, the solar radiant energy absorbed and/or emitted by the coloured surfaces were found to be 729.866 Wm^{-2} for black-coloured surface; and 384.450 Wm^{-2} for the white-painted surface; with the corresponding values for other coloured surfaces falling in-between these two extreme values. Noted is that different makes of paints can give different results depending on the composition and quality of the paints but the trend of gradation is unlikely to follow a different pattern.

The results obtained validate/are in line with Kirchhoff's law of radiation. The trend of absorptivity/emissivity of solar radiant energy between blue-, red-, and green-painted surfaces suggest that a blue coloured surface has absorbance characteristics which are close to that of black-painted surface. This probably suggests why blue dye is sometimes used instead of black charcoal to improve the yield of solar stills. The result also suggests why unceiled houses covered with blue roofs are warmer than those covered with either red or green coloured roofs. It further suggests that while it may be absurd to cover buildings with black coloured roofing materials, it may also be most appropriate to use white coloured roofing materials in buildings. Canopies painted black come useful during cold seasons while those painted white are the choice during hot weather. The same reasoning goes for the painting of vehicles and the ceilings, house building materials, clothing materials, among several others; and why barns built with red earth materials make better storage facilities than those built with darker earth materials. Thus, the colour of earth materials has implications on its ability to retain or dispose heat within its interior.

Table 1: Typical results of the hourly surface temperature T_s measurements on the etched tins

Time (Hour)	Surface Temperature, T_s (^{0}C)					Ambient Temperature,T_0 (^{0}C)
	1	2	3	4	5	
10.00	26.0	26.0	26.0	26.5	26.0	30.5
11.00	29.0	29.5	29.0	29.0	29.5	31.5
12.00	31.0	30.5	31.0	30.5	31.0	32.5
13.00	35.0	35.0	35.5	35.0	35.0	35.5
14.00	37.5	37.0	37.0	37.0	37.5	37.0
15.00	33.5	33.0	33.5	33.0	33.5	33.0
16.00	29.5	29.5	29.5	29.0	29.5	30.0
17.00	27.5	27.0	27.5	27.5	27.0	29.5

Table 2: Typical results of the hourly cavity temperature T_c measurements on the etched tins

Time (Hour)	Surface Temperature, T_c (^{0}C)					Ambient Temperature,T_0 (^{0}C)
	1	2	3	4	5	
10.00	27.0	26.5	26.5	27.0	26.5	30.5
11.00	29.5	30.5	30.0	30.5	30.5	31.5
12.00	33.0	33.5	33.5	33.0	33.5	32.5
13.00	38.0	37.5	37.5	38.5	38.5	35.5
14.00	41.5	41.0	41.0	41.5	41.5	37.0
15.00	43.5	43.0	43.0	43.5	43.5	33.0
16.00	42.5	42.5	43.0	42.5	42.5	30.0
17.00	39.5	39.0	39.0	39.5	39.0	29.5

Table 3: Typical results of the hourly surface temperature T_s measurements on the coloured samples

Time (Hour)	Surface Temperature, T_s (^{0}C)					Ambient Temperature,T_0 (^{0}C)
	Black	Blue	Red	Green	White	
10.00	36.0	35.0	33.0	33.0	35.0	30.0
11.00	41.0	41.0	39.0	40.0	39.0	32.0
12.00	52.0	50.0	45.0	48.0	47.0	37.0
13.00	60.0	56.0	53.0	54.0	49.0	38.5
14.00	62.0	57.0	55.0	55.0	52.0	39.0
15.00	58.0	54.0	51.0	53.0	49.0	39.0
16.00	52.0	49.0	46.0	47.0	46.0	38.0
17.00	48.0	44.0	43.0	45.0	38.0	36.0

Table 4: Typical results of the hourly cavity temperature T_c measurements on the coloured samples

Time (Hour)	Cavity Temperature, T_c (^{0}C)					Ambient Temperature,T_0 (^{0}C)
	Black	Blue	Red	Green	White	
10.00	38.0	38.0	35.0	35.0	35.0	30.0
11.00	43.0	42.0	40.0	41.0	40.0	32.0
12.00	54.0	53.0	45.0	47.0	44.0	37.0
13.00	56.0	54.0	47.0	50.0	46.0	38.5
14.00	57.0	53.0	43.0	48.0	40.0	39.0
15.00	44.0	43.0	40.0	42.0	39.0	39.0
16.00	40.0	40.0	38.0	38.0	37.0	38.0
17.00	38.0	36.0	36.0	36.0	36.0	36.0

Table 5: Computed average surface temperature T_s measurements of the various coloured samples

Time (Hour)	Average Surface Temperature, T_s (^{0}C) of the coloured samples					Ambient Temperature, T_0 (^{0}C)
	Black	Blue	Red	Green	White	
10.00	36.5	36.5	34.0	35.0	34.5	31.0
11.00	41.0	41.0	38.0	39.5	39.5	37.0
12.00	49.5	48.0	43.5	45.5	43.0	39.0
13.00	50.0	48.0	44.5	45.0	42.5	40.0
14.00	47.5	44.5	40.5	41.5	38.0	38.5
15.00	45.0	40.5	39.0	40.0	36.0	36.0
16.00	39.5	38.0	34.0	36.0	33.0	35.0
17.00	31.0	29.5	28.0	28.5	25.5	33.0

Table 6: Computed average cavity temperature T_c measurements of the various coloured samples

Time (Hour)	Average Cavity Temperature, T_c (^{0}C) of the coloured samples					Ambient Temperature, T_0 (^{0}C)
	Black	Blue	Red	Green	White	
10.00	36.5	34.0	32.0	32.5	32.5	31.5
11.00	40.0	38.5	37.0	37.5	37.0	34.0
12.00	46.0	45.0	42.0	43.5	41.0	39.0
13.00	54.0	50.5	47.0	47.5	44.0	40.5
14.00	51.5	49.0	44.5	46.0	40.5	38.5
15.00	49.0	46.0	42.0	45.0	40.5	36.0
16.00	45.0	42.5	40.0	41.5	38.0	35.0
17.00	42.0	40.0	36.0	37.5	35.0	33.0

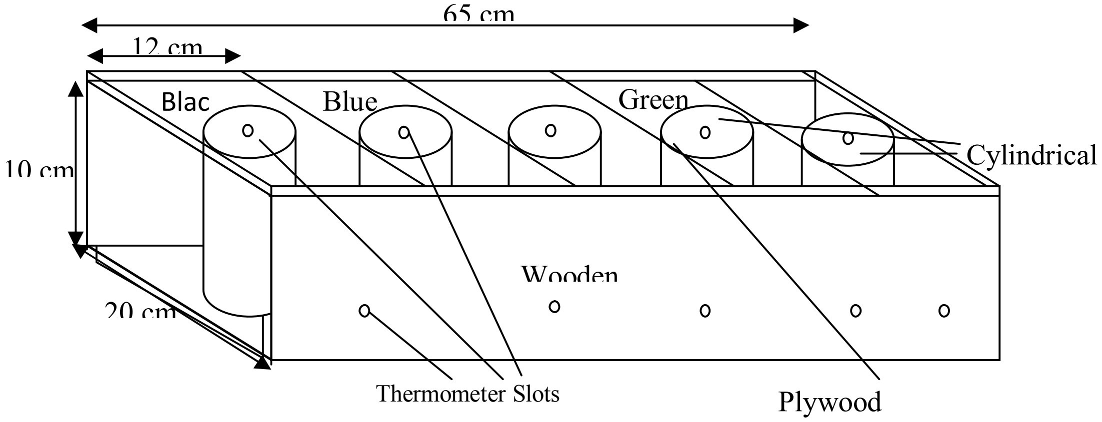

Figure 1: Experimental Set up

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