a reprint from

Applied Energy

an International Journal

Edited by

S. D. PROBERT

Published by

APPLIED SCIENCE PUBLISHERS LTD
Ripple Road, Barking, Essex, England

RADIATION COOLING OF BUILDINGS AT NIGHT

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SUMMARY

The cooling of small buildings at night by radiation loss to the sky has been investigated by monitoring the thermal performance of two huts: one roofed with galvanised steel decking painted white, which acts as a 'black body' for wavelengths greater than 3 μm; the other with aluminium decking to which aluminised 'Tedlar' sheet had been glued, the 'Tedlar' acting as a selective surface absorbing and radiating mainly in the 8–13 μm band.

The hut with the painted roof was cooled marginally better than that with the 'Tedlar' covered roof. Useful cooling powers of 22 $W\,m^{-2}$ were achieved at a roof temperature of 5 °C, ambient 10 °C, and the gross cooling power probably exceeded 29 $W\,m^{-2}$. Calculations based on a simple simulation of the sky radiation yield an upper limit of 40 $W\,m^{-2}$ for the cooling power of the surfaces and suggest that an ideally selective surface operating under the best possible clear-sky conditions has little advantage over a black body radiator unless the temperature of the surfaces is significantly lower than the ambient air temperature.

INTRODUCTION

It is well known that at night a body may be cooled by radiating energy to the clear night sky and that the temperature of the body may fall considerably below the ambient temperature.

Head[1,2] postulated the use of 'selective' surfaces which reflect all radiation outside the wavelength range 8–13 μm but absorb and emit within these limits as a black body. With surfaces of this kind, and suitable shading, cooling may be obtained over the whole 24-h period of the day provided that the sky is clear. The lowest temperature available with a selective surface is believed to be considerably lower

Applied Energy 0306-2619/79/0005-0263/$02·25

than those attainable with a black body radiator. Griffith[3] developed selective surfaces based on the ideas of Head and these were tested at Malta during October, 1970. Temperatures of about 6 °C below ambient were obtained at various times during the whole 24-h period of the day. Michell,[4] in a series of experiments, demonstrated that a thermally insulated aluminium plate, with a selective surface, could be maintained at 10–13 °C below ambient during a 24-h period. A group of workers at the Institute of Experimental Physics, Naples,[5,6] carried out a number of experimental and theoretical studies of selective radiation cooling, in particular using 'Tedlar' (a polyvinyl fluoride sheet made by Du Pont) as the selective surface. They concluded that, with suitable shading and thermal insulation, temperatures as much as 15 °C below ambient may be obtained in this way during daytime operation. Harrison and Walton[7] studied the cooling of surfaces painted white with titanium dioxide based paints and obtained reductions in temperature of 10–15 °C over the whole 24-h period of the day. They attribute this performance to the selective nature of the paint in the 8–13 μm region.

The accent in most of this work has been on the attainment of low temperatures. The surface has been well insulated from the surrounding environment and the final temperature reached has been determined by a thermal balance between the energy radiated to the sky, the energy absorbed by the surface from the sky and the relatively small heat gain from the surrounding environment.

One possible application for radiation cooling is the cooling of houses[8] in hot dry regions where ambient temperatures may be in excess of 30 °C. Under these conditions circulation of room air below a radiating surface at 20 °C may maintain the temperature within the building at an acceptable value of 25 °C. In this situation the final temperature of the radiating surface is determined essentially by a balance between the net loss of energy by radiation and the heat gain by the radiating surface from the air circulating beneath it. The higher operating temperature of the radiating surface will result in an increase in the cooling power attainable by this means.

This paper reports the results of some experiments aimed at establishing, first, the practicality of cooling a small building by radiation loss at night (or at least of providing a localised area of cooling within a building at night) and, secondly, whether there are, in this application, significant differences in the cooling produced by selective rather than black body radiators during the period between sunset and sunrise. Measurements were made in Melbourne, Australia, between February and April, 1978. The experimental buildings were approximately 40 m above sea level.

MECHANISM OF HEAT TRANSFER

The underlying principles of 'black body' and 'selective' radiation cooling may be better understood by considering Figs. 1 and 2. In Fig. 1 curve A represents the

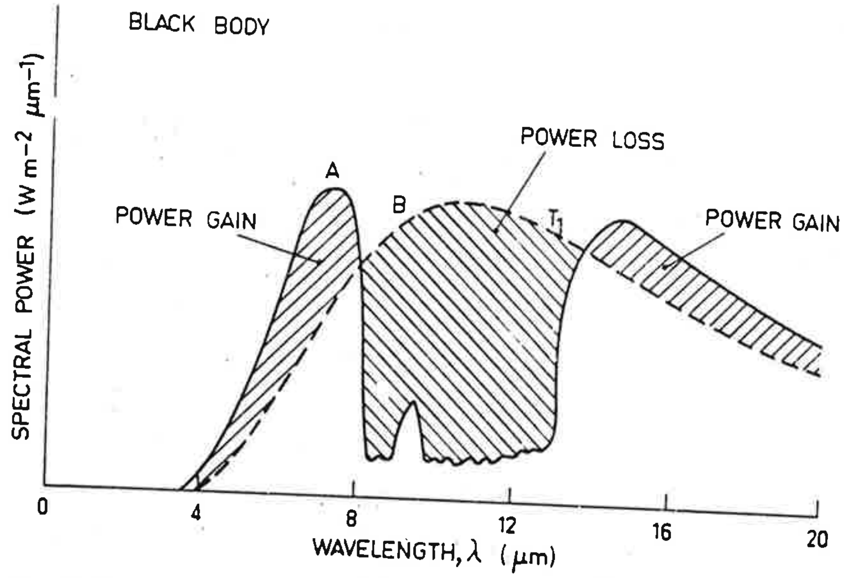

Fig. 1. Relative spectral distribution of radiation falling on the earth from a clear sky (Curve A) and of radiation emitted by a black body at temperature T_1 (Curve B).

power–wavelength distribution of the radiation incident on the surface from a clear sky[9] whereas curve B represents the power–wavelength relationship for the emission of a black body at temperature T_1. The shaded central region represents the net power loss by the surface whilst the shaded areas to the left and right of the central region represent net power gain. The surface will be cooled or heated depending on whether the power losses exceed the gains, or vice-versa, and as the temperature of the surface changes curve B will be modified so that the final equilibrium temperature of the surface is such that there is a balance between the rates of energy gained and lost. A black body exposed to a clear sky (at night time or with solar radiation excluded) may be cooled as much as 10–20 °C below the ambient

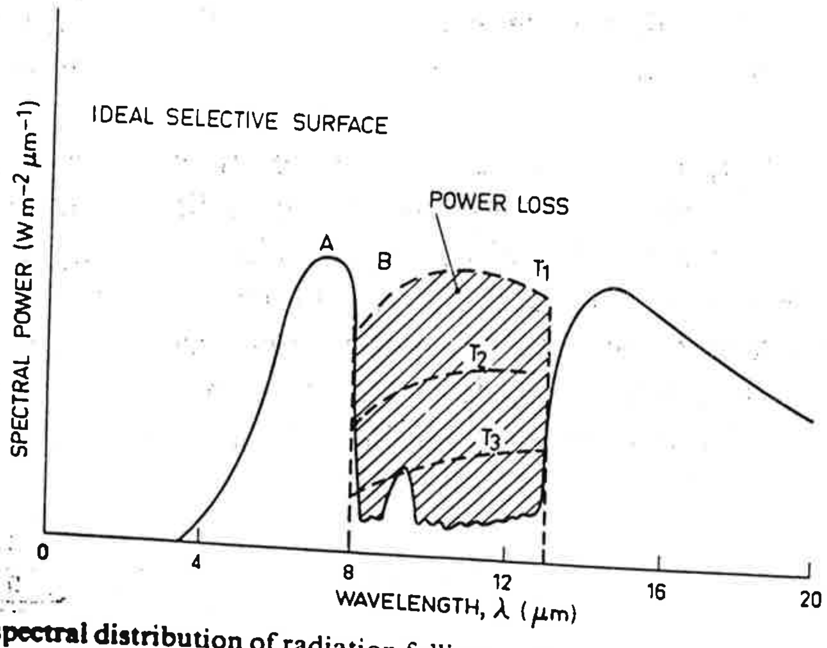

Fig. 2. Relative spectral distribution of radiation falling on the earth from a clear sky (Curve A) and of radiation emitted by an ideal selective surface at temperatures T_1, T_2 and T_3 (Curve B).

temperature. This phenomenon accounts for the formation of frost and local freezing of ponds on nights when the air temperature does not fall below 0 °C.

The situation for a selective surface is shown in Fig. 2. Curve A again represents the power–wavelength distribution of the radiation incident on the surface from a clear sky whereas curve B represents the characteristics of the selective surface. This selective surface consists of a highly reflective surface of polished aluminium on which has been deposited a thin layer of a suitable substance which absorbs and emits radiation only in the 8–13 μm wavelength band. When this composite surface is presented to a clear sky and shielded from solar radiation it emits energy in the 8–13 μm band but absorbs very little from sky radiation and the polished surface ensures that all wavelengths outside the 8–13 μm wavelength band are reflected. The shaded area in Fig. 2 represents the net power loss by the surface and this power loss will decrease as the temperature falls from T_1 to T_2 to T_3. Provided that the direct rays of the sun are shaded from the surface, cooling will be effective on days of clear sky for the full 24-h period of the day. When the sky is clouded, the cooling effect will be modified depending upon the extent of the cloud cover and the nature and height of the clouds. The minimum temperature attainable by a surface having these ideal characteristics is estimated to be less than -50 °C.

The cooling power of both black body and selective surfaces is a function of their temperature. For the selective surface, the loss of energy depends only on that radiated in the 8–13 μm wavelength band. For the black body at surface temperatures near ambient, there will be little gain or loss of energy outside the 8–13 μm region. Consequently, 'the black body' and 'ideally selective' surfaces will radiate at essentially the same rate. At surface temperatures higher than ambient, the black body radiator will emit more radiation than the selective surface since there is a loss of energy outside, as well as within, the 8–13 μm region whereas, for surface temperatures lower than ambient, the black body will radiate less energy than the selective surface due to the gain in energy by the former outside the 8–13 μm band.

EXPERIMENTAL

Two huts approximately 3 m square and 2·4 m in height were constructed, one roofed with galvanised steel decking and covered with white titanium dioxide based paint, the other with aluminium decking of the same profile (37 mm upstand at 200 mm centres) but treated to give it selective properties. A schematic drawing of a cross-section of the huts is shown in Fig. 3. The titanium dioxide based paint contained 17·5 per cent of pigment (TiO_2) volume concentration in a binder of long soya bean modified alkyd, corresponding to a concentration of 44·1 per cent by weight on the non-volatiles. The infra-red characteristics of a sample of roofing material painted with this material were determined using a Gier–Dunkle spectroradiometer and are shown in Fig. 4(a). This surface has a high value of reflectance to the solar spectrum and a high absorptance to wavelengths above 3 μm.

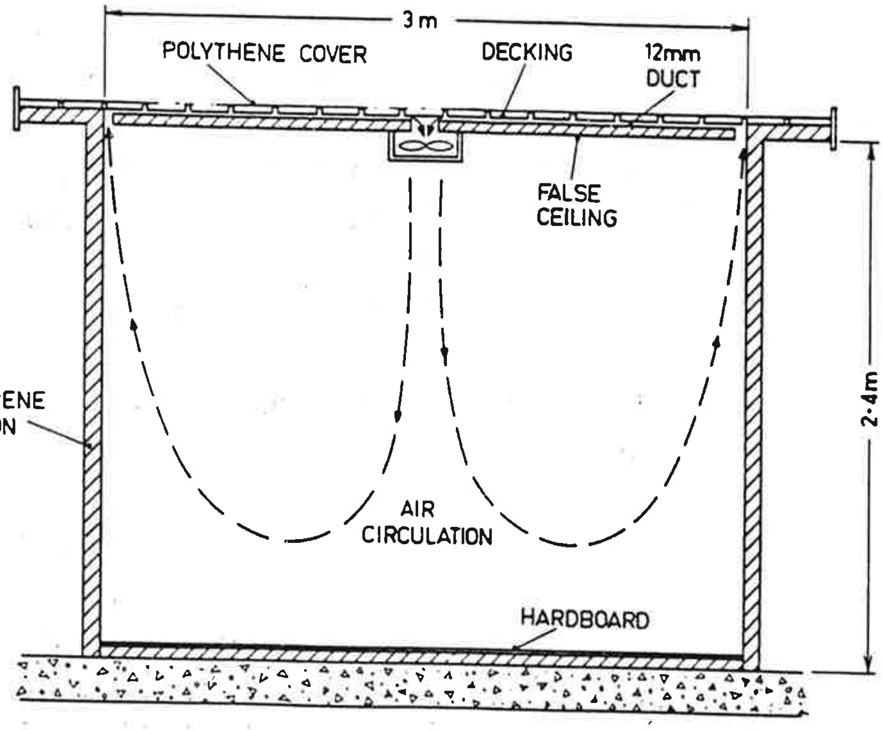

Fig. 3. Cross-section of experimental huts.

Thus, whilst being selective between short and long wavelength radiations, this surface behaves, in the infra-red regions relevant to radiation cooling, essentially as a non-selective surface approaching that of a black body. For nocturnal cooling, the low absorptance in the 1–3 μm region is relatively unimportant in the cooling process because only a small proportion of energy of the radiation involved lies in this wavelength band. For diurnal cooling the reflection of solar radiation is clearly advantageous. Thus, this painted roof should, during the daytime, reflect a high proportion of the solar radiation incident on it but during the night time act as a near black body.

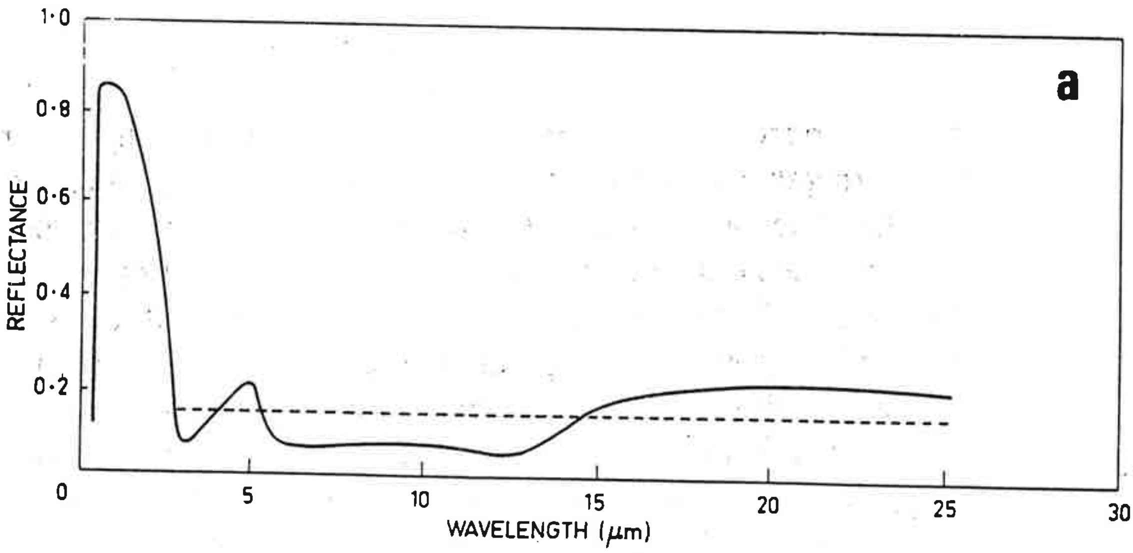

Fig. 4(a). Reflectance as a function of wavelength for TiO_2 based paint.

The roof of the other hut was given selective properties by gluing 12μm thick sheets of 'Tedlar', aluminised on one side, to the surface of the decking, with the 'Tedlar' surface uppermost. This aluminised sheeting emits and absorbs mainly in the 8–13 μm range but reflects radiation outside this band. The specular reflectance of this composite material was measured on a Beckman Model IR20 infra-red spectrophotometer with the aid of suitable attachments (Perkin Elmer type 0220-0063). The reflectance as a function of wavelength is shown in Fig. 4(b).

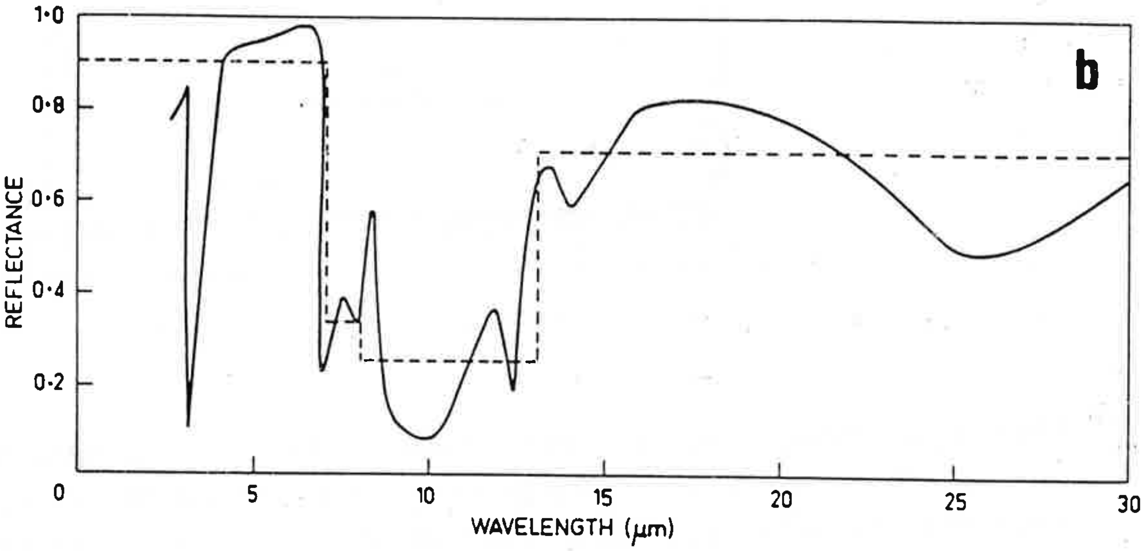

Fig. 4(b). Reflectance as a function of wavelength for aluminised Tedlar sheet (12 μm thickness).

The roof surfaces of both huts were covered by a sheet of polythene 50 μm thick separated by approximately 37 mm from the main surface of the decking. The walls were insulated with 75 mm of polystyrene insulation; the upper surface of the concrete slab on which the huts were erected was insulated with 50 mm of polystyrene and covered with 5 mm hardboard to provide a hard surface. The huts were fitted with false ceilings, of 50 mm of polystyrene, some 12 mm below the decking. Air, from the hut, was circulated by drawing it with a fan through openings provided in the ceiling near the outer edges of the hut, passing it through the narrow duct formed by the ceiling and the decking and discharging it into the centre of the room. The fans were automatically switched on at 1900 h each day and off at about 0700 h the following day to minimise heating within the huts during the day time.

The temperature of the air at some ten points within the huts was monitored, as well as the temperature of the air entering and leaving the ceiling ducts. Floor, ceiling and roof decking temperatures and the humidity within each hut were recorded. Externally, the air temperature, wind velocity and direction, and humidity were recorded. A net radiometer was used to determine the effective sky temperature. All parameters were recorded at hourly intervals over a period of approximately 100 days by means of a Digitrend Model 200 data logger.

RESULTS

The number of nights with clear skies of extended duration was limited during this period; nevertheless, on many nights roof-deck temperatures 5–6 °C below outdoor ambient were obtained for short periods. On some occasions the deck temperatures fell below 3 °C. Frequently, cooling was obtained for extended periods. Typical of the behaviour during these times are the results shown in Fig. 5 for the period 1630 h on 27 April to 1030 h on 28 April, 1978.

Cooling of the roof decking commenced around 1700 h and the temperature of the decking on both huts fell rapidly to some 8 °C below ambient. A pronounced change in the temperature of the decking and the air within the huts occurred when the circulating fans came into operation at approximately 1900 h. The temperature of the decking increased sharply by some 3–4 °C due to the increased thermal load and the air temperature within the huts fell steadily to some 4–6 °C below outside ambient and remained below ambient for some hours after the fans were turned off at 0700 h. The spatial variation in temperature within the major part of the hut was less than 0·5 °C. From the change in temperature of the air circulated through the ceiling ducts (0·7 °C), the measured flow rate of the air through the ducts (170 litres sec^{-1}) and the power dissipated by the fan motor (50 W), the useful cooling power of the roof with respect to the interior of the huts was determined to be 200 W, which represents a cooling power of about 22 W m^{-2}.

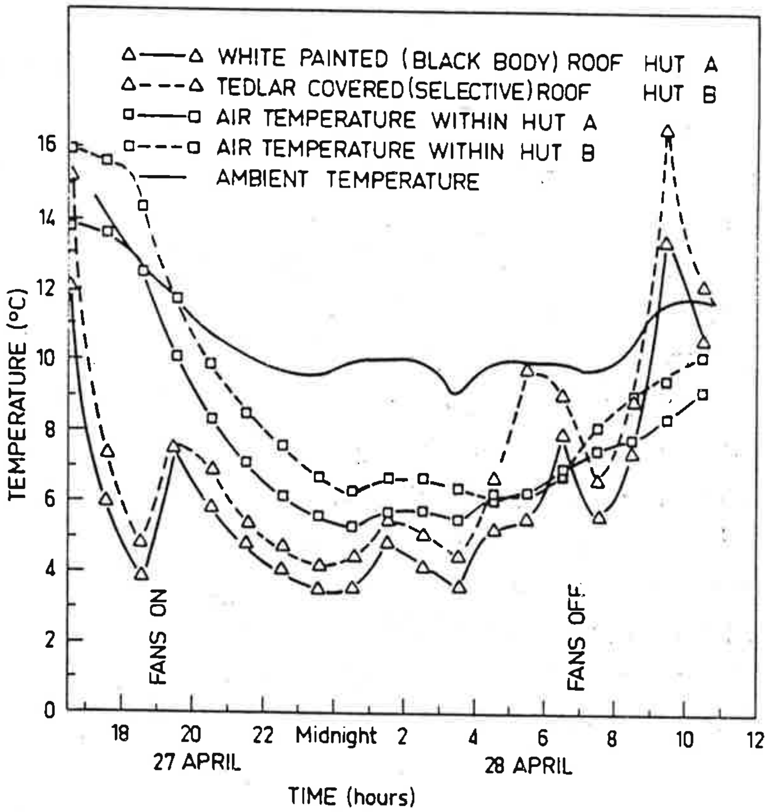

Fig. 5. Temperatures recorded during period 27–28 April, 1978.

The 'effective sky temperature' between 1800 h on 27 April and 0300 h on 28 April was between -4 and -6 °C.

The wind velocity recorded was less than $1{\cdot}5\ \mathrm{m\ sec^{-1}}$ up to 0500 h on 28 April but increased to $3\ \mathrm{m\ sec^{-1}}$ over the next 3 h.

The relative humidity rose from a value of 53 per cent at 1700 h to a maximum of 74 per cent at 0330 h and decreased to 62 per cent at 0730 h. The latter corresponds to an atmospheric moisture content of $6{\cdot}5\ \mathrm{g\ m^{-3}}$.

DISCUSSION

The results indicate that the reduction in temperature of the roof with the 'Tedlar' covered 'selective' surface is slightly, but significantly, less than that for the roof with the white painted, 'black body' surface. Since the huts are virtually identical in construction, it must be concluded that this temperature difference is due to additional radiation transfer from the roof with the 'black body' surface. This implies that the practical, selective surface used has radiation characteristics slightly inferior to those for the 'black body' surface at the temperatures of operation (4–6 °C).

To understand the present results it is necessary to consider the radiation exchanges between the clear sky and the roof surfaces.

Measurement of the radiation characteristics of the sky is complex and no precise data are available for the night in question. Sloan *et al.*[9] made measurements of sky radiation and their results suggest that outside the 8–13 μm wavelength band, the sky radiation characteristics approximate to those from a black body at about ambient temperature and that within the 8–13 μm band, on nights of low humidity and clear sky, there is little sky radiation. For the purpose of calculation it has been assumed here that the sky characteristics outside the 8–13 μm band are those of a black body at temperature T and that within the 8–13 μm band there is no radiation. Values of 10, 15, 20 and 30 °C have been selected for the black body temperature T.

An estimate of the relative transfer of energy by radiation between the sky and the various surfaces may be obtained from a consideration of the reflectivity, ρ, absorptivity, α, and emissivity ε of the respective surfaces and Planck's Law:[10]

$$e_{b\lambda} = \frac{2\pi h C_0^2}{\lambda^5[\exp(hC_0/\lambda k T) - 1]} \tag{1}$$

where $e_{b\lambda}$ is the energy emitted per unit area per unit time per unit wavelength interval at wavelength λ for a black body; T is the absolute temperature; h is Planck's constant; k is Boltzmann's constant; $2\pi hC_0^2$ and hC_0/k are the first and second radiation constants, C_1 and C_2, and have the values $C_1 = 3{\cdot}7405 \times 10^{-16}\ \mathrm{Wm^2}$ and $C_2 = 0{\cdot}0143879\ \mathrm{mK}$.

For a black body, $\varepsilon_\lambda = \alpha_\lambda = 1$ and the net rate of transfer of energy E_b is given by:

$$E_b = E_{\text{sky}} - E_{\text{black body}}$$

$$E_b = [\int_0^{y} e_{b\lambda s} \cdot \mathrm{d}\lambda + \int_{13}^{\infty} e_{b\lambda s} \cdot \mathrm{d}\lambda] - [\int_0^{\infty} e_{b\lambda b} \cdot \mathrm{d}\lambda] \tag{2}$$

where $e_{b\lambda s}$ represents the sky radiation at temperature T and $e_{b\lambda b}$ represents the radiation from a black body roof at temperature T_R.

For an ideally selective surface the energy transfer E_i is independent of the temperature of the sky characteristic assumed here, because $\rho = 1$ for all wavelengths outside the 8–13 μm band, and since energy transfer takes place only within this band, and there is no radiation in this band incident on the surface from the sky.

Thus

$$E_i = \int_8^{13} e_{b\lambda i} \cdot \mathrm{d}\lambda \tag{3}$$

where $e_{b\lambda i}$ represents the radiation from an ideal selective surface roof at a temperature T_R.

For the aluminised 'Tedlar' surface the energy transfer is more complex and the infra-red characteristic of the composite surface has been approximated by dividing it into a number of wavelength bands and assuming constant parameters for each band. This is indicated by the dotted lines in Fig. 4(b). The parameters adopted for the various bands were:

0—7 μm, $\rho_1 = 0{\cdot}9$, $\alpha_1 = \varepsilon_1 = 0{\cdot}1$
7—8 μm, $\rho_2 = 0{\cdot}35$, $\alpha_2 = \varepsilon_2 = 0{\cdot}65$
8—13 μm, $\rho_3 = 0{\cdot}25$, $\alpha_3 = \varepsilon_3 = 0{\cdot}75$
13—∞ μm, $\rho_4 = 0{\cdot}7$, $\alpha_4 = \varepsilon_4 = 0{\cdot}3$.

The net transfer of energy E_t is thus:

$$E_t = [\alpha_1 \int_0^7 e_{b\lambda s} \cdot \mathrm{d}\lambda + \alpha_2 \int_7^8 e_{b\lambda s} \cdot \mathrm{d}\lambda + \alpha_4 \int_{13}^{\infty} e_{b\lambda s} \cdot \mathrm{d}\lambda]$$
$$- [\varepsilon_1 \int_0^7 e_{b\lambda t} \cdot \mathrm{d}\lambda + \varepsilon_2 \int_7^8 e_{b\lambda t} \cdot \mathrm{d}\lambda + \varepsilon_3 \int_8^{13} e_{b\lambda t} \cdot \mathrm{d}\lambda + \varepsilon_4 \int_{13}^{\infty} e_{b\lambda t} \cdot \mathrm{d}\lambda] \tag{4}$$

where $e_{b\lambda t}$ represents the radiation from a composite Tedlar surface roof at temperature T_R.

Using these equations, calculations of the transfer of energy by radiation between 'black body', 'ideal selective' and aluminised 'Tedlar' surfaces and the sky have been made for a number of surface temperatures T_R and for sky simulation temperatures T of 10, 15, 20 and 30°C. These results are plotted in Fig. 6.

It is apparent from eqns. (1) and (3) that for a sky characteristic based on a black body at a temperature T, the black body radiator and ideally selective surface will have the same cooling power when the surface temperature is T. At surface temperatures higher than T, the black body will have a higher cooling power than the selective surface but for temperatures below T its cooling power will be lower than that for the selective surface.

From Fig. 6 it is evident that the cooling power of the 'Tedlar' surface is lower than

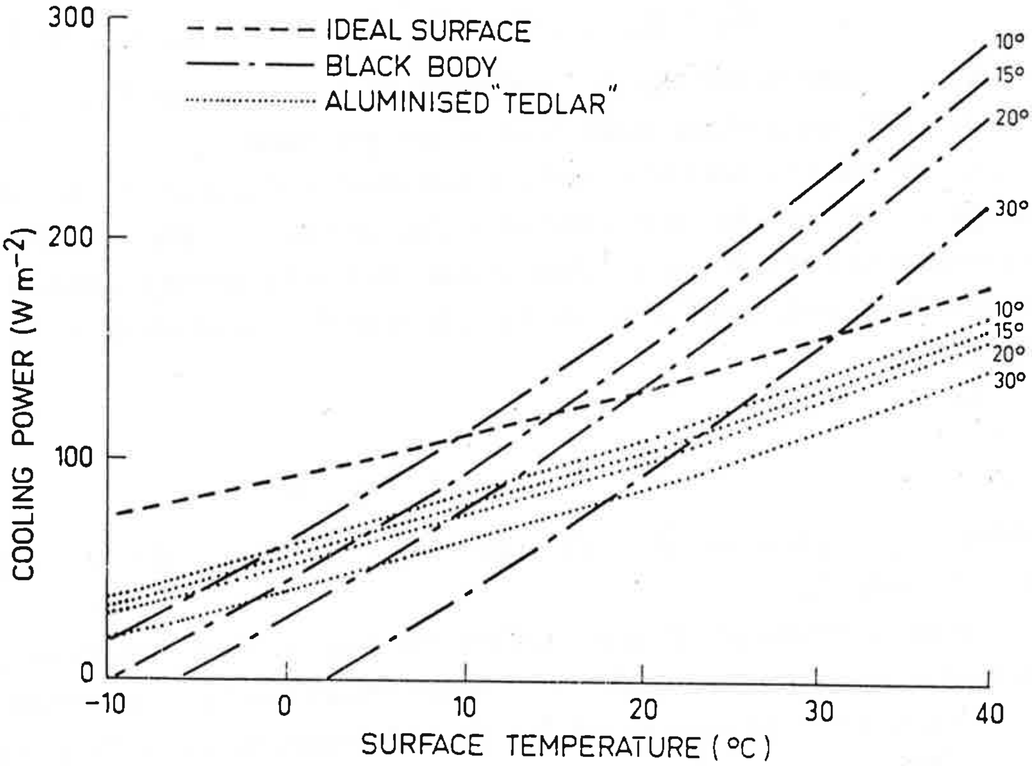

Fig. 6. Calculated values of cooling power of various surfaces as a function of surface temperature for simulated sky emission characteristics based on 'black body' emission at 10°, 15°, 20° and 30°C outside the 8–13 μm wave band and zero emission within the 8–13 μm wave band.

that for the ideally selective surface for surface temperatures in the range −10 to 40°C. The cooling power of this surface and that for a perfect black body only achieve equality for surface temperatures some 11°C lower than the assumed sky simulation temperature.

For the experiments of 27 April, the cooling power of the painted roof and the 'Tedlar' coated roof were similar when the surface temperatures were about 5°C. If the painted roof were a perfect black body this would imply a sky simulation temperature of about 16°C. It would be more realistic, however, to assume $\alpha = \varepsilon = 0{\cdot}85$, as in Fig. 4(a), for this painted surface, in which case a similar analysis leads to a value of 10°C for the sky simulation temperature. Since the ambient temperature at this time was 10–11°C such a value seems reasonable.

The simple model used for the representation of the sky radiation completely neglects the radiation in the 8–13 μm band. The radiation in this band is very dependent on the cloud cover and moisture content in the air and although, for the simple models considered here, this radiation will have relatively little effect on the surface temperature at which the crossover points of the respective cooling power–temperature curves occur, the radiation energy involved in this band may significantly reduce the net cooling. Since the model based on a 'simulated sky characteristic' and that utilising an 'effective sky temperature' derived from measurements of net radiation should yield the same cooling power for a given set of conditions, it is possible to arrive at a temperature for a black body radiating in this

8–13 μm band such that the energy radiated by the simulated sky is equal to that radiated by a black body at the effective sky temperature. Thus, for the conditions at 2400 h on 27 April, the sky radiation characteristics may be represented by a spectral distribution for a black body at 10 °C outside the 8–13 μm band and by another spectral distribution for a black body at about −40 °C within this band.

The cooling power of both painted and Tedlar surfaces, calculated in the manner of eqns. (2) and (4) but on the basis of this complete simulated sky characteristic, was about 40 W m^{-2} for a surface temperature of 5 °C. This value must be considered an upper limit since this simple treatment has assumed all radiation transfer to occur normal to the surface and has ignored the angular dependence of the emittance and absorptance of the roof surface. Furthermore, no allowance has been made for the effects of the polythene sheeting which covers the roof area. This sheeting will reduce the effective cooling by absorbing radiation from the sky and that emitted by the surface and, since its temperature will be close to that of ambient, it will itself radiate to the roof surface. The 50 μm sheet used in the experiments was the minimum thickness considered practical for an exposed roof and had a transmission (normal incidence) in the infra-red region of about 85 per cent.

The measured cooling power of 200 W within the huts, which represents a cooling power of 22 W m^{-2} of roof area, is consistent with the calculated heat gain for the huts at 2400 h assuming equilibrium conditions existed at that time. The total cooling power of the roof is greater than this value by the heat gain to the outside surface of the roof decking due to conduction from the surrounding structure and from the overlying ambient air through the 37 mm layer of air between the decking and the polythene cover. It is difficult to calculate these heat gains since the resistance to heat flow through such an air space depends on many factors including the air velocity above the polythene sheeting and within the air cavity as well as the emittance of the boundary surfaces of the cavity. A minimum value for this heat gain across the air gap may be obtained assuming still air conditions. The thermal resistance of a 37 mm air space, with one high-emittance and one low-emittance surface,[11] is of the order of 0·75 m^2 kW^{-1}. For a difference in temperature of 5 °C across this space the heat gain to the roof would be 7 W m^{-2}. Thus 29 W m^{-2} represents a minimum value for the total cooling power of the roof deck at 5 °C compared with an upper limit of some 40 W m^{-2} as discussed above.

The geographical location of the huts and the weather pattern experienced during the course of these experiments led to the best cooling conditions occurring when the ambient temperature was 10–12 °C and resulted in a room temperature of some 5–6 °C. In locations where cooling is required, the ambient temperature is often 30 °C and above, and under these conditions a room temperature of 25 °C would be quite acceptable. For these situations the thermal coupling between the room and the roof area should be such that the temperature of the roof deck does not fall below 20 °C. Under these circumstances, assuming a sky characteristic based on a simulated sky temperature of 30 °C, there could be an increase of up to 25 per cent in

the cooling power of the roof over the values obtained here (Fig. 6). There would again be no significant advantage in using an aluminised Tedlar surface rather than a painted one. The thermal loading on the roof must be arranged so that the increased temperature differential between ambient and roof is maintained.

The reduction in surface temperature in these experiments (4–5 °C) was relatively low compared with the values obtained by previous workers but this is due mainly to the thermal coupling between the surface and the huts instead of the thermal isolation of the surface as in the former experiments.

Harrison and Walton[7] infer that the white painted surface used in their experiments behaves as a selective surface utilising the 8–13 μm window; however, the present experiments suggest that their painted surface would behave as a black body in the infra-red region relevant to radiation cooling. The substantial reduction in temperature achieved in their experiments is due not only to the thermal isolation of their surface but also to the relatively low moisture content (range 2·2–4·1 g m^{-3}) in the atmosphere at the higher elevation of their site (1·1 km) as compared with the 6·5 g m^{-3} which occurred during the present experiments at essentially sea level.

CONCLUSIONS

This work refers specifically to the cooling of buildings *at night*.

The useful cooling power achieved was 22 W m^{-2} at a radiating surface temperature of 5 °C although the gross cooling power probably exceeded 29 W m^{-2}. The upper limit for the cooling power was calculated to be 40 W m^{-2} under these conditions.

At a roof temperature of 5 °C and an ambient temperature of 10 °C there was no advantage in using the selective surface of aluminised 'Tedlar' rather than the painted roof. In regions where cooling would be required the surface temperature of the roof is more likely to be 20 °C and under these conditions for an ambient temperature of 30 °C there would again be no significant advantage in using the aluminised 'Tedlar' surface rather than the painted one.

Calculations based on a simple simulation of the sky radiation suggest that an ideally selective surface operating under the best possible clear-sky conditions has little advantage over a black body radiator unless operating at surface temperatures significantly (more than 5 °C) lower than the ambient air temperature.

These experiments establish that it is feasible to cool a stream of air within a room by thermal transfer between the air and a surface which is radiating to a clear sky. Although the cooling power is low it appears reasonable to produce a localised region of thermal comfort by this method in an otherwise thermally uncomfortable situation.

ACKNOWLEDGEMENTS

The authors are indebted to Solarhot Water Systems of Sydney, Australia, who

generously supplied the aluminised 'Tedlar' for these experiments and to Mr Eric Christie of the Division of Mechanical Engineering, CSIRO, who undertook the measurements of the radiation properties of the painted surface.

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