IJE TRANSACTIONS A: Basics Vol. 30, No. 10, (October 2017) 1573-1582

International Journal of Engineering

Journal Homepage: www.ije.ir

Investigation of Radiative Cooling Using a Photonic Composite Material for Water Harvesting

S. T. G. Krishna Teja[a], C. P. Karthikeyan[b], M. B. Shyam Kumar*[a]

[a] *School of Mechanical and Building Sciences, VIT University, Chennai, India*
[b] *School of Engineering Technology, Jain University, Bangalore, India*

PAPER INFO

Paper history:
Received 26 April 2017
Received in revised form 06 August 2017
Accepted 28 August 2017

Keywords:
Radiative cooling
Computational Fluid Dynamics
Photonic Material
Pigmented Foil
UV- Visible
Fourier Transform Infrared

ABSTRACT

The objective of this study is to design and analyse materials which are capable of harvesting water from thin air using condensation phenomenon which employs the radiative cooling approach. These passive cooling materials not only solve the water generating problems, but also employed in various cooling applications. The fundamental concept of radiative cooling is analysed and the performance parameters were identified to test the passive cooling ability of the designed material for water harvesting. The field of Photonics is studied which has the potential to obtain the surface temperature significantly lower than the atmospheric temperature by radiation phenomenon. Important parameters are identified to validate the performance of the proposed materials. ANSYS FLUENT is used to analyse the surface temperature for the given boundary conditions and the potential material which is capable of obtaining a significant temperature difference with respect to the ambient temperature is identified. A sandwich material is designed and its performance is evaluated using Computational Fluid Dynamics (CFD) by which we could achieve temperature difference of 15°C. To reduce the heat gain losses by conduction and convection, we designed a physical system which could maintain significant temperature difference even in the broad day-sunlight. CFD analysis of the designed system under similar boundary conditions gave satisfying results of maintaining the temperature difference of about 15°C for a prolonged period of time due to minimal heat gain losses. Later, two potential materials are manufactured and the performance parameters of these materials are characterized using U-V/Vis (Ultraviolet-Visible) and FTIR (Fourier Transform Infrared) Spectroscopy experiments. The results of absorption phenomenon in the U-V/Vis spectrum and the transmittance phenomenon in the FTIR spectrum of the two materials explain the reason for the passive cooling ability of materials.

***doi**: 10.5829/ije.2017.30.10a.19*

1. INTRODUCTION

Water is the most essential element to life on earth. More than 1.2 billion people lack access to clean drinking water. Since the past two decades, extensive research is dedicated to find ways of generating water to cope with the rising demand. The primary science of harvesting water from water vapor is by condensation. Better understating of this phenomenon can give us the ability to create a system which can harvest fresh drinking water out of air. Literature in this field of study has given importance to passive water generation methodologies to increase the portability of the system. Water in the atmosphere can be harnessed on a surface if, the surface temperature can be lowered to dew point temperature. At dew point, the water vapor in the atmosphere will change its phase to water, which can be collected and used for clean water applications. Dew point temperature is a function of relative humidity and the air temperature. Hence, the dew point temperature varies from place to place. The water yield rate from the atmosphere strongly depends upon cooling power of the material surface on which condensation takes place and also on the area of the surface. This study deals with two type of radiators: a) Photonic radiator and b) Pigmented foil radiator.

*Corresponding Author's Email: shyamkumar.mb@vit.ac.in (M. B. Shyam Kumar)

Please cite this article as: S. T. G. Krishna Teja, C. P. Karthikeyan, M. B. Shyam Kumar, Investigation of Radiative Cooling Using a Photonic Composite Material for Water Harvesting, International Journal of Engineering (IJE), TRANSACTIONS A: Basics Vol. 30, No. 10, (October 2017) 1573-1582

CFD is used as a validation tool to estimate the performance characteristics of the designed photonic radiator material.

2. RADIATIVE COOLING

Radiative cooling will be a guaranteeing technique with its capability to offer a cooling power of more than 100 W/m^2 for optimized gadget that are suitable for different applications [1, 2]. Research about the significance of this approach and its possibilities dates back to late 1990's in the context of passive cooling of buildings [3-5]. The initial research mostly focused on enchancing the selective emitting properties of the material for enchanced radiative cooling. This include painting the surface with TiO_2 [4] and using transparent wind shields [5]. The utilization from claiming hefty (bulk) materials including innate infrared (IR) discharges for significant radiative cooling were examined [6-8]. Although few sun oriented reflecting materials were reported, daytime cooling beneath the encompassing temperature have not been still attained.

$$P_{net}=P_{radiative}-P_{atmospherc\ radiation}-P_{non\text{-}radiative}-P_{sun} \quad (1)$$

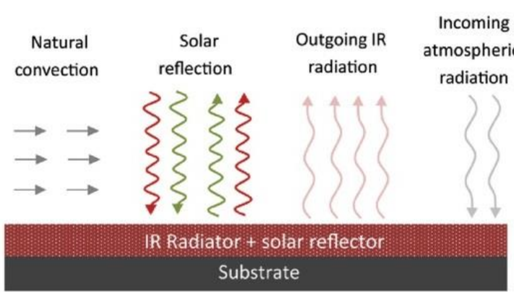
where, P_{net} = Net cooling power of the system $P_{radiative}$ = Radiative power emitted by radiation $P_{atmospheric\ radiation}$ = Incident atmospheric radiation

$P_{non\text{-}radiative}$ = Non radiative heat gain

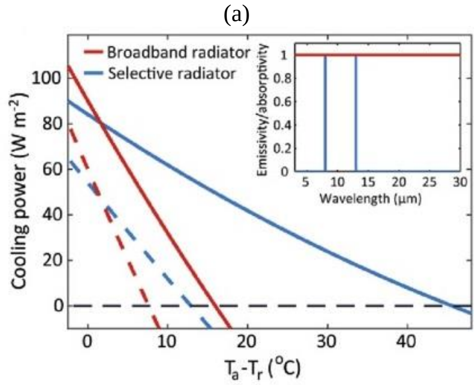
P_{sun} = Absorbed solar power by radiator

Equation (1) relates to the net cooling power P_{net} of the surface, that is the net power outflow of the surface, as a function of its temperature. A surface turns into a daytime cooling gadget if, there is a net positive power outflow when T = $T_{ambient}$ under daylight. It represents the amount of warmth it transmits into outer space than it picks up by retaining daylight and the environmental warm radiation. The objective of the present study is to demonstrate a daytime radiative cooling device with $T_{surface} < T_{ambient}$ and to measure its cooling power as a function of T (temperature) under direct sunlight. To achieve daytime radiative cooling, that is to achieve highest net cooling power P_{net} the device must satisfy the constraints as dictated by the power balance equation (1). First, it should effectively reflect sunlight strongly to minimize P_{sun}. Therefore, it must be strongly reflecting over the visible and near-infrared wavelength ranges. Second, it should strongly emit thermal radiation $P_{radiative}$ from its surface, while minimizing the incident atmospheric radiation $P_{atmospheric\ radiation}$, at wavelengths where the atmosphere is opaque. The earth's atmosphere is transparent in the wavelength window of 8-13 µm and so radiation emitted in this wavelength is directly dumped into the outer space. Thus, the device must selectively and strongly emit radiation only between 8 µm and 13 µm, where the atmosphere is transparent, and reflect at all other wavelengths.

2. 1. Broadband and Selective Radiators Based on spectral emissivity profiles of the radiator materials, they are classified into two types, the first one is a broadband radiator which has emissivity similar to a blackbody within the entire emission band of the atmosphere. The second one is a selective radiator showing emissions only within the wavelengths of 8–13 µm. Figure 1a refers to the theoretical substrate properties for passive cooling. Figure 1b shows the relation between the cooling power and the temperature difference of both broadband and selective radiators. Figure 2 depicts the ability of the selective radiator for cooling below the ambient temperature and thus is vastly superior to that of a broadband radiator. A broadband radiator on the other hand emits thermal radiation more than the incoming atmospheric radiation (outside the 8–13 μm window) and thus has a low net cooling power. However, it may not be able to provide with a cooling temperature well below the ambient temperature that is a high value of $T_{ambient}$ -$T_{radiative}$, in practice. An ideal emitter thus should selectively and strongly emit within the entire 8–13 μm wavelength range.



(a)



(b)

Figure 1. a) Theoretical model of the radiative cooling material which clarifies fundamental parts required for radiative cooling. b) Performance of broadband and selective radiators, inset refers to ideal radiators [2]

This has important consequences. The emitter should selectively emit radiation in the transparent window and doest not absorb radiation outside the transparent window (8–13 μm), where the atmosphere is highly emissive. This characteristic of the radiator is important because the impact of this becomes highly important to achieve cooling significantly below the ambient temperature. In addition, a strong emission within the 8–13 μm window ensures a high emitted power to overcome the non-radiative and solar heat contributions to reach a steady state temperature significantly below the ambient temperature.

Recently, radiative cooling using photonic material approach has been successfully demonstrated by Raman et al. [1] in the context of passive cooling of buildings.

The photonic approach has significant upper edge in overcoming the limitations mentioned in the early literature and claimed to be the efficient alternative. The photonic radiative material has very high emission spectrum in 8–13 μm wavelength range and very low absorption spectrum in the solar spectrum range as shown in the Figures 2a and 2b. This is the primary characteristic for the radiative material to maintain a high degree of temperature difference with the surrounding ambient temperature.

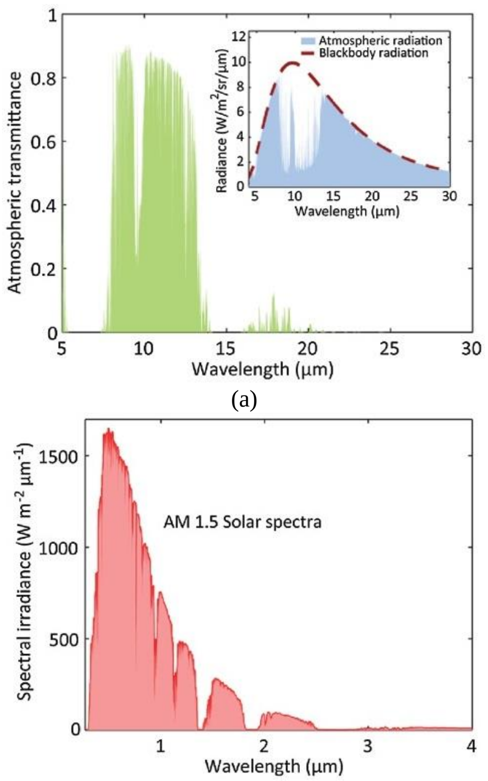


Figure 2. a) Displayed environmental transmittance with the descending atmospheric radiation in the inset. b) A reference AM 1.5 sun based irradiance spectra [2]

2. 2. Pigmented Radiative Foils Dew gathering need those possibilities to serve likewise renewable complementary source of portable water for arid or isolated areas. Exact examinations of high return radiative materials with hydrophilic properties for drop recuperation and adjusted gathering design have been performed in the most recent decade [9-11]. Nilsson et al. [12-14] proposed one such material consisting of a white low thickness polyethylene film incorporating miniaturized scale particles with high infrared emissivity. The film is then placed on a thermally insulated material, which enable it to cool below the air dew point temperature through radiative losses. Plastic foils holding non-absorbing pigments can show a high reflectance of solar radiation combined with a high transmittance in the atmospheric window region in the thermal infrared spectrum. Such foils can be applied as blankets empowering radiative cooling for an underlying material throughout the night and avoid warming in regular daylight throughout the day. A cooling surface that reflects sun based radiation and also absorbs infrared radiation must be designed. It is one of the most widely studied and experimented method in the preparation of radiative material. More than ten years ago, polyethylene foils pigmented with ZnS were suggested for this purpose [15]. A study reported that white paints to a large degree seem to satisfy these requirements [16]. Paints based on TiO_2 are good blackbody emitters and display a fairly high solar reflectance. A radiative cooling effect [17] in direct sunlight was practically demonstrated with a two-layer foil. Eriksson and Granqvist [18] studied single TiO_2 polyethylene foils and found that cooling in direct sunlight was very difficult to obtain. However, the foils might be used to decrease the overheating of an underlying material. We have used similar approach to prepare the pigmented foil by using a combination of TiO_2 and $BaSO_4$. TiO_2 is considered due to its opaque properties of incoming solar radiation and $BaSO_4$ is considered as it is having good optical properties of high solar reflectance.

3. COMPUTATIONAL FLUID DYNAMICS (CFD)

Raman et al. [1] proposed a new kind of material using photonic approach which has good cooling efficiency in the broad daylight. The photonic approach is completely different from the usual approach followed over the past decade as mentioned in the literature, for being the superior and giving the best possible radiative material. Photonic materials are made by combination of materials with superior light reflecting properties in comparison with selectively radiating in the IR spectrum. Similarly, CFD simulations for the pigmented foils were performed by Clus et al. [19, 20] and close relation is established between the theoretical and practical results.

Computational Fluid Dynamics (CFD) offers more noteworthy adaptability for experimentation based advancement approach, because of its proficient, practical and simple techniques to run virtual reproductions. We have taken motivation from Raman et al. [1] from their way to deal with setting up the photonic and created a new material combination as shown in Figure 3. The proposed photonic material was designed after a variety of trial and error combinations, simulated using CFD. It comprises of 13 layers of Hafnium oxide (HfO_2) and Titanium dioxide (TiO_2) both considered because of their predominant photonic properties. Two layers are characterized of same thickness as appearing in Figure 3. At the bottom, Plexi-glass is utilized to diminish conduction from the ground and at the top, polyethylene is used as it is a great reflector of noticeable daylight and good emitter of IR radiation. The reason behind 13 layer blend is because of certainty that the incident sun based radiation will get reflected by the photonic material characterized, and a portion of the consumed radiation will resolve between those 13 layers of material, keeping up the surface temperature cooler.

3. 1. Modeling ANSYS FLUENT is used for virtual simulation of the physical phenomenon for the given input material to find its performance parameters [21, 22]. Here, the real world conditions are simulated as boundary conditions to identify the optimum material combination and the performance parameter is estimated. The CFD model as shown in Figure 4 consists of a flat plate condensation surface on the top of which the input material combination (Figure 3) is defined. The material is placed on the polystyrene block to reduce conduction losses from the bottom. The condensation setup is inclined at an angle of 45^0 with the horizontal. The model is defined inside a wall which mimics the realistic condition of the atmosphere surrounding the material.

Materials	Thickness(m)
Polyethylene	0.03
Titaniumdioxide	0.05
Hafniumdioxide	0.05
Titaniumdioxide	0.05
Hafniumdioxide	0.05
Titaniumdioxide	0.05
Hafniumdioxide	0.05
Titaniumdioxide	0.05
Hafniumdioxide	0.05
Titaniumdioxide	0.05
Plexiglass	0.05
Aluminium	0.03
Polystyrene	0.3

Figure 3. Designed 13-layer photonic material layout as defined in the CFD Study

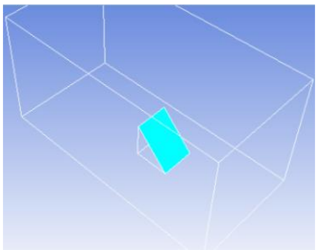


Figure 4. Computational domain

3. 2. Model Details

Inlet Velocity	:	0.1 m/s
Oultlet temperature	:	302 Kelvin
Flow	:	3-D Laminar
Radiation Model	:	Discrete Ordinates
Multiphase	:	Eulerian(2-Phase Air/water) Evaporation/Condensation
Initial conditions	:	Ambient air @ 302K
Pressure-velocity coupling	:	Semi-Implicit Method for Pressure Linked Equations
Solver	:	Steady – Segregated Implict Pressure Based

Following are the governing equations employed:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho \vec{v}\right) = 0 \tag{2}$$

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v}.\nabla\right)\vec{v} = -\frac{\nabla p}{\rho} + \upsilon \nabla^2 \vec{v} + g \tag{3}$$

$$\frac{\partial}{\partial t}(\rho h) + \nabla.\left(\rho h \vec{v}\right) = \nabla.(k \nabla T) + \phi \tag{4}$$

where ρ, g, h, k, $\vec{v}$ and ϕ are the density (kg/m^3), acceleration due to gravity (m/s^2), enthalpy (J/kg), thermal conductivity (W/mK), fluid velocity (m/s) and dissipation function respectively.

Figure 4 illustrates the simulated model in the ANSYS FLUENT. On the flat surface, the tested material is defined. The outer rectangle box enclosing the inclined surface is mimicking the atmosphere as specified by the boundary conditions. The surface is facing the inlet of the domain and the outlet is defined at right angle to the inlet. The simulation is done for the atmospheric pressure condition throughout the domain. The flat plate is inclined at an angle of 45° to the horizontal to mimic the actual realistic conditions in which the condensed dew on the flat condenser plate runs down the surface due to influence of gravity and water can be collected at the bottom. Hence the flat plate is simulated in the inclined position.

3. 3. Meshing The meshing is done using ANSYS WORKBENCH code. Default meshing parameters are applied for this purpose. The default convergence criteria of 10^{-3} is set. Tetra mesh with high smoothing and fine mesh is given as the input criteria.

3. 4. Mesh Quality Minimum Orthogonal Quality = 2.14245e^{-01}
(Orthogonal Quality ranges from 0 to 1, where values close to 0 correspond to low quality)
Maximum Ortho Skew = 7.25871e^{-01}
(Ortho Skew ranges from 0 to 1, where values close to 1 correspond to low quality)
Maximum Aspect Ratio = 1.60840e^{+01}

Figure 5 illustrates the various steady-state surface temperatures of the flat material surface. CFD predicts a temperature difference of about 15°C that can be achieved. The graphical illustration of this phenomenon is shown in Figure 6. It is found that with the increasing number of iterations the temperature difference is reducing and approaching the thermal equilibrium with the surroundings. This is because of the heat gain from the surrounding due to heat transfer as explained in Equation (1). To maintain the surface temperature for a considerable amount of time, a design is made which prevents the heat gain from the surrounding thereby affecting the performance of the given input photonic material. Figure 6 illustrates the surface temperature difference between the flat plate surface and the surrounding air and their variation with respect to the iteration steps.

This is the steady state iterative cases and is plotted on the x-axis. As shown in Figure 6, the temperature difference is reducing with the increase in the iterative steps approaching equilibrium conditions. This steady case shows the potential of the defined material and encourages to further optimize the design to maintain the temperature difference for prolonged iterative steps or maintain the surface temperature below 288 K, which is the average estimated dew point temperature for Indian climatic conditions.

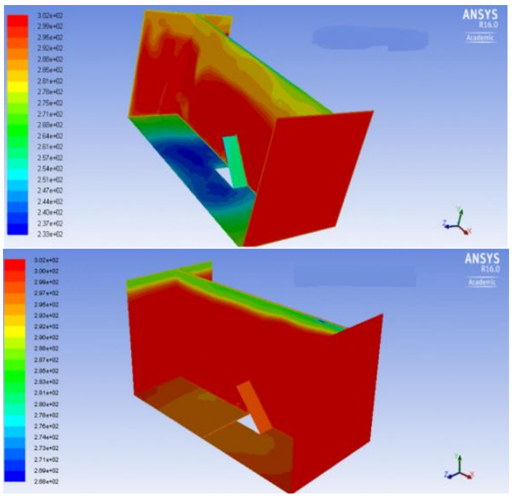


Figure 5. CFD simulation of photonic material defined on a flat surface

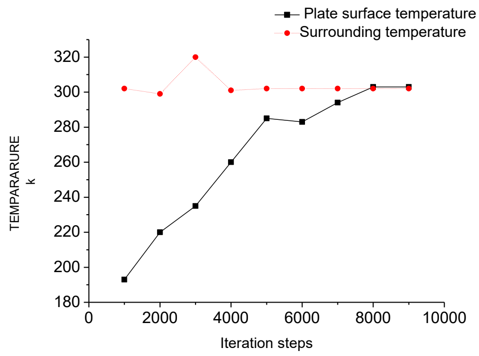


Figure 6. Temperature difference between the surface and the surroundings

Figure 7 shows the designed model which is made up of a Polystyrene surrounding block which act as a shield for the photonic material to reduce the convection and conduction losses that are responsible for decreasing the temperature difference as shown in Figure 6. The photonic material is placed inside the polystyrene block on the plate made of polystyrene or wood to prevent conduction from the bottom. The model is placed at an inclination of 45° to the platform.

To avoid the solar irradiation effect when the model is facing the sun in its zenith direction during the mid-day, a covering foil made from LDPE (Low Density Poly-Ethylene) is covered on top of the polystyrene block maintaining sufficient air gap with the photonic radiator. The reason to choose LDPE foil is that it has good solar reflectance and it is transparent to IR radiation which is very essential to achieve significant cooling during mid-day.

3. 5. Performance of the Designed Model The designed model is then simulated under similar boundary conditions as discussed earlier. Figure 8 shows the steady-state temperature of the LDPE surface on top of the model which is maintained at sufficient air gap with the photonic radiator, which is defined below it. The results are satisfying as it maintains the temperature difference of about 15°C with increasing iteration.

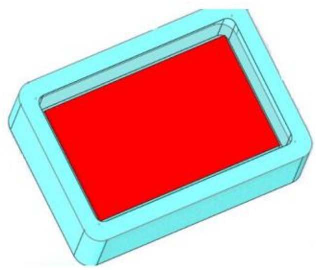


Figure 7. Designed model

These results show the effectiveness of the designed model in reducing the heat gain losses and also show the cooling capacity of the proposed photonic radiator.

From the CFD studies, we have identified potential of the proposed new photonic material and its operational characteristics. As shown in the contour plot (Figure 8), the effective surface temperature of the polyethylene surface is maintained at a temperature difference of 12°C on an average. This shows that the proposed model is effective in reducing the heat addition losses from the surroundings and also effective in maintaining significant temperature difference for a prolonged period of time. Further optimization can be done by optimally maintaining the airgap of the upper polyethylene surface with the underlying photonic radiator material.

Figure 9 illustrates the surface temperature difference between the LDPE foil surface and the surrounding air and their variation with respect to the iteration steps. This is the steady state iterative cases which are plotted along the x-axis. The temperature variation of the surface of LDPE foil is on an average at 290 K. This virtual analysis shows the potential of the defined material and encourages to further optimize the design to maintain the temperature difference for prolonged iterative steps or maintain the surface temperature below 288K, which is the average estimated dew point temperature for Indian climatic conditions.

4. MANUFACTURING OF RADIATIVE COOLING MATERIALS

In this study, two types of radiators, namely the photonic and pigmented radiator is experimentally realised to compare their performance with the virtual results.

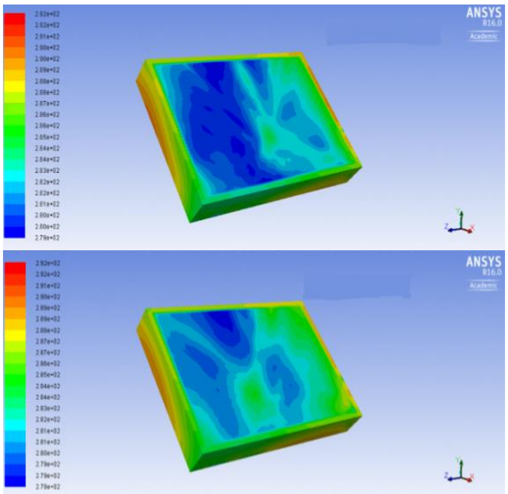


Figure 8. Surface temperature contour plot of polyethylene protective cover

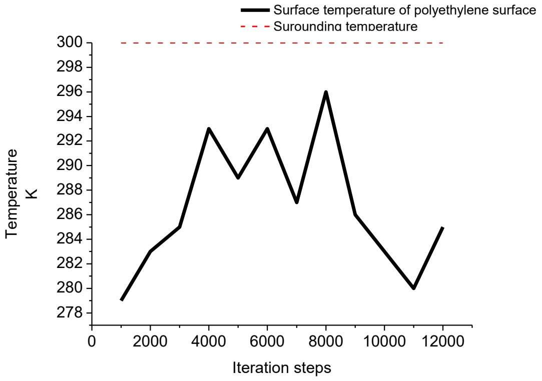


Figure 9. Temperature difference between the polyethylene surface and the surroundings

4. 1. Pigmented Foil Preparation

LDPE Granules are first heated to the melting temperature till the granules are completely melted. The pigmented powder consisting of 98% TiO_2 and 2% $BaSO_4$ is introduced in the liquid and stirred for a few minutes. The mixture is then rolled over a flat granite rock and hard pressed against it with a counter weight to obtain a flat surface. After cooling for some time we obtain a foil with the thickness of about 2 mm (Figure 10).

A small sample part of the prepared foil as shown in the Figure 10 is taken for testing purpose; nevertheless the foil must be uniform without any damage. Later during characterization, minimal foil thickness of the order in µm is preferred for better performance.

4. 2. Preparation of Photonic Radiator Material

Vacuum deposition is a family of processes used to deposit layers of material atom-by-atom or molecule-by-molecule on a solid surface. These processes operate at pressures well below the atmospheric pressure (i.e. Vacuum). The stored layers can run from a thickness of one particle up to millimetres, forming freestanding structures. Multiple layers of different materials can be used, for example to form optical coatings. The process can be qualified based on the vapour source; physical vapour deposition uses a liquid or solid source and chemical vapour deposition uses a chemical vapour.

Figure 10. Manufactured Pigmented foil with TiO_2 and $BaSO_4$ embedded in LDPE matrix

Here we have used TiO_2 instead of HfO_2 as both posing similar optical properties and also TiO_2 is available cheaply compared to HfO_2 [2]. Thin films of TiO_2 and SiO_2 were developed onto glass substrate alternatively under vacuum conditions. Substrates were cleaned with acetone and by refined water, and then ultrasonically cleaned by ethanol then again by refined water. A pressure of 10^{-6} mbar is accomplished in the vacuum coating chamber and maintained amid the coating. The dissipated material was then consolidated onto the glass substrate. Similar procedure is followed for coating SiO_2 as well.

4. 3. Coating Conditions The pressure conditions are maintained at 10^{-6} mbar with a voltage of 220 V. The temperature is maintained at 1600-2000°C for TiO_2 and 1400-2000°C for coating SiO_2.

5. RESULTS AND DISCUSSION

The important characteristic to estimate the performance of radiators are to evaluate their performance in UV and IR spectrum. Important parameters to be evaluated are the Absorbance and Transmittance.

5. 1. UV Characterization The materials are characterized for their optical properties using Spectroscopy techniques for evaluating the performance in both U-V/Vis and IR spectrum. For characterization in UV-Vis Evolution™ 300 UV-Vis Spectrophotometer is used. It gives the output performance in terms of the percentage of absorbance, reflectance and transmittance with respect to wavelength in the Ultra-violet visible spectrum of Electromagnetic radiation.

5. 2. Glass Substrate Coated with Photonic Material Figure 11 explains the performance of the realised photonic material prepared using vacuum technique in the UV spectrum. The stand AM 1.5 solar spectra which is given by ASTM standard, used as the reference to compare the performance of the photonic material. From the plot (Figure 11) it can be inferred that the realised photonic material is showing high resistance to absorb the UV-Vis solar spectrum as denoted by the thick line. The area under the thick line is very minimal compared to area under the dashed line (Standard spectrum), which explains the resistivity of the photonic material to absorb UV-Vis spectrum. This is essential for our material to avoid heat gain even if, the material is exposed to direct sunlight.

5. 3. Pigmented Foil Figure 12 explains the performance of the prepared pigmented foil in the UV spectrum. The stand AM 1.5 solar spectra (Thin Line) which is given by ASTM standard, used as the reference to compare the performance of the photonic material. From the plot (Figure 12) it can be inferred that the pigmented foil is showing minimal resistance to absorb the UV-Vis solar spectrum (Thin Line) as denoted by the thick line. The obtained material is found to absorb considerable amount of solar spectrum, which is not desirable. The full potential of the pigmented foil in showing high resistivity to solar spectrum is not realised, but by optimal manufacturing of the pigment foil using the best techniques and by choosing the right combination of TiO_2 and $BaSO_4$, the efficiency of this pigmented foil can be further increased.

5. 4. IR Characterization For characterization of performance of materials in IR Spectrum, Nicolet™ iS™ 10 FT-IR Spectrometer - Thermo Fisher Scientific is used. It gives the output performance in terms of the percentage of absorbance and transmittance with respect to wavelength in the Infrared spectrum of Electromagnetic radiation. Figure 13 shows the measured absorbance of the photonic material in the IR spectrum of the Electromagnetic radiation.

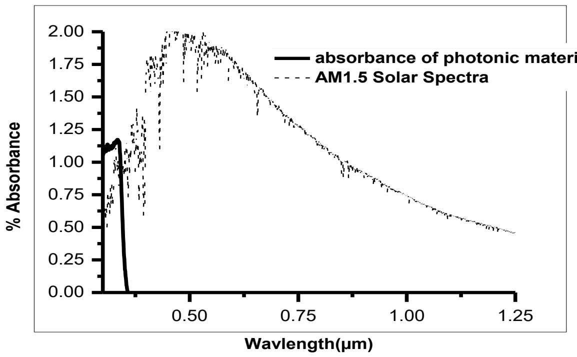


Figure 11. Performance comparison of the photonic material (Thick Line) with the standard AM 1.5 Solar spectra (Dash Line)

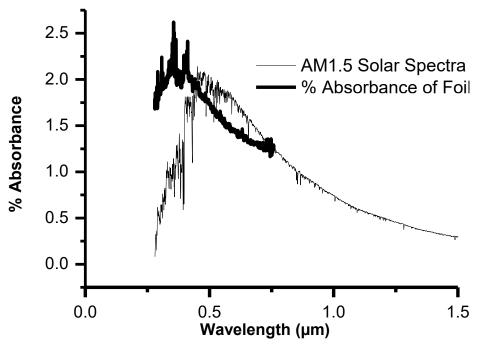


Figure 12. Performance comparison of the Pigmented Foil (Thick Line) with the standard AM 1.5 Solar spectra (Thin Line)

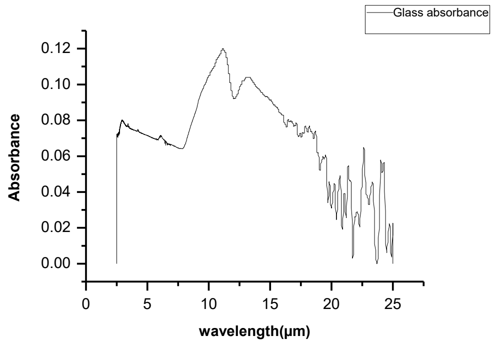


Figure 13. Glass absorbance plot in the I-R spectrum

The photonic radiator made with the combination of SiO_2 and TiO_2 shows good absorptivity in the wavelength between 8-16 µm. Since the atmospheric window is transparent in the 8-13 µm window, the absorptivity in this wavelength will not affect the cooling performance of the photonic radiator. If the emissivity of the photonic radiator is very high (approx. Ɛ=0.9), then the radiative performance (emissivity/absorbance) of the material is significant in achieving higher cooling performance.

5. 5. IR for Photonic Material Figure 14 shows the measured transmittance of the photonic material in the IR spectrum of the electromagnetic radiation. The photonic radiator made with the combination of SiO_2 and TiO_2 shows good transmissivity in the wavelength between 8-15 µm. As mentioned earlier, to achieve the passive cooling ability of the radiator, the material should selectively emit the heat in the IR spectrum in the atmospheric transparent window i.e. in the wavelength 8-13 µm. Figure 14 depicts the desired performance of material showing the considerable transmittance in the 8-13 µm wavelength. However, to further improve the cooling performance of the material, it can be tailored to reduce transmissivity in the rest of the spectrum and emit selectively in the transparent window of wavelength 8-13 µm to obtain the ideal passive cooling power.

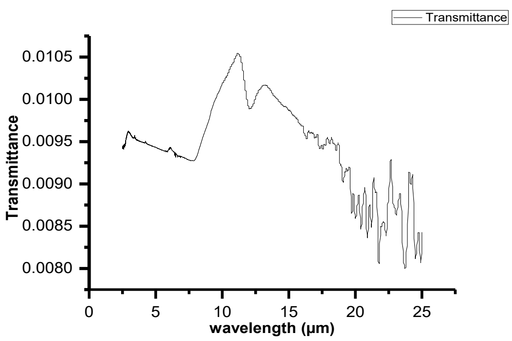


Figure 14. Glass transmittance plot in the I-R spectrum

5. 6. IR for Pigmented Foil Figure 15 shows the measured absorbance of the pigmented foil in the IR spectrum of the electromagnetic radiation. The pigmented foil made of TiO_2 and $BaSO_4$ imbedded in the polyethylene matrix shows a broad absorptivity spectrum in the wavelength between 5-20 μm. Since the atmospheric window is transparent in the 8-13 μm window, the absorptivity in this wavelength will not affect the cooling performance of the photonic radiator. But some considerable emissive losses can be obtained with the broadband radiators as explained above. There is a need for selectively emitting in the transparent window which can be achieved by manufacturing the foil using optimal manufacturing technique with a proper mixture of TiO_2 and $BaSO_4$, in the order of thickness in µm rather than obtained thickness in mm in our experiment. This plot shows the potential of the radiative foil to yield higher efficiency in obtaining better cooling performance, provided the best possible foil to be made as explained before.

Figure 16 shows the measured transmittance of the pigmented foil in the IR spectrum of the electromagnetic radiation. The pigmented foil made of TiO_2 and $BaSO_4$ imbedded in the polyethylene matrix shows a broad transmissivity spectrum ranging from 4-20 µm.

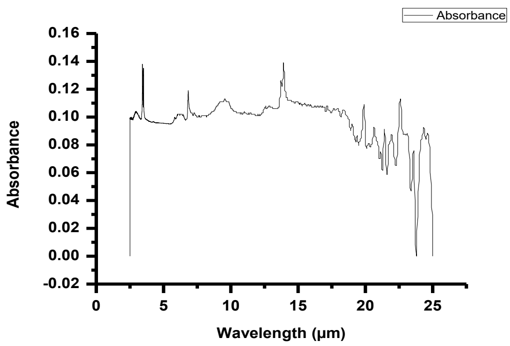


Figure 15. Pigmented foil absorbance plot in the I-R spectrum

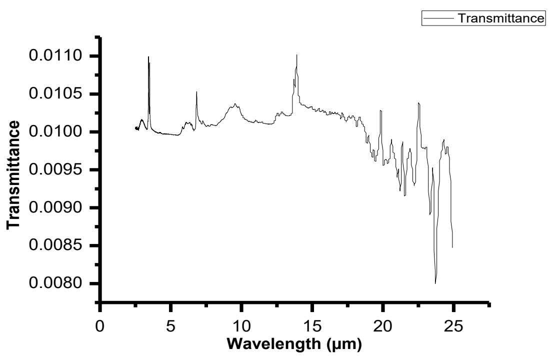


Figure 16. Pigmented Foil transmittance plot in the I-R spectrum

This falls under the broadband radiator which is comparatively less efficient than the selective emitters. Transmitting in the broad band encourages some heat gain during thermal radiation process which in turn affects the cooling performance of the radiator.

However, to improve the efficiency of the pigmented foil, better manufacturing technique with theoretically proven combination of pigment material (TiO_2 and $BaSO_4$) embedded in LDPE matrix in the order of thickness in μm range can outperform the existing pigmented foil. The unnecessary peaks in the wavelength other than that in the range of 8-13 μm can be controlled, as they are the function of physical material characteristics which can be improved by optimal manufacturing realisation of the pigmented foil as explained earlier.

6. CONCLUSION

The radiative cooling applications involving pigmented plastic foils and photonic radiative materials have been studied in great detail. A selective foil is designed which exhibits a very high solar reflectance as well as a high transmittance in infrared region of solar spectrum in the wavelength 8-13 μm region, is partially realised experimentally. Such foils may be used as protective covers for underlying infrared emissive materials to eliminate heat gain losses during daytime. This study shows a satisfactory agreement existing between the experiment and theory, of the proposed photonic radiative material. Even with optimized foils, the average dew water volume obtained will be around 1 litre per night in drought periods. A new sandwich photonic material is designed based on the previous literature practices used for passive cooling of buildings. The designed 13- layer photonic material has the potential to maintain the average surface temperature difference of 15°C on an average in a day. A protecting system is designed to improve the efficiency of the photonic material. The designed system gave satisfying results as shown by CFD. Practical realization of both the pigmented foil and the photonic material is done and their properties are portrayed. The cooling execution of the pigmented foil can be additionally expanded by the perfect assembling strategy and right mix of materials, and for the photonic material, appropriate coating techniques ought to be utilized to accomplish better efficient material as predicted by CFD.

7. REFERENCES

1. Raman, A.P., Anoma, M.A., Zhu, L., Rephaeli, E. and Fan, S., "Passive radiative cooling below ambient air temperature under direct sunlight", ***Nature***, Vol. 515, No. 7528, (2014), 540-544.
2. Hossain, M. and Gu, M., "Radiative cooling: Principles, progress, and potentials", ***Advanced Science***, Vol. 3, No. 7, (2016), 1500360 (1-10).
3. Michell, D. and Biggs, K., "Radiation cooling of buildings at night", ***Applied Energy***, Vol. 5, No. 4, (1979), 263-275.
4. Harrison, A. and Walton, M., "Radiative cooling of TiO_2 white paint", ***Solar Energy***, Vol. 20, No. 2, (1978), 185-188.
5. Johnson, T., "Radiation cooling of structures with infrared transparent wind screens", ***Solar Energy***, Vol. 17, No. 3, (1975), 173-178.
6. Givoni, B., "Solar heating and night radiation cooling by a roof radiation trap", ***Energy and Buildings***, Vol. 1, No. 2, (1977), 141-145.
7. Catalanotti, S., Cuomo, V., Piro, G., Ruggi, D., Silvestrini, V. and Troise, G., "The radiative cooling of selective surfaces", ***Solar Energy***, Vol. 17, No. 2, (1975), 83-89.
8. Berdahl, P., Martin, M. and Sakkal, F., "Thermal performance of radiative cooling panels", ***International Journal of Heat and Mass Transfer***, Vol. 26, No. 6, (1983), 871-880.
9. Nilsson, T.M.J., "Using radiative cooling to condense air moisture: Review and theory", in Internal report, Institute of Physics, Chalmers University of Technology, GIPR-321 0380 2872., (1994).
10. Nilsson, T.M., "Optical scattering properties of pigmented foils for radiative cooling and water condensation: Theory and experiment, Chalmers University of Technology, (1994).
11. Nilsson, T.M., Niklasson, G.A. and Granqvist, C.G., "A solar reflecting material for radiative cooling applications: Zns pigmented polyethylene", ***Solar Energy Materials and Solar cells***, Vol. 28, No. 2, (1992), 175-193.
12. Nilsson, T., "Initial experiments on dew collection in sweden and tanzania", ***Solar Energy Materials and Solar Cells***, Vol. 40, No. 1, (1996), 23-32.
13. Al-Nimr, M., Kodah, Z. and Nassar, B., "A theoretical and experimental investigation of a radiative cooling system", ***Solar Energy***, Vol. 63, No. 6, (1998), 367-373.
14. Nilsson, T.M., Vargas, W.E. and Niklasson, G.A., "Pigmented foils for radiative cooling and condensation irrigation", in Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII, International Society for Optics and Photonics. Vol. 2255, (1994), 193-204.
15. Beysens, D., Clus, O., Mileta, M., Milimouk, I., Muselli, M. and Nikolayev, V., "Collecting dew as a water source on small islands: The dew equipment for water project in Bis evo (croatia)", ***Energy***, Vol. 32, No. 6, (2007), 1032-1037.
16. Granqvist, C., "Radiative heating and cooling with spectrally selective surfaces", ***Applied Optics***, Vol. 20, No. 15, (1981), 2606-2615.
17. Granqvist, C. and Hjortsberg, A., "Radiative cooling to low temperatures: General considerations and application to selectively emitting SiO films", ***Journal of Applied Physics***, Vol. 52, No. 6, (1981), 4205-4220.
18. Eriksson, T. and Granqvist, C., "Radiative cooling computed for model atmospheres", ***Applied Optics***, Vol. 21, No. 23, (1982), 4381-4388.
19. Clus, O., Muselli, M., Beysens, D., Nikolayev, V. and Ouazzani, J., "Computational fluid dynamic (CFD) applied to radiative cooled dew condensers", in Environment Identities and Mediterranean Area. ISEIMA'06. First international Symposium on, IEEE., (2006), 217-221.
20. Clus, O., Ouazzani, J., Muselli, M., Nikolayev, V., Sharan, G. and Beysens, D., "Comparison of various radiation-cooled dew condensers using computational fluid dynamics", ***Desalination***, Vol. 249, No. 2, (2009), 707-712.

21. Bahreini, S., Nassab, S.G. and Addini, M.M., "Inverse boundary design problem of combined radiation-convection heat transfer in laminar recess flow", ***International Journal of Engineering-Transactions C: Aspects***, Vol. 29, No. 3, (2016), 394-402.

22. Rahnama, M., Djavidi, M., Mansouri, S.H. and Sinaie, A., "Numerical investigation of combined radiation and natural convection heat transfer in a horizontal annulus", ***International Journal of Engineering-Transactions C: Aspects***, Vol. 12, No. 4, (1999), 259-270.

Investigation of Radiative Cooling Using a Photonic Composite Material for Water Harvesting

S. T. G. Krishna Teja[a], C. P. Karthikeyan[b], M. B. Shyam Kumar[a]

[a] *School of Mechanical and Building Sciences, VIT University, Chennai, India*
[b] *School of Engineering Technology, Jain University, Bangalore, India*

P A P E R   I N F O

Paper history:
Received 26 April 2017
Received in revised form 06 August 2017
Accepted 28 August 2017

Keywords:
Radiative cooling
Computational Fluid Dynamics
Photonic Material
Pigmented Foil
UV- Visible
Fourier Transform Infrared

چکیده

هدف از این مطالعه طراحی و تحلیل موادی است که قادر به جذب آب از هوا با استفاده از پدیده‌ی تقطیر است با بهره گیری از اصل خنک کردن تشعشعی است. این مواد خنک کننده غیر عامل نه تنها مشکلات تولید آب را حل می‌کنند، بلکه در کاربردهای سرمایشی مختلف خنک نیز به کار می‌روند. مفهوم اساسی سرد شدن تشعشعی تحلیل شده و پارامترهای عملکرد برای اندازه‌گیری قابلیت خنک کنندگی غیر عامل مواد طراحی شده برای برداشت آب شناسایی شد. حوزه‌ی فوتونیک مطالعه شده است. این حوزه قابلیت به دست آوردن دمای سطح در حد چشم‌گیری پایین‌تر از دمای جو با پدیده تابش (تشعشع)است. پارامترهای مهم برای تایید عملکرد مواد پیشنهاد شده شناسایی می شوند. از نرم‌افزار ANSYS FLUENT برای تحلیل دمای سطح برای شرایط مرزی مورد استفاده استفاده شده و مواد بالقوه‌ای که می توانند اختلاف دما را با توجه به درجه حرارت محیط به دست دهند معرفی شده‌اند. یک ماده‌ی ساندویچی طراحی و عملکرد آن با استفاده از دینامیک سیالات محاسباتی (CFD) ارزیابی شده است. به این ترتیب می توانیم تفاوت دمایی در حدود ۱۵ درجه سانتی‌گراد به دست آوریم. برای کاهش تلفات گرما از طریق هدایت و جابه‌جایی، یک سیستم فیزیکی را طراحی کرده‌ایم که می تواند این اختلاف دما را حتی در زیر نور خورشید روز نیز حفظ کند. تحلیل CFD سیستم طراحی شده تحت شرایط مرزی مشابه نتایج رضایت بخش برای حفظ اختلاف دمایی در حدود ۱۵ درجه‌ی سانتی‌گراد را برای یک دوره طولانی مدت به دلیل کم شدن تلفات حرارت نشان داد. سپس، دو ماده‌ی بالقوه مناسب تولید شده و پارامترهای عملکردشان با استفاده از آزمون‌های طیف سنجی U-V / Vis (Ultraviolet-Visible) و FTIR (Transform Infrared) اندازه‌گیری شد. نتایج پدیده جذب در طیف U-V / Vis و پدیده انتقال توان در طیف FTIR از دو ماده که دلیل قابلیت خنک کنندگی غیر عامل مواد را توضیح می‌دهد.

doi: *10.5829/ije.2017.30.10a.19*