Exploring the properties of Solar Energy

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This article describes practical activities that reveal the spectral composition of solar radiation and the thermal properties of surfaces and coatings developed for solar heating and 'sky cooling' applications. Such activities help to clarify the radiative energy flows in the environment and how they can be exploited to reduce fossil fuel consumption for heating and air conditioning.

While researching previous articles on Renewable Energy education (D&T Practice 06.2010 and 01.2011), I found that there are far fewer resources available for teaching solar (thermal) energy than for other renewable energy topics. This article is an attempt to explain key concepts, and identify resources and practical activities, for use in solar energy education.

Solar, longwave and terrestrial radiation

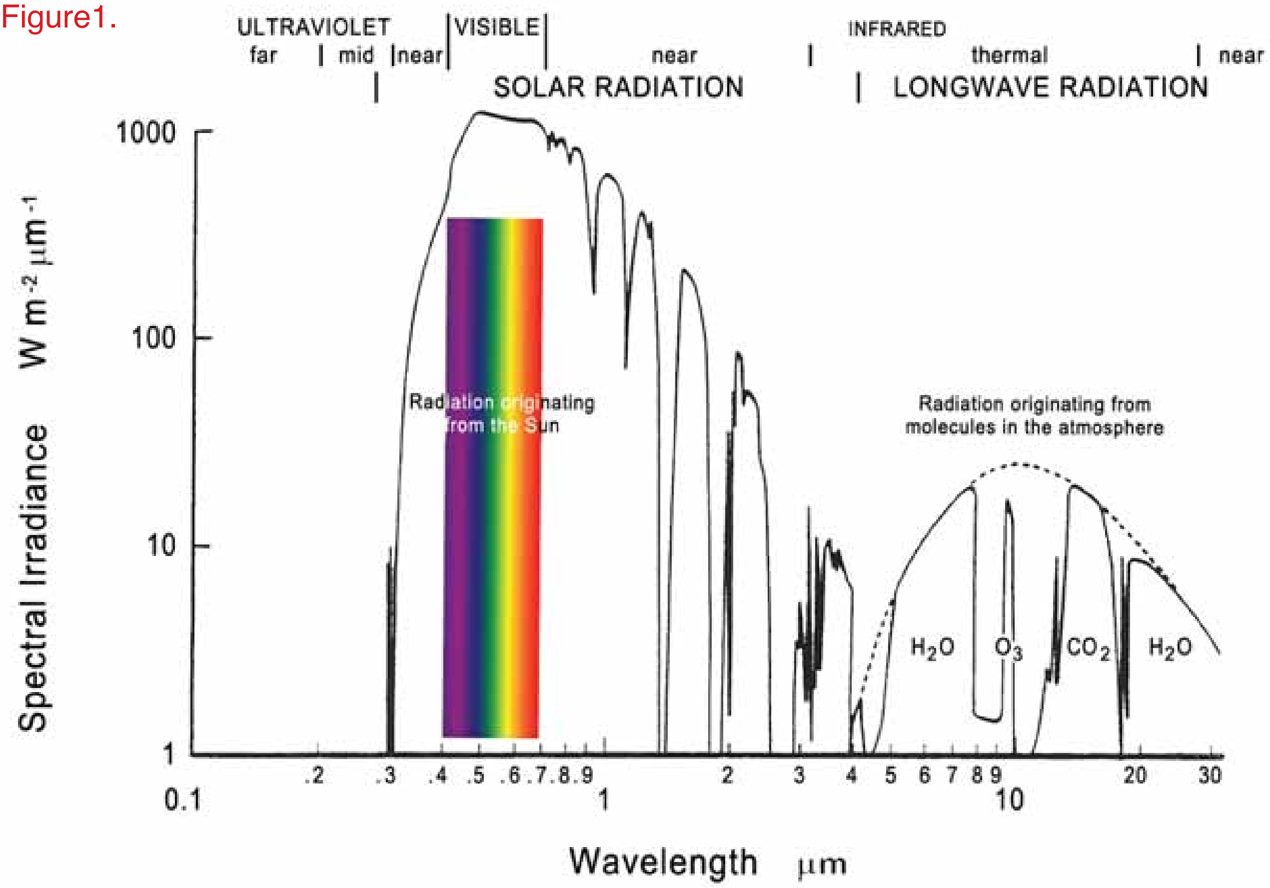
In the daytime, a surface in any outdoor location is irradiated by ultraviolet, visible and infrared radiation of wavelengths in the range 0.28 – 50 µm. (µm is the abbreviation for the micron, which is one-millionth of a metre, or one-thousandth of a millimetre. Visible light spans the wavelength range ~0.4 – 0.7 µm). Figure 1 shows a typical spectral distribution of the radiation incident on a horizontal surface beneath a clear sky. The radiation arriving at the top of Earth's atmosphere, directly from the Sun, is of wavelengths greater than about 0.18 µm, having a spectral distribution approximating that of an ideal 'blackbody' radiator at the Sun's surface temperature (~ 6000°C) and extending into the far-infrared (wavelengths greater than 25 µm). During transmission through the atmosphere, most of the radiation of wavelengths less than 0.28 µm or greater than 4 µm, and within narrow intermediate wavebands, is absorbed by water (H_2O), carbon dioxide (CO_2) and ozone (O_3) molecules, so the solar radiation reaching Earth's surface has a characteristically interrupted spectral distribution.

The thermal infrared radiation of wavelengths greater than about 4 µm emitted by all solids, liquids and most gaseous molecules (nitrogen and oxygen being important exceptions) at terrestrial ambient temperatures is commonly termed 'longwave' radiation. Little of the solar radiation of wavelengths greater than 4 µm incident at the top of the atmosphere reaches Earth's surface. Nearly all the longwave radiation incident on the surface of a building therefore originates from atmospheric constituents and terrestrial objects in its field of view. In contrast, all the incident 'shortwave' radiation originates from the Sun and hence is usually termed 'solar' radiation.

H_2O, CO_2, O_3, trace and pollutant molecules, pollen and dust in the atmosphere emit thermal infrared radiation, termed 'terrestrial' (or 'atmospheric') radiation, of wavelengths greater than about 4 µm. The intensity and spectral distribution of this radiation are particularly dependent on the cloud cover, and on the humidity and temperature of the lowest few hundred metres of the atmosphere. Typical spectral distributions of terrestrial radiation incident on a horizontal surface beneath clear and overcast skies are shown respectively as the unbroken and broken curves in the right-hand section of the graph. The spectral distribution of terrestrial radiation beneath low cloud cover approximates that of a perfect 'blackbody' radiator at the cloud base temperature.

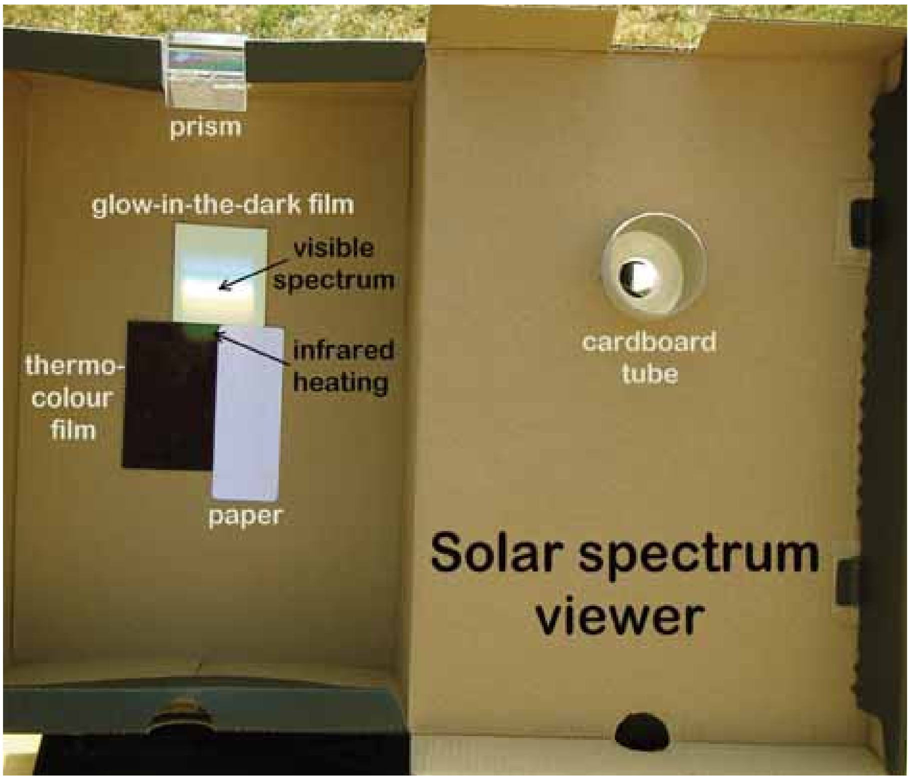
The relatively small amount of 8 – 13 µm wavelength radiation incident from a clear sky is a consequence of the sky being fairly transparent at those wavelengths. This 'atmospheric window' or 'sky window' is responsible for ground cooling and dew/frosts on clear nights and can be exploited for 'sky cooling' applications.

Figure1.



Solar spectrum

The spectral composition of sunlight was first demonstrated by Sir Isaac Newton in 1665, using a glass prism to disperse the light. The presence of invisible 'infrared' radiation beyond the red end of the spectrum was discovered by Sir William Herschel in 1800, whilst using thermometers to investigate the heating effect of different colours of sunlight. The following year, Johann Ritter used the rate of darkening of silver chloride in different parts of the solar spectrum to demonstrate the presence of invisible 'ultraviolet' radiation beyond the violet end of the spectrum.



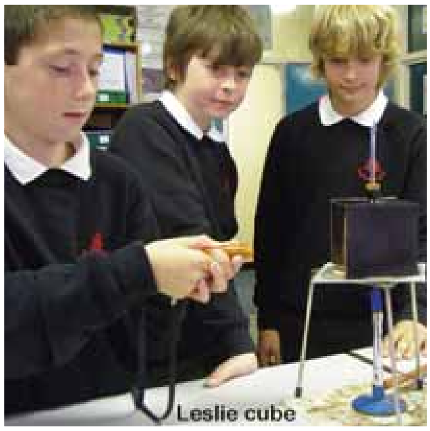
These discoveries can be replicated using an equilateral glass prism mounted securely in one end of a cardboard box, as shown in the image above. The box should be oriented with the prism toward the Sun on a clear day, so that a spectrum is cast on the floor of the box. The heating effect of the red end of the spectrum and beyond can be demonstrated using a small piece of liquid crystal thermocolour film, as shown. (The film changes colour simultaneously in both the red and near-infrared regions of the spectrum, so its coloration in the near-infrared region is not due to conduction of heat, via the film, from the red region.) The heating effect seems to be greatest at the red end of the spectrum, but this is due to compression of that end of the spectrum resulting from non-linear variation of the refractive index of glass with wavelength. Although roughly half of solar radiation is in the near-infrared range, its spectral intensity actually peaks near the middle of the visible range.

The presence of invisible radiation beyond the violet end of the spectrum can be demonstrated using a small piece of glow-in-the-dark film. The phosphorescent glow of the film beyond the violet end of the spectrum is best viewed through a tube mounted in the lid of the box. The glow persists for a few seconds after the sunlight is cut off. Using a hand to momentarily block sunlight from entering the box through the prism reveals the full extent of the greenish glow. (Note that the violet end of the spectrum is stretched owing to the aforementioned non-linear variation of the prism's refractive index with wavelength.) Although only a few percent of solar radiation is in the ultraviolet range, solar UV has many important effects, including tanning and burning of skin, skin cancers, bleaching of dyes and embrittlement of plastics.

Spectrally selective surfaces

The fact that the spectral range (~0.28 – 4µm) of sunlight reaching Earth's surface is separate from that of longwave radiation enables the optical properties of surfaces to be quite different for solar and longwave radiation. For example, white paint is a very good reflector of sunlight but a very poor reflector of longwave radiation. (Most organic substances, including the binders used in paints, strongly absorb and emit thermal infrared radiation.) Surfaces that have very different optical properties for solar and longwave radiation are called 'spectrally selective'. Polished metal surfaces tend to be good reflectors (and hence poor absorbers) of both solar and longwave radiation, which also makes them poor emitters of longwave radiation (Kirchhoff's law of thermal radiation).

The effectiveness of different surfaces at emitting longwave radiation can be easily demonstrated using a Leslie cube and an inexpensive handheld infrared thermometer. A Leslie cube comprises a copper cube, which is filled with water and heated from below by a Bunsen burner. One of the surfaces of the cube is bare polished copper. another is coated with matt black paint. another is either roughened copper, or coated with gloss black paint. The fourth surface is usually coated with white paint. I've modified an inexpensive Leslie cube so that its third surface is covered with a spectrally selective black MAXORB™ film developed for use in solar collectors, and its fourth surface is a white SkyCool™ roof coating developed for passive cooling of buildings in hot, dry climates.



The Leslie cube should be almost filled with water and heated until the water is gently boiling. An infrared thermometer can then be used to measure the effective radiative temperatures of the four vertical surfaces. The thermometer must be held close enough to each surface (about 10 cm) to ensure that its field of view is filled by that surface. Typical measurements (at an ambient room temperature of 22°C) are ~30°C for the polished copper surface, ~98°C for the matt black painted surface, ~36°C for the MAXORB surface and ~91°C for the SkyCool surface. (The actual temperatures of all four surfaces are, of course, very close to 100°C.)

The infrared thermometer has been calibrated for 'high emissivity' surfaces, i.e. surfaces which approximate an ideal 'blackbody' radiator. Most natural surfaces do have high emissivities, but polished metal surfaces do not. Mirror-like surfaces are good reflectors (and therefore poor emitters) of thermal infrared radiation, so an infrared thermometer pointed toward such a surface reads a temperature closer to that of the object (e.g. wall) whose reflection is being viewed in that mirror-like surface, than to that of the surface itself. This explains the near-ambient effective radiative temperature of the polished copper surface.

The MAXORB film comprises an ultra-thin nickel foil with an electrodeposited 'black nickel' surface. The latter strongly absorbs solar radiation but is quite transparent to thermal infrared radiation, so the longwave optical properties of the film are largely those of the mirror-like nickel foil substrate. Such 'spectrally selective' absorber surfaces combine good absorption of solar radiation with low emission of longwave radiation, making them very efficient at converting solar energy to heat and retaining that heat. (They do, however, lose heat via conduction and convection.)

SkyCool is a thermal coating which strongly absorbs and emits thermal infrared radiation at the 'sky window' wavelengths (8 – 13 μm) but is highly reflective at other wavelengths. It was developed in Australia for application to the exterior of metal roofed buildings, to help keep them cool in summer by 'pumping' thermal infrared radiation through the sky window into deep space. Its high reflectance at wavelengths either side of the sky window accounts for its somewhat lower effective radiative temperature than that of ordinary paint.

Temperatures and heat losses

The 'coldness' of a clear sky can be demonstrated by pointing an infrared thermometer vertically upwards. Clear sky 'zenith' measurements in the UK are typically about 30°C lower than the ambient air temperature, day or night (e.g. -14°C when the ambient temperature is 18°C). Slowly scanning the infrared thermometer from the zenith down to the horizon (in a direction other than that of the Sun) reveals that the effective sky temperature is lowest at the zenith, where the optical pathlength through the atmosphere is shortest, and gradually increases at decreasing elevations, as the optical pathlength through the atmosphere becomes progressively longer. Near the horizon, where the optical pathlength is greatest, the sky window is almost 'closed', even for a dry clear sky. That is why vertical surfaces take much longer to cool on clear nights than upward facing surfaces.

It is worth spending some time pointing an infrared thermometer at clouds, the ground and various types of building façade, in order to gain some sense of the amounts of longwave radiation emitted by each. Comparing the readings for roofs, walls, doors, and single- and double-glazed windows on a cold winter day readily reveals the building elements that are losing the most heat (the higher the reading, the greater the heat loss).

It is important to appreciate that the heat losses from a building, or solar collector, are largely determined by the temperature difference between its external surfaces and their surroundings. The better insulated (or 'thermally decoupled') its external surfaces are from its warm interior, the smaller will be that temperature difference, and the lower the loss of heat to the environment.

Solar collectors

My next article in this series will focus on resources and practical activities to illustrate the construction and operation of flat plate and evacuated tube solar collectors.

Acknowledgements

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Further reading

Smith, G.B. and Granqvist, C.G. Green nanotechnology: solutions for sustainability and energy in the built environment. CRC Press. 2011 (ISBN 978-1-4200-8532-7)

Hot links

Glow-in-the-dark film: www.mindsetsonline.co.uk/product_info.php?products_id=528
Infrared thermometer: www.inds.co.uk/physics/infra_red_thermometer.htm
Leslie cube: http://betterequipped.co.uk/Leslie-Cube-prd0903
SkyCool: www.skycool.com.au
Solar absorber samples: www.solexenergy.co.uk
Solar-Active: http://new.solar-active.com/
Solar Spark: www.thesolarspark.co.uk
Solar Spark STEM: www.nationalstemcentre.org.uk/elibrary/collection/788/the-solar-spark
Thermocolour sheet: www.inds.co.uk/physics/liquid_crystal.htm
US Energy Education lesson plans: www1.eere.energy.gov/education/lessonplans/
US Energy Kids – Solar: www.eia.gov/kids/energy.cfm?page=solar_home-basics
US Solar in the Schools: www.solarenergy.org/solar-schools