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EFFECT OF SURFACE CHARACTERISTICS AND ATMOSPHERIC CONDITIONS ON RADIATIVE HEAT LOSS TO A CLEAR SKY

B. LANDRO and P. G. MCCORMICK
Department of Mechanical Engineering, University of Western Australia, Nedlands, W.A. 6009, Australia

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Abstract – The factors influencing the net heat loss of surfaces exposed to atmospheric thermal radiation have been investigated. Measurements of net heat loss as a function of surface temperature, ambient temperature, and humidity, have been carried out on both gray and spectrally selective surfaces. Gray surfaces of high emissivity are found to exhibit the highest net cooling power at temperatures near ambient. Spectrally selective surfaces with spectral emissivities matched to the 8–13 μm atmospheric window exhibit the highest cooling powers at temperatures well below ambient. Conduction heat transfer between the radiating surface and surroundings is shown to significantly limit the net cooling power. The experimental results are in good agreement with an analysis of sky–radiator–ambient heat exchange.

NOMENCLATURE

ε_c,	hemispherical cover emissivity;
$\varepsilon_r(\lambda)$,	hemispherical spectral emissivity of radiating surface;
$\varepsilon_s(\theta,\lambda)$,	directional spectral sky emissivity;
$i_b(\lambda, T)$,	blackbody spectral intensity;
$i_s(\lambda, T)$,	atmospheric spectral intensity;
h_c	conduction heat-transfer coefficient;
λ,	wavelength;
ρ_c,	hemispherical reflectivity of cover to diffuse radiation;
$\rho_r(\lambda)$,	hemispherical spectral reflectivity of radiating surface;
$\tau_c(\theta)$,	directional transmissivity of cover;
T_0,	ambient temperature;
T_r,	temperature of radiating surface;
q_r,	net radiative heat loss from radiator;
q_{nr},	net heat flux from radiator;
$dq_{i,r}$, $dq_{0,r}$, $dq_{i,c}$, $dq'_{0,c}$,	heat fluxes defined in Fig. 2.

1. INTRODUCTION

THE PHENOMENON of radiative cooling is based on the fact that the thermal energy emitted by a clear, sunless sky is less than that emitted by a blackbody at ambient temperature. If such a surface is exposed to sky radiation and insulated to minimize convective and conduction heat transfer to ambient a net cooling effect will occur.

The thermal emittance of the atmosphere is well known to be a function of both wavelength and zenith angle. Of particular importance to radiative cooling is the region of high atmospheric transmittance which is observed in the I.R. emission spectrum of the atmosphere between 8–13 μm. Bell *et al.* [1] and others [2] have shown that the thermal energy emitted by a clear sky at zenith in the 8–13 μm region may be as low as 0.1–0.2 of that emitted by a blackbody at ambient temperature. In Fig. 1, the measurements of Bell *et al.* [1] are compared to the ambient temperature blackbody emission spectrum. It is seen that the regions of minimum atmospheric emission and maximum blackbody emission coincide, and that sky radiation emitted in the 8–13 μm region increases with increasing zenith angle. The thermal energy emitted by the atmosphere is also influenced by atmospheric and geographical conditions, and correlations have been established which relate atmospheric radiation to water vapour pressure and ambient temperature [3–6].

At temperatures below ambient the net energy radiated by a surface to a clear sky may be increased by matching the emittance spectrum of the surface to that of the atmosphere [7, 8]. A spectrally selective surface for radiative cooling is characterized by a high emittance in the 8–13 μm region and a high reflectance elsewhere, where the thermal radiation from the

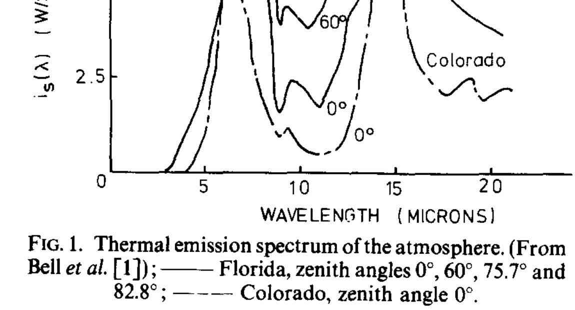

FIG. 1. Thermal emission spectrum of the atmosphere. (From Bell *et al.* [1]); —— Florida, zenith angles 0°, 60°, 75.7° and 82.8°; – – – Colorado, zenith angle 0°.

atmosphere approaches that of a blackbody. Further matching of the radiating surface to the atmosphere may be attainable using surfaces which selectively reflect incident radiation from large zenith angles.

At present most radiative cooling studies have been limited to measurements of the equilibrium temperature attained by well insulated surfaces exposed to clear sky radiation through a polyethylene top cover. Equilibrium temperatures of 6–24 K below ambient have been measured [8–12] with lower temperatures generally being obtained with spectrally selective surfaces [8] or at high elevations [9]. Catalanotti *et al.* [8] have given an approximate analysis of radiator–sky heat exchange and, using a spectrally selective aluminized polyvinyl-fluoride (PVF) radiator, have reported a net heat loss of ~ 57 W/m^2 at an ambient temperature of 281 K, decreasing to ~ 35 W/m^2 at 10 K below ambient. Other investigators [12, 13] have reported net cooling powers of approximately 50 W/m^2 at temperatures near ambient.

In the present paper experimental measurements of the net radiative heat loss as function of temperature below ambient of both spectral and gray surfaces are reported. The effects of surface selectivity, humidity, and ambient temperature on the net heat radiated are shown to be consistent with an analysis of the radiator–clear sky heat exchange based on the net radiation method.

2. ANALYSIS OF RADIATOR PERFORMANCE

A radiative cooling system, such as used in the present study, is shown in Fig. 2. The construction is similar to a flat plate solar collector except that polyethylene is used for the top cover because of its high I.R. transmittance. In the subsequent treatment the net heat transfer due to radiation between the radiator surface, cover and atmosphere, and conduction through the top air gap and insulation is determined. The top cover and outer surface of the insulation are conservatively assumed to be at ambient temperature.

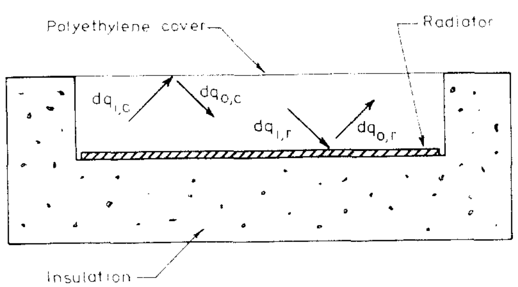

FIG. 2. Radiative cooler.

2.1. *Net heat transfer*

Using the net radiation method for surfaces with spectrally dependent properties [14] the heat fluxes (in the wavelength interval $d\lambda$) as defined in Fig. 2 may be expressed as

$$dq_{o,r} = \varepsilon_r(\lambda)\pi i_b(\lambda, T_r)d\lambda + \rho_r(\lambda)dq_{i,r} \quad (1)$$

$$dq_{o,c} = \pi i_b(\lambda, T_0)\left[2\int_0^{\pi/2} \varepsilon_s(\lambda,\theta)\tau_c(\theta) \times \sin\theta\cos\theta\, d\theta + \varepsilon_c\right]d\lambda + \rho_c\, dq_{i,c} \quad (2)$$

where $\varepsilon_r(\lambda)$ and $\rho_r(\lambda)$ are the hemispherical spectral emissivity and reflectivity respectively of the radiator; $\varepsilon_s(\lambda, \theta)$ is the directional spectral sky emissivity; $\tau_c(\theta)$ is the directional transmissivity of the cover; ε_c is the hemispherical emissivity of the cover; ρ_c is the hemispherical reflectivity of the cover to diffuse radiation; and $i_b(\lambda, T)$ is the blackbody spectral intensity. The radiator is assumed to be a diffuse reflector and the emissivities of both the radiator and cover obey Lambert's cosine law. The optical properties of the polyethylene are assumed to be independent of λ.

The net radiative heat loss from the radiator is

$$q_r = \int_{\lambda=0}^{\infty} dq_{o,r} - dq_{i,r}. \quad (3)$$

Combining equations (1–3), assuming that the radiator—cover configuration factor is unity gives

$$q_r = \int_0^{\infty} \frac{\varepsilon_r(\lambda)\pi\left\{(1-\rho_c)i_b(\lambda, T_r) - i_b(\lambda, T_0)\left(2\int_0^{\pi/2}\varepsilon_s(\lambda,\theta)\tau_c(\theta)\sin\theta\cos\theta\, d\theta + \varepsilon_c\right)\right\}}{1-\rho_c(1-\varepsilon_r(\lambda))}\, d\lambda. \quad (4)$$

The net heat flux from the radiator may be expressed as

$$q_{nr} = q_r - h_c(T_0 - T_r) \quad (5)$$

where h_c is the heat-transfer coefficient due to conduction.

2.2. *Effect of spectral selectivity*

The effect of spectral selectivity of the radiator on the net radiative power loss has been determined by numerical integration of equation (4), using values of ε_s (λ, θ) obtained from the clear sky measurements of Bell *et al.* [1] at Florida and Colorado by taking the ratio of the measured spectral directional sky radiance and the blackbody radiance. The directional dependence of the optical properties of the polyethylene cover were taken from the measurements of Catalanotti *et al.* [8].

In Fig. 3 the net radiative heat loss, q_r, of an ideal spectrally selective radiator, defined by $\varepsilon_r(\lambda) = 1$ for $8 < \lambda < 13$ and $\varepsilon_r(\lambda) = 0$ elsewhere, is compared to that of a blackbody radiator for both Florida and Colorado skies. It is seen that lower equilibrium temperatures and higher cooling powers at temperatures below ambient are obtained when the radiant heat exchange with the sky is restricted to the 8–13 μm region by using the ideal spectrally selective radiator. As indicated from Fig. 1 values of $\varepsilon_s(\lambda)$ for the Colorado sky measurements fall below unity in the 15–20 μm wavelength region, and this has caused the net radiative heat loss for the blackbody radiator to be greater than that of the spectrally selective radiator at temperatures near ambient. It may be seen from equation (4) that the slopes of the q_r vs $(T_0 - T_r)$ curves should only be a function of radiator characteristics (i.e. $\varepsilon_r(\lambda)$, ρ_c, and T_r) and independent of sky emissivity.

The conduction heat gains for h_c equal to 1 and 2 W/m^{2}K are also shown in Fig. 3. The value h_c = 1 W/m^{2}K corresponds approximately to conduction through a 50 mm top air gap and 50 mm of insulation. In Fig. 4, the net heat flux, from an ideal selective surface under a Florida sky taking into account both radiative and conduction heat transfer is shown for values of h_c equal to 0–4 W/m^2. It is clear that conduction heat transfers, even for well insulated radiators, substantially limits the net cooling power.

2.3. *Effect of directional selectivity*

The energy radiated by surfaces exhibiting both spectral and directional selectivity may be determined from the previous analysis by assuming the surface to be an ideal spectral radiator for $0<\theta<\theta_1$, and for $\theta>\theta_1$, $\varepsilon_r(\lambda) = 0$. The net radiative heat loss may be expressed as

$$q_r = \int_0^{\infty} \frac{\varepsilon_r(\lambda)2\pi\left\{(1-\rho_c)i_b(\lambda, T_r)\int_0^{\theta_1}\sin\theta\cos\theta\,d\theta - i_b(\lambda, T_0)\int_0^{\theta_1}(\varepsilon_s(\lambda,\theta)\tau_c(\theta)+\varepsilon_c)\sin\theta\cos\theta\,d\theta\right\}}{1-\rho_c(1-\varepsilon_r(\lambda))}\,d\lambda \quad (6)$$

where

$$\rho_c = \frac{\int_0^{\theta_1}\rho_c(\theta)\sin\theta\cos\theta\,d\theta}{\int_0^{\theta_1}\sin\theta\cos\theta\,d\theta}. \quad (7)$$

The effect of θ_1 on the net radiative heat loss is shown in Fig. 5. The conduction heat gain for h_c = 1 W/m^{2}K is also shown in Fig. 5. From the radiative heat loss curves it is apparent that, although decreasing θ_1 results in lower equilibrium temperatures, the main effect of surface directionality is to limit the radiative heat loss at temperatures near ambient. When conductive heat gains are included it is clear that decreasing θ_1 decreases both the net heat loss and equilibrium temperature. The radiative heat loss curves for $\theta_1 = 75°$ and 90° are nearly identical because of the decreasing transmissivity of polyethylene with increasing θ.

3. EXPERIMENTAL TECHNIQUE

Measurements of net cooling power were carried out using a test panel similar to that shown in Fig. 2 which allowed four identical surfaces, each in an individual compartment, to be simultaneously tested. The area of each sample was 0.01 m^2. The samples were insulated on sides and bottom with 50 mm of polystyrene and a thin film ($\sim$12.5 μm) of poly-

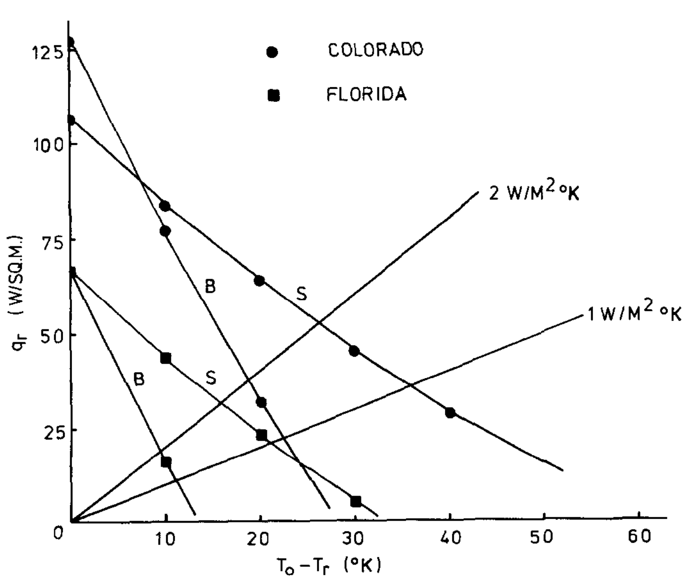

FIG. 3. Variation of radiative heat loss with $T_0 - T_r$ for ideal selective and blackbody surfaces under Florida and Colorado skies. B—Blackbody surface; S—ideal spectrally selective surface.

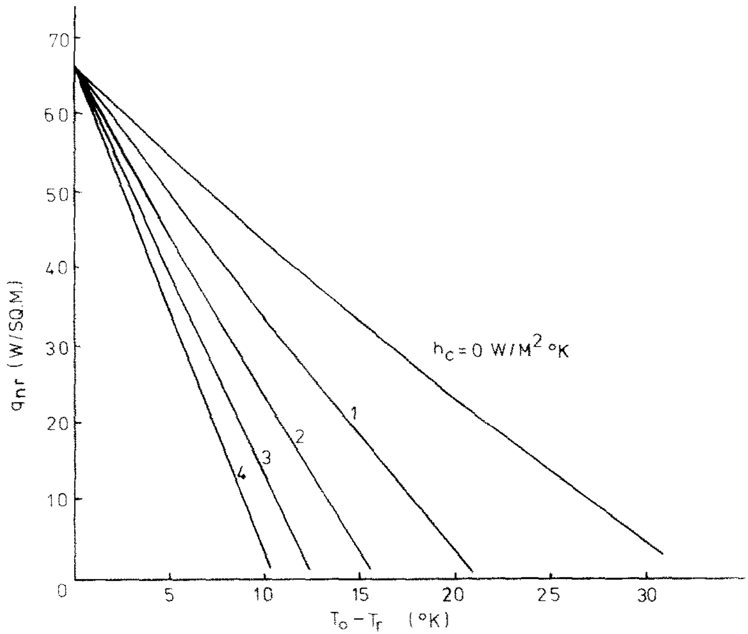

FIG. 4. Effect of conduction heat-transfer coefficient on net cooling power of ideal selective surface under Florida sky.

ethylene was used as the top cover. The cover-sample spacing was 25 mm. Thin resistance wire heaters attached to the backs of the samples were used to supply a predetermined power level to each sample and the resulting temperatures were continuously measured using Chromel–Alumel thermocouples bonded to the back of the samples and electrically insulated from the heaters. Under steady-state conditions the power supplied by the heaters to each sample at a given temperature is equal to the net heat flux, q_{nr}, or cooling power of the sample at that temperature.

The surfaces studied were a commercial flat black paint applied to a 0.5 mm aluminium backing plate and back aluminized PVF. The hemispherical emissivity of the black paint, measured using a Gier-Dunkle DB100 Infrared Reflectometer was 0.90 [15]. The spectral hemispherical reflectivity of the aluminized PVF surface, measured with a Gier–Dunkle Spectroradiometer, is shown in Fig. 6 [15]. All measurements were carried out at night under clear sky conditions. Ambient dry bulb and dew point temperature measurements were made using aspirated dewpoint and ambient temperature sensors.

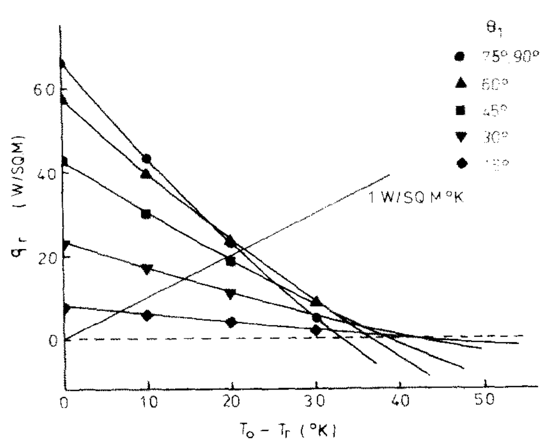

FIG. 5. Effect of directional selectivity on q_r.

4. RESULTS AND DISCUSSION

In Fig. 7 measurements of q_{nr} exhibited by the black paint and aluminized PVF surfaces under essentially identical atmospheric conditions are shown as a function of the surface–ambient temperature difference, $T_0 - T_r$. It is seen that at ambient temperature the net cooling power of the black surface is greater than that of the aluminized PVF. However, as discussed previously, the rate of decrease of cooling power with temperature of the aluminized PVF surface, because of its lower total hemispherical emissivity, is less than that of the black surface thus resulting in the PVF surface exhibiting a higher cooling power at low temperatures. Also shown in Fig. 7 are the net cooling powers computed from equation (4) using the Florida sky emissivity measurements of Bell *et al.* [1] and the measured emissivities of the black paint and PVF surfaces. A conduction heat-transfer coefficient of 4.2 W/m^{2}K was found to give the best agreement between measured and computed curves for both surfaces. The difference in the magnitude of the net cooling powers is due to the different sky emissivities. The above value of h_c is higher than that calculated assuming only conduction gain through a static air gap and back insulation because of significant edge gains associated with the relatively small radiator area and top gains arising from wind induced vibration of the polyethylene cover.

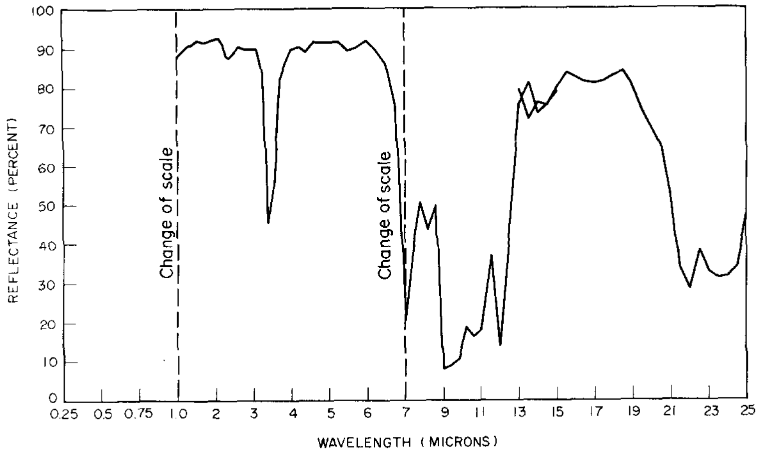

FIG. 6. Hemispherical, spectral reflectivity of aluminized PVF [15].

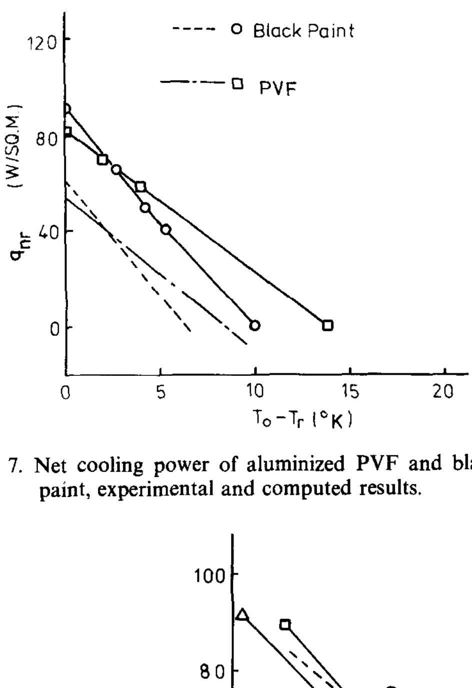

FIG. 7. Net cooling power of aluminized PVF and black paint, experimental and computed results.

In Fig. 8 the effect of absolute humidity on the net cooling power of the aluminized PVF surface is shown for conditions of constant temperature. Although the measurements do not cover a wide range of humidities, it is clear that humidity is an important factor determining sky radiance [1–6] and hence net cooling power. Calculated net cooling powers using the sky emissivities for Florida and Colorado [1] are also shown in Fig. 8 for comparison with the experimental results.

Measurements of the net cooling power of the aluminized PVF surface at various ambient temperatures are shown in Fig. 9 for conditions of constant absolute humidity, i.e. constant $\varepsilon_s(\lambda, \theta)$. It is seen that at constant $(T_0 - T_r)$ the net heat radiated increases with increasing ambient temperature. In Fig. 10 experimental and computed values of the net heat radiated at temperatures of 5 and 10 K below ambient are plotted

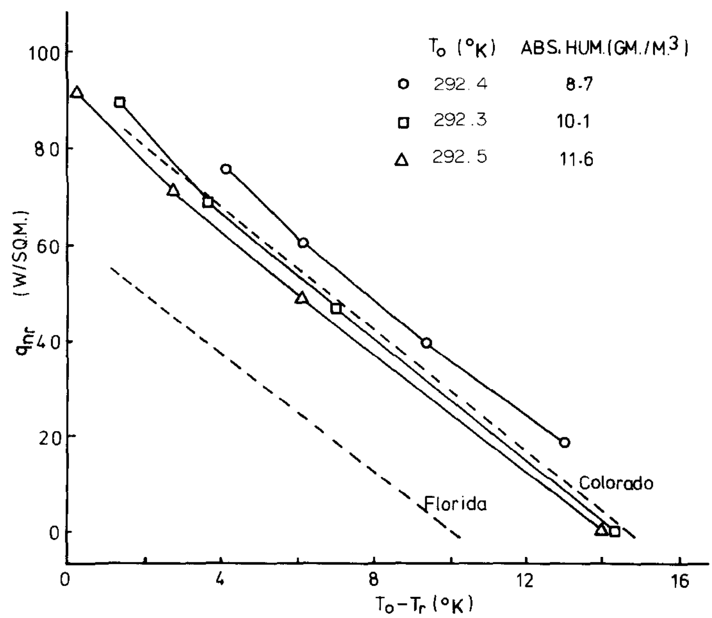

FIG. 8. Effect of absolute humidity on net cooling power of aluminized PVF at constant T_0.

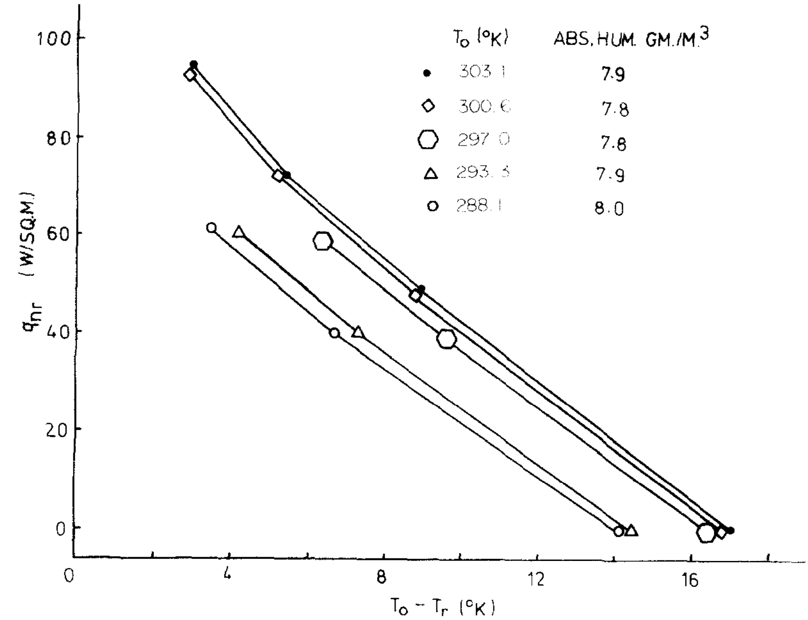

FIG. 9. Effect of ambient temperature on net cooling power at constant absolute humidity.

as a function of ambient temperature. Both the experimental and computed results exhibit a similar variation of net cooling power with ambient temperature.

In practice humidity and ambient temperature are not independent variables and the net radiation cooling losses to the atmosphere over any given period of time will be dependent on variations in both. This is illustrated in Fig. 11 where measurements of the net cooling powers at 5 and 10 K below ambient, absolute humidity, and ambient temperature are plotted over a 12 h period. Also illustrated in Fig. 11 is the fact reported by Catalanotti [8] the spectrally selective radiators exhibit a reduced, but nevertheless positive, net cooling power during the day if shaded from direct beam solar radiation.

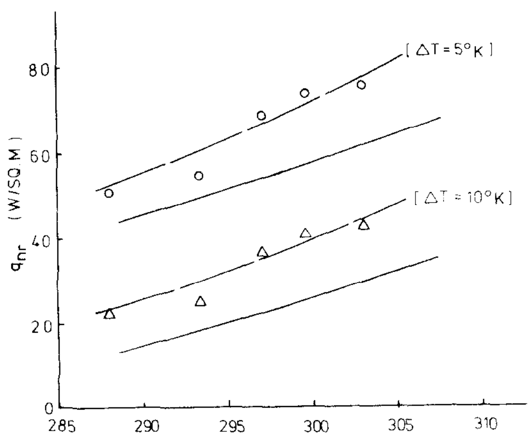

FIG. 10. Effect of ambient temperature on net cooling power at $T_0 - T_r$ = 5 K and 10 K. Solid curves are for calculated cooling powers for Colorado sky.

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REFERENCES

1. E. E. Bell, L. Eisner, J. Young and R. A. Oetjen, Spectral radiance of sky and terrain at wavelengths between 1 and 20 microns, *J. Opt. Soc. Am.* **50**, 1313 (1960).
2. R. Sloan, J. H. Shaw and D. Williams, Infrared emission spectrum of the atmosphere, *J. Opt. Soc. Am.* **45**, 455 (1955).
3. A. Angstrom, The study of radiation of the atmosphere, *Smithsonian Inst., Misc. Coll.* **65**, 3 (1918); Effective radiation during the second international polar year, *Medde. Stat. Met. Hydrogr. Anst.*, Stockholm **6**, No. 8 (1936).
4. D. Brunt, Notes on radiation in the atmosphere, *Q. Jl R. Met. Soc.* **58**, 389 (1932).
5. W. C. Swinbank, Long-wave radiation from clear skies, *Q. Jl R. Met. Soc.* **89**, 339 (1963).
6. S. B. Idso and R. D. Jackson, Thermal radiation from the atmosphere, *J. Geophys. Res.* **75**, 5398 (1969).
7. A. K. Head, Method and means for refrigeration by selective radiation, *Australian Pat. No.* 239364 (1959); Method and means for producing refrigeration by selective radiation, *U.S.A. Pat. No.* 3,043,112 (1962).
8. S. Catalanotti, V. Cuomo, G. Piro, D. Ruggi, V. Silvestrini and G. Troise, The radiative cooling of selective surfaces, *Solar Energy* **17**, 83 (1975).
9. F. Trombe, Exploitation du rayonnement des corps sur l'espace pour obtenir de grands abaissements de température, *Proc. XI. Cong. Refrig.*, Munich (1963).
10. M. V. Griffith, Cooling for air conditioning by selective emission of radiation through the atmosphere, *Proc. XIII Int. Cong. Refrig.* **4**, 127 (1971).
11. A. W. Harrison and M. R. Walton, Radiative cooling of TiO_2 white paint, *Solar Energy* **20**, 185 (1978).

12. D. Michell, Selective radiation cooling, another look, *Comm. Sci. Ind. Res. Org. Rept.*, 62/55 (1976).
13. B. Boldrin, Private communication.
14. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer*. McGraw-Hill, New York (1972).
15. E. A. Christie, Private communication.

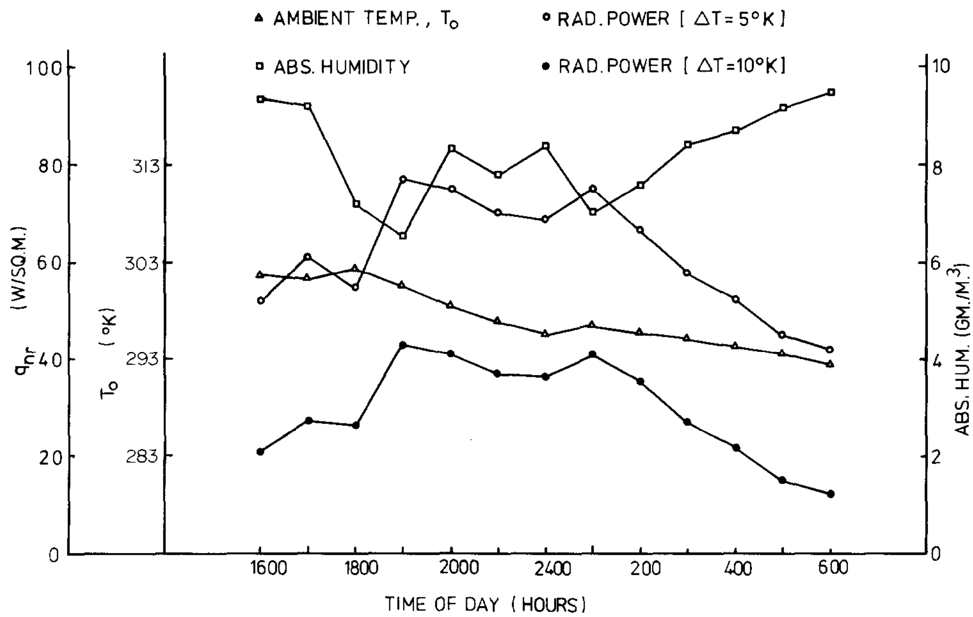

FIG. 11. Measurements of net radiative power at 5 and 10 K below ambient, ambient temperature and absolute humidity over 12 h period. Note change in net radiative power associated with sunset at 1810 h. Radiator shaded prior to sunset.

EFFET DES CARACTERISTIQUES DE SURFACE ET DES CONDITIONS ATMOSPHERIQUES SUR LES PERTES RADIATIVES EN CIEL CLAIR

Résumé — On considère les facteurs qui influencent la perte nette thermique des surfaces exposées au rayonnement thermique de l'atmosphère. Des mesures de perte nette en fonction de la température de la surface, de la température ambiante et de l'humidité, ont été faites à la fois pour des surfaces grises ou spectralement sélectives. Des surfaces grises d'émissivité élevée ont la perte nette la plus élevée à des températures proches de l'ambiance. Des surfaces sélectives avec des émissivités adaptées à la fenêtre atmosphérique 8–13 μm, montrent des puissances les plus élevées à des températures très au dessous de l'ambiance. Le transfert thermique par conduction entre la surface rayonnante et l'environnement limite la puissance nette de refroidissement. Les résultats expérimentaux sont en bon accord avec une analyse de l'échange thermique ciel-radiateur-ambiance.

EINFLUSS DER OBERFLÄCHENBESCHAFFENHEIT UND DER ATMOSPHÄRISCHEN BEDINGUNGEN AUF DEN WÄRMEVERLUST DURCH STRAHLUNGSAUSTAUSCH BEI KLAREM HIMMEL

Zusammenfassung—Es wurden die Faktoren untersucht, die den Gesamtwärmeverlust von Oberflächen beeinflussen, die im thermischen Strahlungsaustausch mit der Atmosphäre stehen. Dazu wurden Messungen des Strahlungsaustausches gemacht, die an grauen und spektral-selektiven Oberflächen den Einfluß der Oberflächentemperatur, der Umgebungstemperatur und der Feuchtigkeit zeigen. Graue Oberflächen mit hoher Emission haben danach die höchste Auskühlung bei Umgebungstemperatur. Spektral-selektive Oberflächen mit spektralen Emissionen, die dem atmosphärischen Fenster (8–13 μm) angepaßt waren, zeigten die größte Auskühlung bei Temperaturen weit unter Umgebungstemperatur. Der Wärmeaustausch durch Wärmeleitung zwischen der strahlenden Oberfläche und der Umgebung begrenzt die Auskühlung maßgeblich. Die experimentellen Ergebnisse stimmen gut mit der Berechnung des Wärmeaustausches zwischen Himmel, Strahler und Umgebung überein.

ВЛИЯНИЕ ХАРАКТЕРИСТИК ПОВЕРХНОСТИ И АТМОСФЕРНЫХ УСЛОВИЙ НА ЛУЧИСТЫЕ ПОТЕРИ ТЕПЛА ПРИ ЯСНОЙ ПОГОДЕ

Аннотация — Исследованы факторы, влияющие на результирующие потери тепла с поверхностей при воздействии атмосферного теплового излучения. Исследование зависимости результирующих потерь тепла от температуры поверхности, а также температуры и влажности окружающего воздуха проведено как для серых, так и спектрально селективных поверхностей. Найдено, что серые поверхности с большой излучательной способностью обладают наибольшей охлаждающей способностью при температуре, близкой к температуре окружающей среды. Спектрально селективные поверхности, спектральная излучательная способность которых находится в диапазоне атмосферного окна прозрачности 8–13 μМ, проявляют наибольшую охлаждающую способность при температурах, намного ниже температуры окружающей среды. Показано, что кондуктивный перенос тепла между излучающей поверхностью и окружающей средой значительно ограничивает результирующие лучистые потери тепла. Экспериментальные данные хорошо согласуются с результатами теоретического анализа.