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A robust convection cover material for selective radiative cooling applications

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ABSTRACT

The enhanced cooling of exposed surfaces by radiative heat loss to the cold sky was investigated using a variety of commonly available materials. Zinc sulphide was identified as a durable substance suitable for the construction of convection covers for radiative cooling radiators. With respect to polyethylene, the most commonly used convection cover to date, the new material is mechanically stronger, impervious to damage by solar ultraviolet and in practical thicknesses is more transparent in the 8–14 μm waveband. Use of this window material with a previously proposed selective radiator material, a form of anodised aluminium that reflects radiation at wavelengths shorter than 8 μm allows for the economical production of an effective selective radiator system. Measurements were made on simple radiator plates and convection covers.

1. Introduction

1.1. Properties of the atmosphere

The formation of frost by emission of infrared radiation from the ground to the cold night sky during a clear night is a common example of the loss of heat to the sky by radiative cooling. While ground temperatures in the early evening may be above the freezing point, the effective temperature of the high atmosphere may be as cold as $-40\,^{\circ}$C. Objects at a higher temperature (such as the ground) lose heat to the cold sky by radiative exchange. Although the ground is covered by air at a similar temperature, the complex nature of the atmosphere means that the sky does not behave as a simple black body and has a number of low absorption windows that are transparent to infrared radiation. The most important window for radiative cooling lies between the wavelengths of 8 and 14 μm. It is through this window that most of the energy transfer associated with radiative cooling occurs (Fig. 1). While radiative cooling is most effective during the night, heat can also be lost to the sky during the day providing the radiator surface is shaded from the sun.

The effectiveness of radiative cooling can be enhanced by technical improvements. Two in particular are important.

The first is the use of selective surfaces that are designed to radiate energy in the 8–14 μm band of the infrared and reflect radiation outside those wavelengths. Selective surfaces that are matched to this atmospheric window are, in this application, more effective radiators than a black body if a depression of the radiator's temperature below ambient is required.

The second is the use of infrared transparent convection covers that insulate the radiator surface from the surrounding atmosphere. With an infrared transparent convection cover, it is possible for the radiator surface to cool to temperatures below ambient.

The rate of radiative heat loss to the sky (and hence cooling of the radiator plate) is equal to the difference between the power emitted by the radiator and the power absorbed by the radiator from the sky. For example, Berdahl et al. [2] report that in a typical cooling experiment, the thermal sky irradiance may be 350 W/m^2 while the radiator emits 420 W/m^2, a difference of 70 W/m^2 being the available cooling power. Any parasitic thermal conduction from the ambient to the radiator would reduce the available cooling power.

1.2. Radiative heat loss to the clear sky

The possibility of cooling by heat loss to the cold sky employing selective radiators has been understood since the work of Ångström [3]. Little further work was published until that of Head [4]. Since that time selective radiation cooling has been investigated sporadically ([2,5–11] and others) and although some

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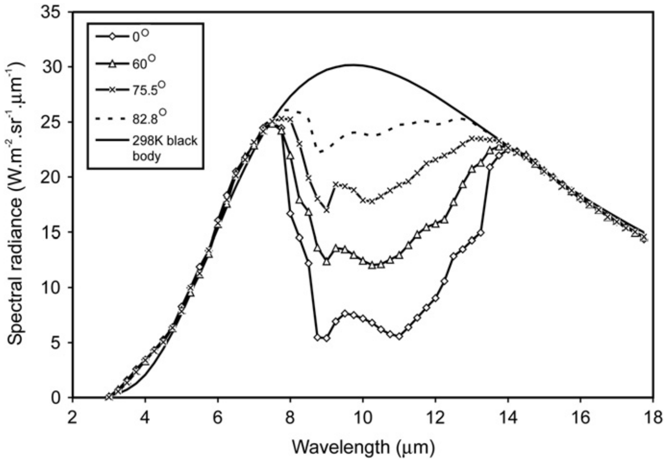

Fig. 1. Spectral radiance of the atmosphere measured at Coco Beach, Florida, by Bell et al. [1] showing the radiance of the 8–14 mm window at various angles from the zenith compared to the radiance of a black body at 298 K (solid black curve).

effective small scale systems have been constructed, to date no large scale use has been made of the technology.

Bell et al. [1] carried out a study of the radiative properties of the atmosphere and defined the resource for radiative cooling. They measured the spectral emittance of the atmosphere between 1 and 20 µm from the zenith to the horizon and documented the energy flux that reaches the ground from the atmosphere. A black body maintained at a temperature of 310 ± 1 K was used as a radiometric reference standard for the measurements. Measurements were made at Cocoa Beach in Florida and at two sites in Colorado—Denver (1800 m) and Pikes Peak (4260 m). Similar recordings were made at each of these sites and it was found that the emission from the zenith declined as altitude increased.

The measurements shown in Fig. 1 illustrate the departure of the atmospheric emission spectrum from that of an ideal black body. Between 8 and 14 µm, the radiant flux intensity is significantly less than for a black body at the equivalent temperature, in this case 298 K. Under a clear sky, there will be a net loss of energy by a radiator at ground level to the colder upper atmosphere. This "net radiative cooling power" is dependent on

- the temperature of the radiator;
- the emissivity of the radiator;
- the inclination of the radiator surface from the zenith;
- the radiant flux emitted by the atmosphere and
- the humidity (water vapour absorbs radiation in the 8–14 µm band).

Taking these factors into consideration, the net radiative cooling power of a radiator ($P_{\rm net}$) is the difference between the power radiated by the radiator at its operating temperature minus the power absorbed by the radiator from the sky:

$$P_{\rm net} = P_{\rm rad} - P_{\rm abs} \tag{1}$$

The radiated power ($P_{\rm rad}$) is calculated by integrating the emission spectrum of a black body at the temperature T of the radiator weighted by the hemispherical spectral emittance (=hemispherical spectral absorptance) of the radiator surface $a(\lambda)$.

The absorbed power ($P_{\rm abs}$) is calculated by integrating the emission spectrum of the sky weighted by the hemispherical spectral absorptance of the radiator surface versus wavelength:

$$P_{\rm net} = A\int_0^\infty u(\lambda,T_{\rm r})a(\lambda)\,{\rm d}\lambda - A\int_0^\infty u(\lambda,T_{\rm s})a(\lambda)S(\lambda)\,{\rm d}\lambda \tag{2}$$

where $T_{\rm r}$ and $T_{\rm s}$ are, respectively, the absolute temperatures of the radiator surface and the sky, $u(\lambda,T)$ is Planck's black body radiance integrated over a hemisphere, $S(\lambda)$ is the sky hemispherical spectral emittance, $a(\lambda)$ is the radiator hemispherical spectral emittance (absorptance) and A is the absorber area. This calculation assumes the radiator couples to the sky over a full hemisphere and is large enough in area to ignore edge or aperture effects.

Parasitic heat gain by the radiator from its surroundings reduces the attainable effective cooling power $P_{\rm c}$ and the experiments reported below show that for the simple design of radiator reported herein, it was the dominant factor in the effectiveness of the radiative cooling system and has to be minimised by insulation.

1.3. Radiator surfaces

Consider the radiator under steady-state conditions (i.e. negligible rate of temperature change). The steady-state temperature difference $\Delta T_{\rm ss}$ between the radiator surface and the surrounding atmosphere is determined by the difference between the net radiative cooling power to the sky, $P_{\rm net}$, and the parasitic heat flow $\sigma\Delta T_{\rm ss}$ between the radiator and the surrounding environment. σ is the linear heat transfer coefficient in W/m^2/K and signifies the non-radiative heat inflow to the radiator surface. Both convection and true conduction are here rolled together into the coefficient σ.

At steady-state, the effective cooling power $P_{\rm c}$ of the radiator is given by

$$P_{\rm c} = P_{\rm net} - \sigma\Delta T_{\rm ss} \tag{3}$$

$\Delta T_{\rm ss}$ can be increased by

- reducing the non-radiative heat flow coefficient σ by increasing the insulation around the radiator and placing an infrared transparent convection cover over the radiator;
- increasing the radiative heat loss $P_{\rm rad}$ by modifying the surface emissivity and
- reducing the cooling load $P_{\rm c}$.

1.4. Convection covers

Although a number of materials exist that are suitable for use as radiator surfaces, materials that are suitable for use as convection covers are much harder to identify and to date, polyethylene film has been the only material employed as proof-of-concept, despite its vulnerability to rapid degradation by solar ultraviolet.

A number of investigators have attempted to improve the durability of polyethylene by either incorporating ultraviolet resistant pigments into the film or by impregnating the surface with similar materials; however none have reported that these measures have greatly improved the long term durability. In particular, measurements of polyethylene durability made by Hamza et al. [12] in Egypt (an arid region where radiative cooling could have utility) demonstrated conclusively that polyethylene film failed completely over period of a few months. The failure to identify a suitable cover material has been a major stumbling block for the development of this technology.

1.5. Potential infrared transparent cover materials

A number of materials are transparent or partially transparent in the 8–14-µm infrared window. However, their suitability for use as a convection cover varies widely (Table 1).

Zinc sulphide is transparent to infrared in the 8–14 µm waveband. The transmittance measurements reported here were performed on a Shimadzu IR-470 spectrophotometer using a slab of material without any attempt to suppress the surface reflectance. Reflectance is high for the high refractive index material ZnS and