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EXPERIMENTAL TEST FACILITY FOR SELECTIVE RADIATIVE COOLING SURFACES

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ABSTRACT

The newly constructed radiator test facility at Lawrence Berkeley Laboratory is described and preliminary results are presented for cooling rates from two radiating surfaces.

1. INTRODUCTION

Spectrally selective radiating surfaces are used extensively for heating purposes in solar collectors. For such applications a surface should have high absorptivity in the visible region of the solar spectrum and low emissivity in the thermal infrared region. Incident solar energy is thereby absorbed efficiently while reradiation losses from the hot collector surface are suppressed. Such a selective surface appears "black" in the visible spectrum and "white" in the infrared.

During the past few years efforts have been made to develop surfaces having spectrally selective properties tailored to enhance the radiative cooling effect [1,2]. The problem here is essentially the inverse of the solar collector case. Visible radiation and portions of the infrared spectrum in which radiation from the sky is intense should be rejected and only within the portions of the spectrum where atmospheric emission is low should the radiator have high emissivity. A typical clear sky radiance plot is shown in Fig. 1 revealing the low-emissivity region of the sky between about 8 and 13 microns known as the atmospheric "window". An ideal selective emitter would have a high emissivity only within this limited spectral region, and would be reflective in all other parts of the spectrum. In particular, it would appear white or reflective with respect to visible solar radiation.

Limited experimental results have been presented for the performance of selective emitters, and few surfaces have been tested (essentially only white paint and Tedlar coated aluminum). Interest in the cooling properties of a variety of selective and non-selective emitter assemblies has motivated the design and construction of the radiator panel test facility which is the subject of this paper.

Fig.1: Typical spectral infrared sky radiance (solid curves) for clear sky conditions showing the atmospheric "window" between 8 and 13 microns.

If a radiator were to be thermally isolated from the environment by suppressing conduction and convection processes it would come into radiative equilibrium with the portion of the sky to which it is exposed. Summer-time zenith sky "temperatures" are typically below freezing under cloudless conditions.

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Unfortunately, the concept of sky temperature is misleading since the apparent temperature varies widely depending on the wavelength interval over which it is observed. Within the 8-13 micron window region, for instance, we have observed a zenith temperature of -24°C in Tucson (the ambient air was +35°C), while a "temperature" of -4°C was obtained at the same time by observing the entire thermal radiation spectrum [3]. This difference can be highly significant if the performance of selective radiators is being considered.

The radiator panel test facility allows the side-by-side comparison of up to 8 radiator assemblies. The temperature of each radiator surface is monitored and controlled automatically while the electric power required to maintain the set temperature is recorded. Preliminary results are presented in which two radiator surfaces are allowed to cool from above the ambient temperature with no heater power applied.

2. THEORETICAL BACKGROUND

The total radiant emittance $W$ of a surface is given by

$$W = \int N \cos \theta \sin \theta \cos \phi \, d\Omega$$

(1)

where $\theta$ is the polar angle, $\phi$ is the azimuth angle, $N$ is the radiant power per unit solid angle, and $\Omega$ is the solid angle.

For a Lambertian surface where $N(\theta, \phi) = \text{const}$, the radiant emittance is thus

$$W = \pi N$$

(2)

The general equation for the radiant hemispherical emittance $W_1$ of a surface at temperature $T$ for the entire spectrum is

$$W_1(T) = \int_0^{\pi/2} \int_0^{2\pi} \epsilon_\lambda(\theta, \phi) \frac{\partial b_\lambda(T)}{\partial \phi} \sin \theta \cos \theta \sin \theta \cos \phi \, d\phi \, d\theta$$

(3)

where $\epsilon_\lambda$ is the monochromatic emissivity of the surface and $b_\lambda(T)$ is the blackbody radiance per unit solid angle in the wavelength interval between $\lambda$ and $\lambda + d\lambda$.

The radiant heat absorbed by the surface is

$$W_2(T) = \int_0^{\pi/2} \int_0^{2\pi} \alpha_\lambda(\theta, \phi) \frac{\partial b_\lambda(T)}{\partial \phi} \sin \theta \cos \theta \sin \theta \cos \phi \, d\phi \, d\theta$$

(4)

where $\alpha_\lambda$ is the monochromatic absorptivity of the surface and $b_\lambda(\theta, \phi)$ is the radiant power incident on the surface between $\lambda$ and $\lambda + d\lambda$.

For a large surface covered with a partially transparent windscreen the total emittance $E_1$ is

$$E_1 = \pi \int_0^{\pi/2} \int_0^{2\pi} \epsilon_\lambda(\theta, \phi) \frac{\partial b_\lambda(T)}{\partial \phi} \sin \theta \cos \theta \sin \theta \cos \phi \, d\phi \, d\theta$$

(5)

where $\rho$ and $\rho_w$ are the reflectances of the surface and the windscreen respectively. It has been assumed that only specular reflectance is important and that the material properties are independent of $\phi$.

The radiant energy emitted by the atmosphere which passes through the windscreen and is absorbed by the radiator is

$$E_2 = \pi \int_0^{\pi/2} \int_0^{2\pi} \epsilon_\lambda(\theta) \frac{\partial W_{\text{atm}}(\theta, \lambda)}{\partial \phi} \sin \theta \cos \theta \sin \theta \cos \phi \, d\phi \, d\theta$$

(6)

where $\tau$ is the windscreen transmittance and $W_{\text{atm}}$ is the atmospheric spectral radiance.

The radiant energy emitted by the windscreen and absorbed by the radiator is

$$E_w = \pi \int_0^{\pi/2} \int_0^{2\pi} \epsilon_\lambda(\theta) \frac{\partial b_\lambda(T_w)}{\partial \phi} \sin \theta \cos \theta \sin \theta \cos \phi \, d\phi \, d\theta$$

(7)

where $T_w$ is the windscreen temperature, and $\epsilon_w$ is the spectral emissivity of the windscreen.

The net radiant energy lost by the surface is:

$$E_{\text{net}} = E_1 - (E_2 + E_w + E_0)$$

where $E_0$ is the solar energy absorbed by the surface.

The intensity of radiation coming from the sun and within the atmospheric window is in the range of 1 W/m² and may be neglected for an ideal selective infrared radiator.
surface. Outside the atmospheric window, and especially in the visible spectrum, it should be noted that for real surfaces where $\varepsilon_\lambda \neq 0$ a serious error may be committed if the solar energy is not included in the calculation.

The effect of a selective surface on the radiant energy exchanged and the equilibrium temperature of the surface has been discussed by Catalanotti et al [1] and Ph. Grenier [4]. Fig. 2 shows the emissive power of a thermally insulated blackbody within the wavelength range between 8 and 13 microns [4] in order to establish an upper limit for net radiative transfer from a selective surface having unit emissivity within this region and zero emissivity outside. The lower curve shows that the radiation emitted in this region comprises between one quarter and one third of the total power that can theoretically be emitted by a blackbody. This limit is achieved under the idealized assumption of zero sky emissivity in the atmospheric window. The abovementioned references demonstrate that the selective surface can lose heat at a faster rate than a blackbody and in the absence of a cooling load the final temperature of the selective surface is lower than that of a blackbody.

For an actual selective cooling surface the minimum temperature attainable depends mainly on the degree of selectivity, which may be defined as the ratio of the radiant power emitted between 8 and 13 microns and the total power emitted by the surface over all wavelengths.

3. DESCRIPTION OF THE EXPERIMENTAL APPARATUS

Eight radiator assemblies have been mounted on a rooftop rack at Lawrence Berkeley Laboratory. Each of the assemblies consists of an insulated Kydex (Acrylic and PVC) box having outside dimensions 108 x 66 x 12.7 cm as shown in the cross sectional view of Fig. 3. The insulation, which fills the 10 cm thick interior of the box, consists of injected styrofoam.

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Fig. 3: Radiator assembly showing insulating box, radiator, and windscreen.

A recess in the upper surface of the box holds a 0.8 mm thick aluminum radiator plate of dimensions 50 x 90 cm. Convection losses above the radiator are suppressed by means of a 0.050 mm thick polyethylene windscreen located approximately 3 cm above the plate. A resistive heating element is adhered to the bottom side of the radiator plate and the upper side is painted or specially treated to form the radiating surface. The heater capacity is 140 W which allows a maximum outgoing thermal flux of approximately 311 W/m² to be radiated at a constant surface temperature.

The surface temperature of each radiator plate is measured by three AD$590$ two-terminal integrated circuit transducers which produce an output current proportional to the absolute temperature. The heater input power is regulated by a proportional controller and measured with a watt transducer which supplies a linear voltage output to the recorder.
 Ambient air temperature is measured by a dual thermistor probe and the dew point is detected with a lithium chloride dew cell. Both of these sensors are protected from solar and terrestrial radiation by a motor aspirated shield. The intensity of incident infrared sky radiation is detected with a pyrgeometer.

Data reported in this paper was taken with a 12 point chart recorder. An automated microprocessor controlled system is being developed which will be capable of operating the radiators in three modes: (a) no power supplied to the heater elements (stagnation mode), (b) controlled to achieve constant radiator temperatures, (c) controlled so that the radiator temperature tracks ambient plus or minus a specified offset.

4. EXPERIMENTAL RESULTS

Two radiator assemblies were mounted horizontally and covered with polyethylene windscreens. One radiator surface was painted white and the other consisted of an aluminum layer evaporated onto a 0.1 mm Tedlar sheet adhered to the aluminum radiator plate and electric heater element. Transmissivities for the Tedlar and polyethylene are reproduced in Fig. 4. The polyethylene is approximately 80% transmissive in the 8-13 micron region of the spectrum, while the Tedlar is highly emissive over the same wavelengths.

In agreement with [1] the blackbody radiator (painted white) initially radiates heat more rapidly than the Tedlar/aluminum surface, as indicated by the fact that its temperature drops more rapidly to the point where the surface was approximately 5°C below ambient. As the temperature continues to decrease the increased radiative power of the selective surface becomes evident.

Fig. 5 was plotted as a semi-log graph in order to exhibit the anticipated exponential approach to equilibrium, which would be manifested as a straight line. Since the absolute temperature range in the experiment is only 11°C compared to the initial temperature of 287K (a 4% change), it is reasonable to expect that a well-behaved physical process would lead to such an exponential behavior. The fact that this situation is not observed is obvious from the figure.
Quantitative details of this behavior have not yet been elucidated, but the effect appears to be connected with condensate formation on the upper surface of the polyethylene windscreen. As this surface cools to the dewpoint droplets of water condense from the saturated air and the surface should remain at the dewpoint temperature as the size of the droplets grows. Despite the fact that the polyethylene material has a low emissivity, the condensed droplets will radiate like blackbody emitters at the dewpoint temperature. As the cooling process continues an increasing fraction of the windscreen area becomes covered by the droplets and the effective emissivity $\varepsilon_{\lambda}^{(0)}$ in Eq. (7) increases significantly. The net cooling rate thus decreases for the radiator plate as equilibrium is approached.

The experimental results reported here are the first in a series of investigations aimed at understanding the heat transfer processes between various radiating surfaces, with and without windscreens or other convection suppressing devices. Tests will be made under a variety of sky conditions, temperatures, and relative humidities for each configuration studied.

5. ACKNOWLEDGEMENT

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6. REFERENCES


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