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At last! A durable convection cover for atmospheric window radiative cooling applications.

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Abstract

Enhanced cooling of surfaces by radiative heat loss through the 8-14 micron atmospheric window was investigated using commonly available materials. Zinc sulphide was found to be a durable substance suitable as a convection cover. With respect to polyethylene, the most commonly used proof-of-concept convection cover in research to date, ZnS is orders of magnitude stronger, impervious to damage by UV, effectively inert and in practical thicknesses is more transparent in the 8–14 micron 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 microns allows for the economical production of an effective selective radiator system. Measurements were made on simple radiator plates and convection covers. The principal aim of this project was to identify a durable cover, rather than investigate or optimise a novel selective radiator surface.

Keywords: Radiative Cooling; Selective Radiator; Durable Convection Cover

1. Introduction

The phenomenon of passive, selective radiative cooling via infrared atmospheric windows (*e.g.* in the 8–14 μm range [1]) have been exploited accidentally or opportunistically since ancient times. However, scientific understanding of the phenomenon started with the work of Ångström [2]. Little further work was published until that of Head [3] with spates of investigation over the period from the 70s to the 90s [*e.g.* 4–14]. Intensity of research into this technology has diminished since then, presumably due in large part to the failure to identify a suitable material for a convection cover - such a cover must be transparent

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over the wavelength range of the atmospheric window *and* posess sufficient strength and durability. Polyethylene has been the most commonly used proof-of-concept convection cover material in research so far, because of its low cost and suitable transmittance in the 8–14 μm range, but it is subject to mechanical weathering and UV degradation making it impractical for long-term use [15]. Very recent work [16] suggests that polyethylene in the form of a UV stabilised mesh exhibits a considerable improvement in the structural integrity of this material. That paper cites an estimated lifetime of 5 years based on the manufacturer's specifications. However, that appears to be a lifetime based only on structural integrity and no data are presented concerning the effect of UV ageing on the IR optical properties.

The work of Bathgate [17] identified hot-pressed zinc sulphide [18] as a promising robust material for this application.

Nomenclature

P_c	Effective cooling power at steady-state (includes parasitic conduction and convection)
P_{net}	Net radiative-only cooling power
σ	parasitic thermal conductance (combines convective and conductive heat inflow to radiator)
ΔT_{ss}	steady-state temperature difference between radiator plate and ambient

2. Experimental setup

The principal aim of this project was to identify a durable cover, rather than investigate or optimise a novel selective radiator surface. The radiator surface chosen for the test of the convection cover, was based on anodised aluminium following the work of Miller and Bradley [19] who reported that bright anodised aluminium showed promise as an inexpensive selective radiator. Only a moderate effort was made to reproduce the detailed preparative and spectral characterisitics of Miller and Bradley's surface because our anodisation was performed at a commercial establishment, which did not allow a detailed experimental oversight and because of the unavailability (at the time of the experiment) of the same grade of aluminium as used by them. This was not critical because perfection of the qualities of the radiator was beside the point of the investigation.

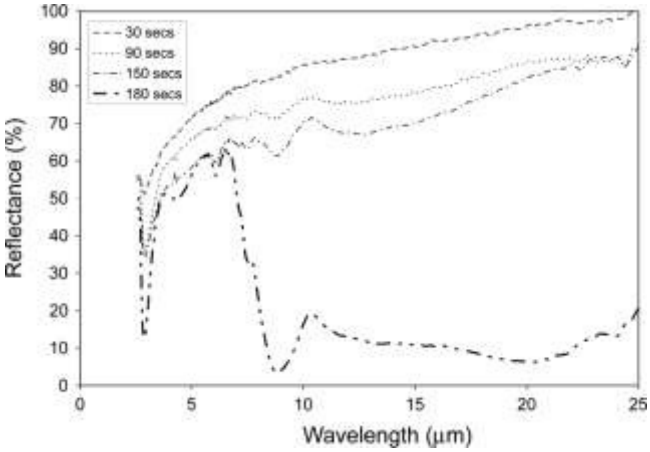

Fig. 1. Reflectance of 1150 grade anodised aluminium showing a marked transition in reflectance at 180 s anodising time.

2.1. Selective radiator surface

Measurements were made of the thermal-IR reflectance of the anodised surface of 1150 grade aluminium and it was found that a useful radiator surface could be produced (Fig. 1).

The anodising conditions employed were:

- voltage = 13 V DC;
- sulphuric acid concentration = 10% (by volume)
- aluminium concentration 5–15 g/l.

The reflectance of the anodised aluminium between 3-20 μm, declined gradually with increasing anodising time until at 180 s when the reflectance beyond 7 μm declined sharply (Fig. 1). The reflectance spectrum of the 180 s anodised test piece approaches the properties of a selective radiator with average reflectance between 8 and 14 μm being around 12% and average reflectance below 8 μm > 1%.

The mean reflectance over $8 < \lambda < 14$ μm relative to mean reflectance over $3 < \lambda < 8$ μm decreases with longer anodising times (Fig. 1). Longer anodising times (up to 12 min) produced surfaces with a reflectance similar to the 180 s anodised test piece.

2.2. ZnS convection cover

Investigation of infrared spectra of a range of materials in the literature identified zinc sulphide (ZnS) as having suitable transmittance T spectrum for a convection cover material. 4 mm thick tile of hot-pressed ZnS was sourced for this work. Our measurements (Fig. 2) indicate that it is sufficiently transparent (mean $T_{mean} = 64\%$) in the 8–14 μm range (similar to that of 100 μm polyethylene film $T_{mean} = 73\%$) to be useful in this application, despite being 40 times thicker than 100 μm polyethylene.

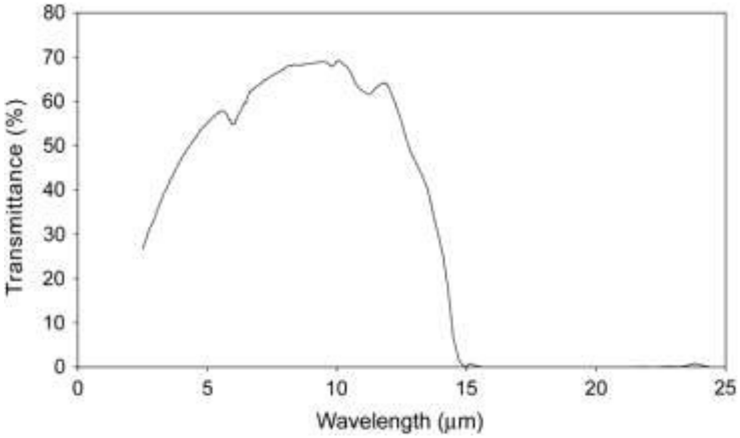

Fig. 2. Measured transmittance of polished hot-pressed 4 mm thick zinc sulphide.

This means that it would not be practical to use thicker polyethylene covers to improve weathering because the reduction in transmittance of the thicker material would defeat the purpose of the cover. However, a thinner ZnS plate could be viable, yielding higher transmittance and lower cost.

2.3. Test boxes

Radiator test boxes (Fig. 3) were constructed from 50 mm thick polystyrene foam arranged to form 100 mm thick walls and a 50 mm thick. base. The radiators were 100 mm^2 anodised square aluminium plates. The radiator cavities were lined with aluminium foil to make the walls reflective to minimise edge effects so as to approximate an infinite radiator. A 330 Ω, 5 W resistor was attached with screws and thermally conducting paste to the underside of each radiator plate to provide a source of heat. Polyethylene or zinc sulphide convection covers were placed over the open tops of the boxes.

The small differences between the temperatures of the radiators and ambient temperature required a precision of ±0.1 K in the relative temperature measurements to make useful comparisons between radiators. LM335 precision temperature sensors were employed, producing an output of 10 mV/K which was 12-bit digitised by an ICL7109 analogue to digital converter. The LM335 sensors were mounted between the polystyrene base and the radiator plate and were kept in thermal contact with the radiator plate with thermal conducting paste. The ambient temperature and the temperatures of two radiator plates were measured simultaneously.

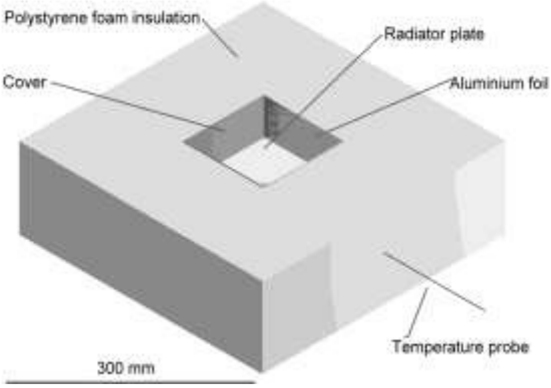

Fig. 3. Test boxes used to measure properties of radiator surfaces and convection covers..

2.4. Parasitic heat loss and gain in test boxes

The combined parasitic heat loss (thermal conductance of the walls, bases and tops of the boxes and the enclosed air and convection at the outer surface) was teated as a single linear thermal conductivity and was measured in the following way. The radiator plates were heated using their attached 330 Ω, 5 W resistors while a sheet of aluminium foil was used in place of the convection cover to act as a reflecting cover of minimal thermal mass to prevent radiative heat loss from the top of the box while heat loss to ambient by conduction and convection was measured.

The temperature difference between ambient and the inside of the boxes versus power delivered to the plate was found to be closely linear and the slope of this was used to calculate the total parasitic thermal conductance σ (*i.e.* linear heat transfer coefficient) for the test boxes.

2.5. Radiative heat loss measurements

The radiative cooling power of the test boxes was tested for two different radiator surfaces, anodised aluminium and pot belly black paint (Fig. 4), and two different convection covers (100 µm polyethylene and 4 mm zinc sulphide). The measurements were conducted at night in Sydney, Australia, during

February, March, April and May 2006 on an exposed flat roof with a clear view of the sky, without nearby surrounding buildings, structures or trees.

Ambient temperature and radiator temperatures were recorded continuously and the sun-down and sun-up times were used as the start and finish times for analysing radiator performances. By consultation of satellite cloud pictures and local weather reports, it was judged that measurements were conducted mostly under minimal cloud conditions although it was not practicable to monitor cloud cover all night.

Heat loss was calculated from the recorded temperatures, using the thermal conductance of the test boxes determined previously to calculate the parasitic heat flow and using the following analysis.

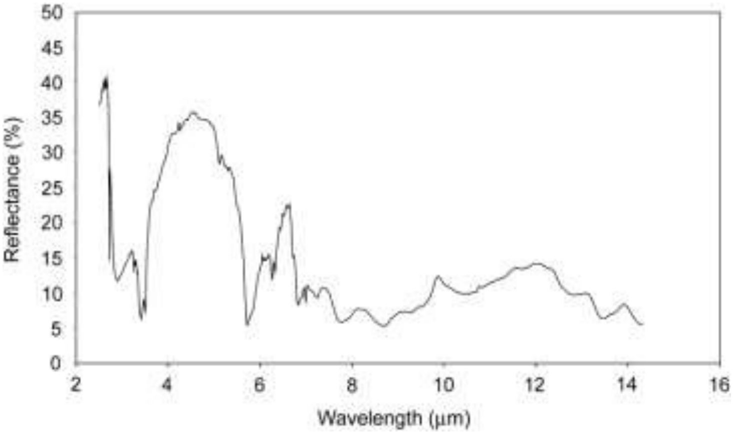

Fig. 4. Reflectance of high infrared emittance black paint (pot belly black).

In these experiments, we assume steady-state conditions, such that the product of test box thermal capacity Q and cooling rate T' is omitted from the heat balance equation, Eq. (1).

$$P_c = P_{net} - \sigma \Delta T_{ss} \tag{1}$$

To confirm the validity of our steady-state assumption, the thermal capacity of the test boxes was estimated using published material properties and a range of night-time cooling rates were taken from our measurements. QT' was calculated and found to be well under 1% of the measured net radiative cooling power, so the term was omitted from equation 1.

Measurements were performed in two modes - passive and active. In passive mode, the boxes were allowed to radiate without externally supplied electrical heating power while monitoring the temperature difference between ambient and the radiator surface. Under the steady-state assumption, the effective cooling power of the system is zero and so the net radiative cooling power of the radiator plate simply equals the rate of parasitic heat gain from the surroundings (deduced from ΔT_{ss} and σ).

The total parasitic heat gain between sunset and sunrise (and hence total energy radiated by the plate) was calculated from the area under the temperature/time curve. That is, the temperature difference ΔT_{ss} between the radiator surface and ambient was recorded and integrated versus time. This integral value was multiplied by the linear heat transfer coefficient σ to yield the total energy transfer.

In active mode, the radiators were heated electrically using the built-in resistors, to simulate the performance of a practical cooling system. Under the steady-state assumption, the net radiative cooling power of the radiator plate equalled the power delivered electrically to the radiator plate minus parasitic heat loss. The passive mode measurements were used to determine the lowest attainable temperatures.

3. Results

Fig. 5 (left) shows a typical single night's plot of the simultaneous temperatures of two heated anodised aluminium radiator plates (active mode) covered respectively by polyethylene and zinc sulphide. The ambient temperature ($T_{ambient}$) and the temperature of the radiators ($T_{polyethylene}$ *and* T_{ZnS}) are plotted.

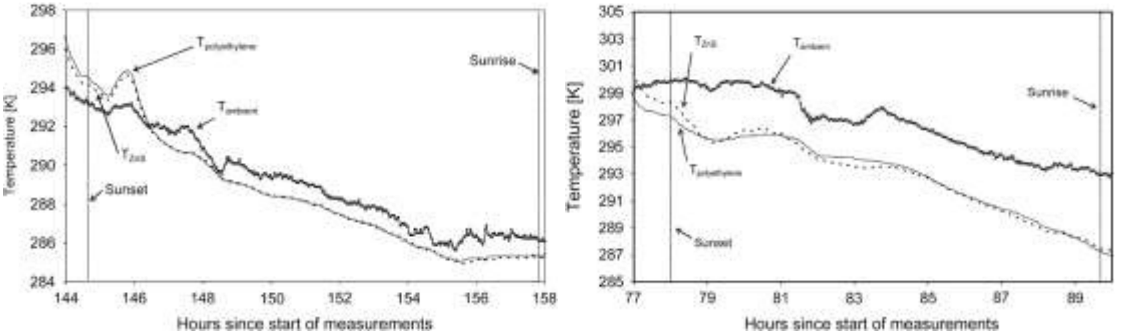

Fig. 5. (Left) Typical active mode measurement. Ambient temperature ($T_{ambient}$) and the respective temperatures of heated anodised aluminium radiators (T_{ZnS} and $T_{polyethylene}$) under zinc sulphide and polyethylene covers . (Right) Typical passive mode measurement.

Fig. 5 (right) shows a typical passive mode measurement. These measurements demonstrate stagnation temperatures of up to 6 K below ambient.

The averaged results from five separate active mode experiments are given in Tables 1 and 2. Results from two separate passive mode experiments are shown in Tables 3 and 4.

Table 1. Comparison of ZnS and polyethylene convection covers over heated anodised Al radiators (active mode).

Measurements (sunset to sunrise)	Zinc sulphide	Polyethylene
Total net radiative heat loss (Wh/m^2)	430±10	420±10
Average net radiative power (W/m^2)	32.5±0.5	32.2±0.5
Peak net radiative power (W/m^2)	49.9±0.5	50.2±0.5
Radiator temp. @ peak radiative power (K)	288.4±0.2	
Ambient temp. @ peak radiative power (K)	289.4±0.2	289.2±0.2

Table 2. Comparison of ZnS and polyethylene convection covers over heated pot belly black painted Al radiators (active mode).

Measurements (sunset to sunrise)	Zinc sulphide	Polyethylene
Total net radiative heat loss (Wh/m^2)	340±10	355±10
Average net radiative power (W/m^2)	29.6±0.5	31.3±0.5
Peak net radiative power (W/m^2)	44.5±0.5	45.0±0.5
Radiator temp. @ peak radiative power (K)	295.3±0.2	295.7±0.2
Ambient temp. @ peak radiative power (K)	295.4±0.2	295.9±0.2

Table 3. Comparison of ZnS and polyethylene convection covers over unheated anodised Al radiators (passive mode).

Measurements (sunset to sunrise)	Zinc sulphide	Polyethylene
Total net radiative heat loss (Wh/m^2)	470±10	580±10
Average net radiative power (W/m^2)	33.9±0.5	41.9±0.5
Peak net radiative power (W/m^2)	49.0±0.5	51.8±0.5
Radiator temp. @ peak radiative power (K)	283.0±0.2	283.0±0.2
Ambient temp. @ peak radiative power (K)	282.5±0.2	282.6±0.2

Table 4. Comparison of ZnS and polyethylene convection covers over unheated pot belly black painted Al radiators (passive mode).

Measurements (sunset to sunrise)	Zinc sulphide	Polyethylene
Total net radiative heat loss (Wh/m^2)	275±10	260±10
Average net radiative power (W/m^2)	23.7±0.5	22.8±0.5
Peak net radiative power (W/m^2)	37.4±0.5	
Radiator temp. @ peak radiative power (K)	292.2±0.2	292.0±0.2
Ambient temp. @ peak radiative power (K)	296.1±0.2	296.1±0.2

4. Discussion

The reader should recall that main purpose of the investigation was to evaluate a novel convection cover for a radiative cooling apparatus using selective and non-selective radiator surfaces and compare its performance against polyethylene. It is not purported that the radiator surfaces presented here are optimised or high performance or that the radiator design is optimal, so the relevant critical comparison to be made is polyethylene cover versus zinc sulphide cover, rather than against the performance of other published (optimised) selective radiative cooling surfaces.

That said, these anodised surfaces were still found to be more effective radiators than black body surfaces and measurements demonstrated that it was possible to use simple and inexpensive materials to construct useful selective radiators that are durable and easy to fabricate.

The most useful general measurement of performance is the average radiative power (or total radiative heat loss divided by total measurement time) since that defines the usable cooling power of the system and determines the area required for a given desired cooling load. The results listed in Table 1 for heated anodised aluminium radiators, in Table 2 for heated high infrared emission ‘‘pot belly’’ black paint radiators, in Table 3 for unheated anodised aluminium radiators and in Table 4 for high infrared emission ‘‘pot belly’’ black paint radiators demonstrate that zinc sulphide and polyethylene covered radiators have comparable thermal performances despite the zinc sulphide tiles being 40 times as thick as the polyethylene sheet. The margins of error for net radiative heat loss, peak radiative power, average radiative power and lowest achieved radiator temperature overlapped for both types of cover with the exception of unheated anodised aluminium radiators.

Zinc sulphide, although presently only available in an expensive optical grade, is (in the form of 4 mm thick tiles), impervious to environmental effects, in particular to degradation by solar ultra-violet radiation. It is possible that since the optical and mechanical requirements for a convection cover are less rigorous than those for scientific or military infrared optics applications, a lower optical/mechanical quality (and lower cost) grade of zinc sulphide could be developed. A reduction in thickness would increase transmittance (and could also reduce costs). Simple calculations (Fresnel equation and Bougher-

Lambert law) suggest a 10% improvement in transmittance at a wavelength of 12mm for a reduction in thickness from 5.0 to 2.5 mm. The performance of zinc sulphide may also be able to be improved by the addition of an anti-reflection coating.

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References

[1] Bell EE, Eisner L, Young J, Oetjen R.A., Spectral radiance of sky and terrain at wavelengths between 1 and 20 microns, II. Sky measurements, *J. Opt. Soc. Am. A* 1960; **50:**1313–20.

[2] Ångström AA, A study of the radiation of the atmosphere, *Smith. Misc. Coll.* 1915;**65:**6–159.

[3] Head AK, Method and means for refrigeration by selective radiation, Australian Patent No. 239364, 1959.

[4] Berdahl P, Martin M, Sakkal F, Thermal performance of radiative cooling panels, *Int. J. Heat Mass Transfer* 1982; **26**:871-80.

[5] Berdahl P, Radiative cooling with MgO and/or LiF layers, *Appl. Opt.*1984; **23**:370–3.

[6] Addeo A, Monza E, Peraldo M, Bartoli B, Coluzzi B, Silvestrini V, Troise G, Selective covers for natural cooling devices, *II Nuovo Cimento* 1978; **1C**:419–29.

[7] Catalanotti S, Cuomo V, Piro G, Ruggi D,. Silvestrini V, Troise, G The radiative cooling of selective surfaces, *Sol. Energy* 1975; **17**:83–9.

[8] Landro B, McCormick PG, Effect of surface characteristics and atmospheric conditions on radiative heat loss to a clear sky, *Int. J. Heat Mass Transfer* 1979;**23**:613–20.

[9] Granqvist CG, Hjortsberg A, Radiative cooling to low temperatures: General considerations and application to selectively emitting SiO films, *J. Appl. Phys.* 1981;52:4205–20.

[10] Nilsson NA, Eriksson TS, Granqvist CG, Infrared transparent convection shields for radiative cooling: initial results on corrugated polyethylene foils, *Sol. Energy Mater. Sol. Cells* 1985;**12**:327–33.

[11] Torbjorn MJ, Nilsson GA, Granqvist CG, A solar reflecting material for radiative cooling applications: ZnS pigmented polyethylene, *Sol. Energy Mater. Sol. Cells* 1992;**28**:175–93.

[12] Al-Nimr MA, Kodah Z, Nassar B, A theoretical and experimental investigation of a radiative cooling system, *Sol. Energy* 1998;**63**:367–73.

[13] Eriksson TS, Jiang S-J, Grandqvist CG, Surface coatings for radiative cooling applications: silicon dioxide and silicon nitride mad by reactive rf-sputtering, *Sol. Energy Mater. Sol. Cells* 1985;**12**:319–25.

[14] Diatezua MD, Thiry PA, Caudano R, Characterisation of silicon oxynitride multilayered systems for passive radiative cooling application, *Vacuum* 1995;**46**:1121–4.

[15] Ali AAH, Saito H, Taha IMS, Kishinami K, Ismail IM, Effects of aging, thickness and colour on both the radiative properties of polyethylene films and performance of the nocturnal cooling unit, *Energy Convers. Manage*.1998;**39**:87–93.

[16] Gentle AR, Dybdal KL, Smith GB. Polymeric mesh for durable infra-red transparent convection shields: Applications in cool roofs and sky cooling. *Solar Energy Materials & Solar Cells* 2013; **115**:79–85

[17] Bathgate SN An investigation of properties of materials suitable for radiative cooling applications: A thesis submitted to The University of Sydney for the degree of Master of Science July 2006

[18] Harris DC, Baranowski M, Heneman L, LaCroix L, Wilson C, Kurzius S *et al.* Thermal, structural and optical properties of Cleartrans multispectral zinc sulphide, *Optical Engineering* 2008;**47**:14001-1 to 12.

[19] Miller WC, Bradley JO, Radiative cooling with selective surfaces in a desert climate, in: *Proceedings of the 4th National Passive Solar Conference*, Kansas City, MO, 1979, pp480–2.