Optimal Characteristics of an Adaptive Windshield for a Solar Collector and Radiative Cooling Combined System

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Abstract

Radiative cooling is a promising technology for space cooling which can be combined with solar heating applications, enabling the production of both energy demands –heat during daytime and cold during nighttime– in a single device; reducing the non-renewable primary energy consumption for space conditioning and domestic hot water. An adaptive cover allows a mode switch, enabling heat or cold production, by combining materials with suitable optical properties for each mode. Another effect derived from the usage of covers is the reduction of convective heat losses, enhancing the performance of the device. Glass covers have been used in solar heating applications; polyethylene has been widely proposed in radiative cooling applications while zinc-based compounds are transparent enough to solar and infrared radiation in the atmospheric window to be used in RCE applications. Smart materials show tunability of properties of radiative surfaces but upon this time, they have not been used as covers neither in radiative cooling applications, nor in combined radiative cooling and solar heating applications.

Keywords: Radiative cooling, solar thermal collection, renewable energy, adaptive cover, convection reduction

1. Introduction

Radiative cooling is a process by which a surface reduces its temperature by emitting thermal radiation towards the outer space, taking advantage of the infrared atmospheric window transparency in the 7-14 µm range (Vall and Castell, 2017). Under clear sky conditions radiation to the outer space is maximized. Radiative coolers can be combined with solar heating applications, thus enabling the combined production of both energy demands – heat during daytime and cold in nighttime– in a single device (Vall et al., 2018). The authors named this device *Radiative Collector and Emitter* (RCE). For the sake of simplicity, this paper also refers to it as RCE.

RCE is presented as a green alternative which may reduce the dependence to non-renewable energy consumption for space conditioning and domestic hot water obtention.

One of the main drawbacks of radiative coolers is the low cooling rates they operate in: between 20-80 W/m^2 on average, with peak values of 120 W/m^2 (Vall et al., 2018). Ambient conditions and optical properties of materials play a role to determine the total performance of these devices. In the last years new metamaterials and photonic crystals have been developed with optimum selective emissivity/absorptance. They have been used as a proof-of-concept of radiative coolers' emitting surfaces (Ko et al., 2018) which allow daytime radiative cooling. These materials present a repeated structure of a size smaller than light; when the wavelengths interact with this structure the material shows properties which cannot be found in nature. However, as these selective surfaces reflect solar radiation, they are not suitable for heating production during the day.

Net cooling is also influenced by conduction and convection heat energy gains. In order to achieve higher cooling rates, the use of convective barriers has been proposed, enabling to cool surfaces below ambient temperature. In solar heating applications, glass has been used as a cover which enables the greenhouse effect of the solar collector and reduces convective heat exchanges. To combine solar heating and radiative cooling functionalities in a single device, an adaptive cover needs to be developed. This cover needs to be transparent to solar radiation and opaque to long-wave radiation during collection mode, and transparent to long-wave radiation during radiative cooling mode. This cover, also named windshield, has to withstand the exposition to climatological conditions: wind, tearing, rain-water (Gentle et al., 2013), snow, degradation due to UV exposition and also the presence of animals (birds and insects) which can damage the structure.

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This field has not been investigated as deeply as the emitting surfaces. In this work the advantages and limitations of a cover for RCE systems will be analyzed, and a literature search of similar existing solutions and materials offering the suitable optical properties in the two modes of operation will be presented and discussed.

2. Cover materials

2.1. Smart Materials

Smart materials are the most appealing solution for the fabrication of an adaptive RCE cover, as the double functionality can be achieved using only one material, which can modify their optical properties in response to external stimuli. These smart materials must show high transmittance in the solar wavelengths and low transmittance in the atmospheric window during the solar collection mode while, during the radiative cooling mode, the transmittance in the atmospheric window should be high.

The use of smart materials on emitting surfaces has been studied in RC applications. According to Kort-Kamp's models, vanadium dioxide (VO_2) (a thermochromic material) arranged in a photonic structure could achieve a reduction of surface temperature. Compared to ambient temperature, it was a 6°C reduction of the surface temperature under ~ 100 W/m^2 cooling rates. Based on a H_2SO_4-doped polyaniline films device, Xu et al. (Xu et al., 2020) achieved changes of emissivity of 0.4 in the 8-14 µm range -atmospheric window- allowing radiative cooling under low voltage.

Confining emitting infrared gases in the air gap between the emitting/absorbing surface and the infrared-transparent convective cover, selective radiative cooling can be achieved. Spectrometry techniques found that ethylene, ethyl oxide and ammonia (Hjortsberg and Granqvist, 1981; Lushiku et al., 1984; Lushiku and Granqvist, 1982) are three gases which - in the presence of low humidity - show high emissivity in the atmospheric window wavelengths (8-14 µm). In an experiment with ethylene gas, under daytime conditions, authors measured a drop of 10ºC with respect to the environment (Hjortsberg and Granqvist, 1981).

2.2. Polymeric covers

Polymers have been the most widely used materials in the manufacture of covers in radiative cooling applications. Optimal polymers in these applications must have a high transmittance in the infrared range, thus allowing the passage of infrared thermal radiation, while separating the emitting surface from the outside and diminishing unfavorable convection exchanges.

According to Tsilingiris (Tsilingiris, 2003), who studied the applicability of ten different polymers in radiative thermal applications, the most suitable polymers were polypropylene and polyethylene as they had a higher transmittance in the infrared range; while fiberglass, kapton and mylar showed the lowest transmittance coefficients not being suitable in radiative cooling applications.

Both for its high availability, cost, and for its optical properties, polyethylene has been the most widely used material in the manufacture of covers. In thin foils, these polymers exhibit an almost ideal transparency (Bartoli et al., 1977). In recent times several authors have used this polymer as a windscreen in both nocturnal radiative cooling and daytime radiative cooling applications (Fu et al., 2019; Xu et al., 2018). As an example, Zhao et al. (Zhao et al., 2019) circulated water under a metamaterial emitting surface covered with a polyethylene windshield, achieving a temperature difference of 10 °C between water and the environment. Polyethylene in the form of an aerogel has also been studied. This material had a high transmissivity in the infrared but a high reflectance in the solar range, making it not optimal in combined applications of RCE (Leroy et al., 2019).

Polyethylene has also been used in combined solar heating and radiative cooling applications (Hu et al., 2018; Long et al., 2019). Matsuta et al. (Matsuta et al., 1987) achieved maximum values of 610 W/m^2 in collection mode and 51 W/m^2 in radiative mode. Without the effect of a glass cover, the efficiency of the solar collection - with circulating water in pipes - decreases to 26.8 - 40.7% when combined with radiative cooling (Hu et al., 2019). Vall et al. (Vall et al., 2018, 2020) proposed a double mobile cover, called adaptive cover, of glass and polyethylene: during the collection mode both materials act as cover while during the radiative cooling mode only polyethylene is present. This configuration presented a main drawback as this sliding mechanism occupies two times the surface of the emitter. Another configuration was proposed using polyethylene film covering a porous cooling material with near-unity infrared emissivity in the 8-14μm range achieving radiative cooling on one side of the device. The other side is configured to achieve solar heating; switching of modes was done with a rotating shaft (Liu et al., 2020).

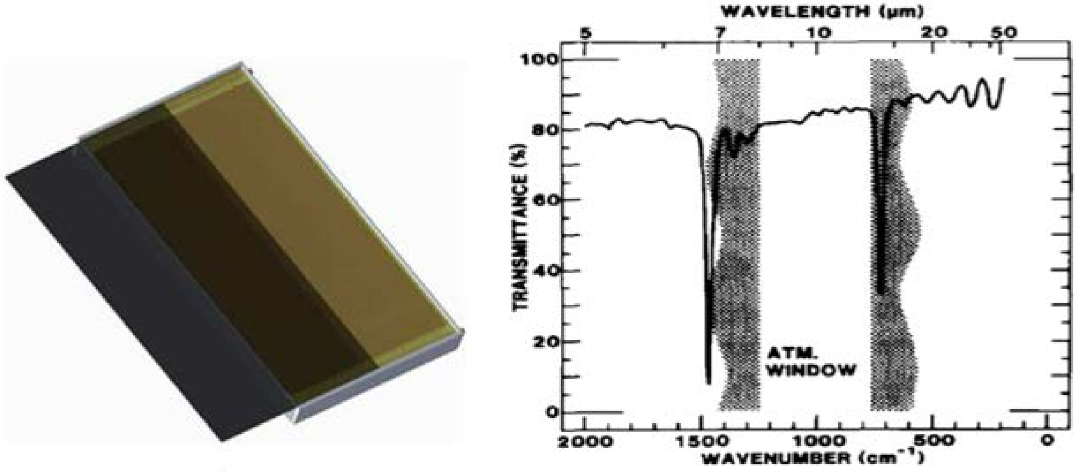

Fig 1. (Left) Sliding adaptive cover: during daytime solar collection the glass cover slides to the top of the absorbing surface and slides off the surface during nightime radiative cooling mode *(Vall et al., 2018)*. **(Right)** Transmittance of 30 μm thick polyethylene's foil *(Nilsson et al., 1985)*.

Other polymers studied were 0.0127 mm thick films of fluorinated ethylene propylene (better known for its commercial name Teflon) (Johnson, 1975), which offered an infrared transmittance of 0.7, and polyester (Orel et al., 1993). Table 1 summarizes the transmittances of these polymeric covers.

Tab.1. Polymeric covers' transmittances

Cover material	Reference	Thickness	τ_{atm}	τ_{sol}	Commentary
Teflon	(Johnson, 1975)	127 μm	~ 0.7	-	-
PE	(Raman et al., 2014)	12.5 μm	-	-	-
PE	(Hu et al., 2015, 2016a, 2018)	20 μm	0.83	0.85	-
PE	(Hu et al., 2016b)	6 μm	0.87	0.89	-
PE	(Hu et al., 2020, 2019)	6 μm	0.87	0.89	-
PE	(Zhao et al., 2019)	-	High	High	-
PE	(Ao et al., 2019)	20 μm	-	-	-
PE	(Liu et al., 2019)	-	-	-	-
PE	(Matsuta et al., 1987b)	30 μm	0.86	0.85	-
PE	(Tsilingiris, 2003)	130 μm	0.79	-	-
PE	(Tsilingiris, 2003)	50 μm	0.88	0.87	-
PE	(Xu et al., 2018)	-	-	-	-
PE	(Fu et al., 2019)	50 μm	-	-	-
PE	(Al-Nimr et al., 1998)	40 μm	High	-	-
PE	(Ali et al., 1998)	50 μm	0.72 0.69 0.57 0.42	-	New film 5 days exposition 30 days exposition 100 days exposition
PE	(Hamza H. Ali et al., 1995)	50 μm	0.74**¡Error! Marca**	-	-

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PE	(Nwaji et al., 2020)	1 µm	0.92	-	-
PE	(Gentle et al., 2013)	Ø150 µm	0.872	-	Fibermesh cover
PE	(Nilsson et al., 1985)	30 µm	0.85	-	-
PE	(Bhatia et al., 2018)	-	0.92	<0.45	-
PE aerogel	(Leroy et al., 2019)	6 mm	0.80	0.11	-
Polyester	(Orel et al., 1993)	50 µm	High	-	-
Polycarbonate	(Tsilingiris, 2003)	1.22 mm	0.06	-	-
Kapton	(Tsilingiris, 2003)	130 µm	0.08	-	-
Mylar	(Tsilingiris, 2003)	130 µm	0.05	-	-
PP	(Tsilingiris, 2003)	130 µm	0.50	-	-
Plexiglass	(Tsilingiris, 2003)	1.52 mm	0.01	-	-
Vinyl	(Tsilingiris, 2003)	125 µm	0.21	-	-
Fiberglass	(Tsilingiris, 2003)	960 µm	0.04	-	-

Polymeric covers have mechanical drawbacks when used as long-lasting covers. These covers are exposed to inclement weather conditions as well as the presence of animals that may end up affecting the structure of this element. Increasing the thickness to deal with this problem does not turn out to be an efficient solution. Ali et al. (Ali et al., 1998; Hamza H. Ali et al., 1995) studied that the increase in thickness has a negative effect on the transmittance of polyethylene and as a consequence, on the overall performance of radiative cooling: when it increased from 25 µm to 50 µm, the performance worsened by 8.6%.

New polymeric structures were also investigated. Nilsson et al (Nilsson et al., 1985) proposed a V-shapped arrangement of three layers of corrugated polyethylene. They obtained an infrared transmissivity close to film configurations but its thicker structure could provide – although it has not been studied - a higher structural rigidity. Gentle et al. (Gentle et al., 2013), for their part, proposed a polymer mesh made of PE fibers of 150 µm diameter that would provide a transparency of 87% and an expected lifespan of 5 years.

Aging due to continuous exposure to outdoors' condition also has a negative effect on the transmittance of polyethylene. Under the climatic conditions of Assiut (Egypt), a 50 µm polyethylene film dropped its transmittance from 0.72 to 0.42 after 100 days of outdoor exposure; the radiative cooling performance decreased by 33.3% (Ali et al., 1998).

2.3. Non-polymeric covers

Zinc crystals are presented as a possible alternative to polymeric coatings. For the purpose of designing a durable convective cover for radiative cooling applications, Bosi et al. (Bosi et al., 2014) identified ZnS crystals as a promising material which, with a thickness of 4 mm, had a transmittance in the atmospheric window of 0.64.

The infrared transmittances of ZnS crystals, as well as ZnTe and ZnSe, lie between 0.66 and 0.77 and in the solar range, transmittances fall between 0.61-0.66 (Laatioui et al., 2018). They can be thought of as transparent enough to be used in combined solar heating and radiative cooling (RCE) applications. These materials were also used in radiative cooling daytime applications: Chen et al. (Chen et al., 2016) achieved a record decrease of 42ºC below ambient of the surface temperature with a complex system consisting on a highly selective emitter covered with a ZnSe cover to minimize solar radiation and supported by a vacuum chamber which minimizes parasitic conductive and convective losses.

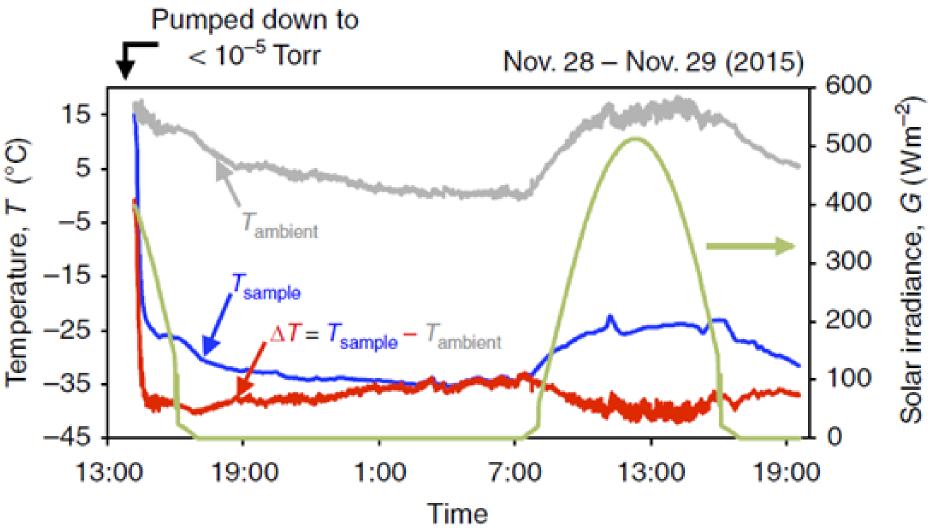

Fig 2. A large temperature reduction below ambient was achieved through radiative cooling in a 24-h day–night cycle in a device which combined a selective emitter, a zinc crystal cover and a vacuum chamber *(Chen et al., 2016).*

The disadvantage of zinc crystals is their high cost. To our knowledge, these crystals are used in commercial applications for thermographic cameras. These crystals are sold in small sizes buttons (Ø 5cm) and their cost is around 500€. Table 2 summarizes the optical properties of zinc-based covers.

Tab. 2. Optical properties of zinc crystal covers

Cover material	Reference	Thickness	τ_{atm}	τ_{sol}	ρ_{atm}	ρ_{sol}	α_{atm}	α_{sol}
ZnS	(Bosi et al., 2014)	4 mm	0.64	-	-	-	-	-
ZnS	(Bathgate and Bosi, 2011)	4 mm	0.64	-	-	-	-	-
ZnS	(Laatioui et al., 2018)	1 mm	0.77	0.66	0.12	0.21	0.11	0.13
ZnSe	(Bathgate and Bosi, 2011)	7.1 mm	0.7	-	-	-	-	-
ZnSe	(Chen et al., 2016)	-	0.87	-	-	-	-	-
ZnSe	(Laatioui et al., 2018)	1 mm	0.71	0.65	0.17	0.20	0.12	0.15
ZnTe	(Laatioui et al., 2018)	1 mm	0.66	0.61	0.21	0.22	0.13	0.17

Cadmium-based films (CdS and CdTe) are another possibility for radiative cooling applications as they presented an average transmittance between 0.61 and 0.8 in the range of the atmospheric window. These materials, however, had a low transmittance and a high absorbance in the solar range. At first glance it seems to be an unsuitable material for RCE applications but RCE designs can be thought of in which the cadmium film acts as an absorber during the solar capture mode and as a convective screen during the radiative cooling mode.

3. Discussion

The most attractive solution are smart materials with the ability to switch their optical properties as a result of external stimuli (temperature, electricity or gas presence) and, although they have been used as radiative surfaces in radiative cooling researches, in the literature it has not been found yet any use in the construction of convection covers for combined radiative cooling and solar heating.

To date, there is no proof-of-concept of non-polymeric coatings in RCE applications. However, as we have seen, the optical characteristics seem to indicate that the presented non-polymeric materials could become possible materials in RCE applications. Same as happened with polymeric covers, in order to obtain better performances in the solar collection mode, these should be combined with glass covers.

Current existing solutions involve the use of materials transparent to radiation in the solar band and in the atmospheric window, which reduces the performance during solar collection. The other proposed solution is the combination of these materials with glass screens during the solar collection mode. This solution, however, implies more complex RCE designs with greater space availability requirements.

Among the transparent materials for both solar and infrared radiation in the atmospheric window are polymers, with polyethylene as the most used material in radiative cooling, and zinc-based crystals, which have better mechanical properties than polymers at the expense of worse optical properties and a higher cost.

4. Conclusions

In this paper we have presented the optical properties that a convective cover (or windshields) must have in order to achieve the best performance of a combined diurnal solar collector and nocturnal radiative cooler (RCE).

After reviewing the existing literature, it can be pointed that much of the effort has been put on developing surfaces that maximize the absorbed or emitted radiation, whereas little research has been conducted on new covers that minimize convective exchanges. So far there is no definitive material for this type of covers. This results points towards a new line of research in the field of radiative cooling.

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