Evaluation of Passive Radiative Cooling for Building Applications

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Abstract:
Passive radiative cooling is a sustainable cooling method by using radiation effects from selective emitting layer. It utilizes outer space as heat sink and radiative energy within atmospheric transmission window. The spectral feature is characterized by the emitting layer and this paper evaluates a passive radiative cooer with inorganic emitting material, composed of Silicon, Nitrogen and Oxygen. The inorganic material is expected to provide long lasting cooling performance with higher durability, and it is combined with silver layer to reflect solar radiation, thus daytime cooling effects can be achieved. The paper discusses sample fabrication methods and the cooling performance of inorganic cooling material is evaluated with selective spectral-dependent approach. Analytical analysis on possible integration for building applications is conducted to verify the potential of passive radiative cooler in building applications. Three possible integrations, which are air-based system, water-based system and hybrid system, are discussed in this paper. The results indicate the potential of passive radiative coolers to be an energy saving solution for building applications.

Keywords: passive radiative cooling, sample fabrication, cooling performance, building implementation, mathematical analysis.

Contents

1. Introduction

Over the last few decades, the world has achieved enormous economic growth by emerging economies such as China and India that have huge manpower to work with. In exchange for economic growth, global warming has arisen as one of the most critical environmental issues today. The principle dilemma of climate change comes from the fact that as the planet becomes hotter, more energy is used for cooling which results in even more greenhouse gas emission; therefore, a viscous cycle is created. The ever-accelerating pace of global warming does not seem to slow down despite the technological advancement in current cooling systems. There is a little doubt that a new technology is in desire need to solve climate change conundrum, and passive radiative cooling has emerged as one of the promising technologies that can help resolving global warming.

Passive radiative cooling is a cooling technology that dissipates heat directly to outer space while reflecting most incident sunlight. In a nutshell, it takes the advantage of materials that can absorb short-wavelength energy and emit it as a long-wavelength energy straight back to outer space which acts as a heat sink without getting trapped within the Earth's atmosphere. As its name suggests, this technology does not require energy input or coolant input for its operation once installed.

Passive radiative cooling could become one of the future cooling technologies if it can be efficient and affordable. Therefore, our Final Year Design Project (FYDP) team mainly focuses on the development of a low-cost passive radiative cooling system in the building with the basis of selective infrared emitter and evaluation of its potential application in real buildings through a prototype.

2. Objectives

The primary objective of this project was to develop a large-scale fabrication method of passive radiative cooler for building applications and evaluate the performance of the prototype design via field test. Passive radiative cooler in this project was designed to be a thin film with three layers which are cooling layer, reflective layer and substrate. The unique feature of this project is using inorganic cooling material, which is expected to achieve higher durability with consistent cooling performance. PHPS solution is used for cooling. The target fabrication size was set to be an A4-size to demonstrate that it is viable to produce the cooler at a large scale. After the production of the passive radiative cooler prototype, a field test would be carried to evaluate the performance of the prototype. The produced passive radiative cooler would be integrated with a house model, and various integration methods would be tested to measure the performance of passive radiative cooler. After the field test, a thorough analysis would be performed to evaluate the efficiency of the designed passive radiative cooler.

Unfortunately, the original objective of this FYDP became infeasible due to political instability in Hong Kong during fall semester as well as COVID-19 during spring semester. The fabrication of passive radiative cooler could not be further proceeded because the access to the labs was very limited and most members were not able to return to Hong Kong during the pandemic.

Therefore, after discussion with supervisor, Professor Huang, the original, primary objective of FYDP was revised so that the project could be completed with the given situation. The revised objective of this project was to evaluate the potential of passive radiative cooler for building applications based on literature data. A theoretical model would be developed and the performance of the theoretical passive radiative cooler model on various implementations would be evaluated. Data from published literature was utilized when making a theoretical model since it was impossible to get real data from the real experiment.

3. Project plan

Table 2.1 Original plan of project (valid until November 2019)

Time	Tasks
Sep 2019	Understanding principles of passive radiative cooler
Oct 2019	Sample fabrication
Oct 2019	Testing substrates
Nov 2019	Substrate selection with experimental and analytical data
Dec 2019	Final sample fabrication
Jan 2020	Investigation on large-scale fabrication methods
Feb 2020	Large-scale sample fabrication
March 2020	Investigation on implementation methods
March 2020	Manufacture a simple building model
April 2020	Implement sample on the building model
April 2020	Evaluation on implementation of cooler

Table 2.2 Updated plan of project (revised on February 2020)

Time	Tasks
March 2020	Evaluation of cooling performance
April 2020	Investigation on implementation methods
April 2020	Modeling of possible implementation
April/May 2020	Analytical / Computational evaluation of models

4. Methodology

a. Sample fabrication

Sample fabrication is conducted with two layers of spin coating. Figure 1 illustrates the schematic of layer structure. Emitting layer cool down the surface by emitting radiative energy within atmospheric range. In addition, reflective layer reflects solar radiation to reduce energy income. The thickness of reflective layer is designed as 120 nanometers, so the acceptable range is set as 100 nanometers to 200 nanometers. So, spin coating is conducted with information on Table 1. After coating reflective layer, emitting layer is coated with inorganic compound solutions, which is composed of Silicon, Nitrogen and Oxygen. This process is also handled by spin-coating with information in Table 2. Each process will build up 0.6 to 0.8 micrometers. To achieve desired thickness, 4 micrometers, the process is repeated five to six times.

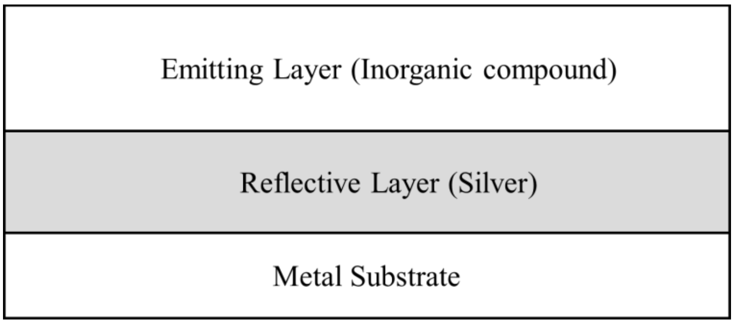


Figure 1. Schematic of passive radiative cooler structure

Table 1. Spin coating for reflective layer

	Rotational speed (unit: rpm)	Duration (unit: seconds)
Pre-spinning	1000	5
Main spinning	3000	10

Table 2. Spin coating for emitting layer

	Rotational speed (unit: rpm)	Duration (unit: seconds)
Pre-spinning	500	10
Main spinning	1000	30

However, the sample fabrication is failed as illustrated in Figure 2. This failure is caused by lack of adhesiveness between metal substrate and reflective layer. The silver layer is dropped off from substrate and being powdered. Instead of spin-coating method, using silver film to construct reflective layer would build sufficient adhesiveness force to prevent this failure. Furthermore, this method is appropriate to the large-scale fabrication. After covering the surface of metal substrate with silver film, large scale fabrication of passive radiative cooler would be achieved when inorganic compound coating is done.

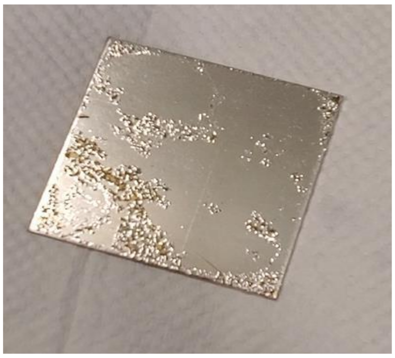


Figure 2. Failure of sample fabrication on copper substrate

So, investigation on large-scale coating is conducted for coating emitting layer with inorganic compounds since spin-coating cannot be utilized for large-scale fabrication. As potential candidates, dip-coating, spraying and knife coating methods are considered. Among them, knife coating method is chosen as the best option even though it is the most complicated. Figure 3 illustrates the knife coating method. The quality of coating is crucial since the irregularity could highly reduce the performance of passive radiative cooler. The knife coating can achieve coating with regular surface, thus the project planned to use knife coating method for inorganic compounds.

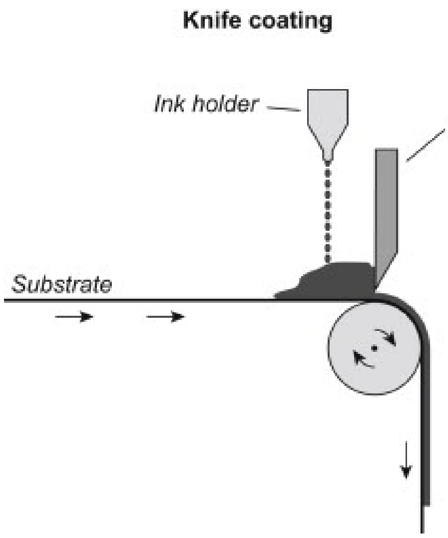


Figure 3. Knife coating [1]

b. Cooling performance evaluation

As previously mentioned, the project initially aimed to conduct a field test with a fabricated passive radiative cooler sample to evaluate the performance. However, the project progress is limited due to unusual academic conditions due to Hong Kong protests and outbreak of COVID-19. The actual field tests are restricted in Spring 2020 semester. Instead, the evaluation of passive radiative cooling performance is conducted in theoretical method. X. Lu [1] demonstrated selective spectral-dependent approach is used to evaluate the cooling performance. This approach considers spectral data of radiations and spectral emissivity of materials to be used. Since this project aims to implement inorganic cooling material, spectral data of this inorganic material is required. The spectral data is taken from the past experiment results by PhD candidate student, Justin. The details of method will be explained as followings.

The performance of passive radiative cooler is computed based on Equation (1). To evaluate the performance of cooler, all terms on right hand side should be analyzed. Figure 4 illustrates corresponding energy balance for passive radiative cooler.

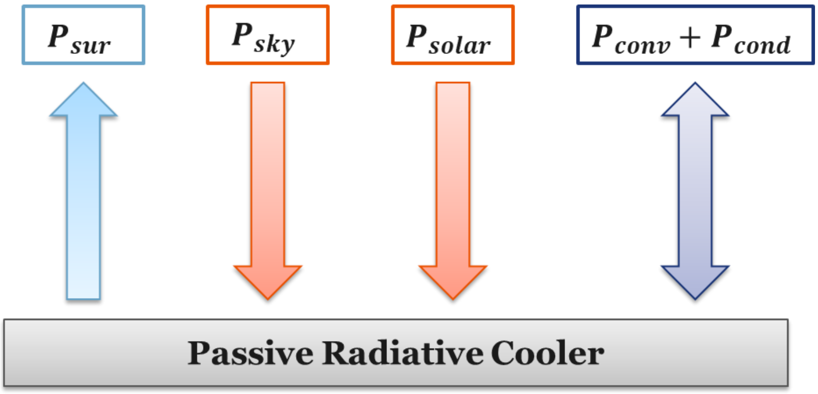


Figure 4. Schematic of energy balance for passive radiative cooler

$$P_{net}(T_s) = P_{sur}\ (Ts) - P_{sky}(T_{amb}) - P_{solar} - P_{conv} - P_{cond} \tag{1}$$

where $P_{net}(T_s)$ is the net radiative cooling power at specified surface temperature, T_s, $P_{sur}(T_s)$ represents power radiated by surface emitter at given surface temperature, $P_{sky}(T_{amb})$ represents atmospheric radiation at

ambient temperature, T_{amb}, P_{solar} represents the incident solar radiation absorbed by surface, P_{conv} represents convection heat transfer and P_{cond} represents conduction heat transfer.
The infrared radiative heat transfer consists of incoming and outgoing terms. The outgoing term, $P_{sur}(T_s)$, is radiation emitted by cooler and it is governed by the spectral emissivity data of the material and its surface temperature. Equation (2) demonstrates the outgoing term in detail and Equation (3) demonstrates Planck's law, which defines the blackbody spectral radiance at specific temperature. The incoming term, $P_{atm}(T_{amb})$, is radiation emitted by atmosphere and this term is demonstrated in Equation (4).

$$P_{sur}(T) = \int_0^{\pi/2} d(\sin^2\theta) \int_0^\infty d\lambda I_{BB}(T,\lambda)\varepsilon(\lambda,\theta) \tag{2}$$

$$I_{BB}(T,\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{(hc/\lambda k_B T)}-1} \tag{3}$$

$$P_{sky}(T_{amb}) = \int d\Omega \cos\theta \int_0^\infty d\lambda I_{BB}(T_{amb},\lambda)\varepsilon_{sky}(\lambda,\theta)\varepsilon(\lambda,\theta) \tag{4}$$

where $I_{BB}(T,\lambda)$ is the blackbody spectral radiance at specific temperature, $\varepsilon(\lambda,\theta)$ is spectral emissivity of the cooler and $\varepsilon_{sky}(\lambda,\theta)$ is spectral emissivity of atmosphere.

Assume that the radiator is facing sun at a fixed angle, the solar radiation is described by Equation (5). This term weakens the performance of cooler. This part only considered daytime radiation.

$$P_{sun} = A\int_0^\infty d\lambda\varepsilon(\lambda,\theta_{sun})I_{AM1.5}(\lambda) \tag{5}$$

where $I_{AM1.5}(\lambda)$ is the solar illumination and it is specified as the AM1.5 spectrum and *A* is the amplitude of solar radiation.

Non-radiative term includes both convection and conduction. It combines both term by using combined non-radiative heat coefficient, h_c. It is described with Equation (6).

$$P_{conv}(T_s,T_{amb}) + P_{cond}(T_s,T_{amb}) = h_c(T_{amb} - T_s) \tag{6}$$

MATLAB is used to utilize the selective spectral-dependent approach. Spectral data of range from 0.3 μm to 16 μm is used. One function code generates blackbody radiation spectrum with given temperature value by using Equation (3). The other function code calculates cooling performance by using the first code with two input temperature: ambient and surface temperature. This function calculates all components in Equation (1). So, it will generate unit cooling power in W/m^2. Lastly, an execution code will use two function codes to calculate the cooling power and steady-state surface temperature with two input values: ambient temperature and initial surface temperature of cooler. Thus, the cooling performance of cooler can be evaluated by using execution code with different input temperatures. The evaluation is performed with five different ambient temperature with different dT values, which define temperature difference between ambient and initial surface temperature.

$$dT = T_{surf} - T_{amb} \tag{7}$$

c. Analytical analysis of possible implementations
K. Zhang [2] provided three possible implementations for building application by using cooling panel as illustrated in Figure 5 [3]. All three implementation methods utilize cooling panel to achieve cooling for building applications.

Figure 5. Cooling panel with passive radiative cooler [3]

The first implementation method is air-based system. This system utilizes air as working fluids for panel. So, it can cool down the room temperature directly. So, it can achieve high efficiency of cooling performance for room. Figure 6 illustrates the schematic of air-based system by K. Zhang [2].

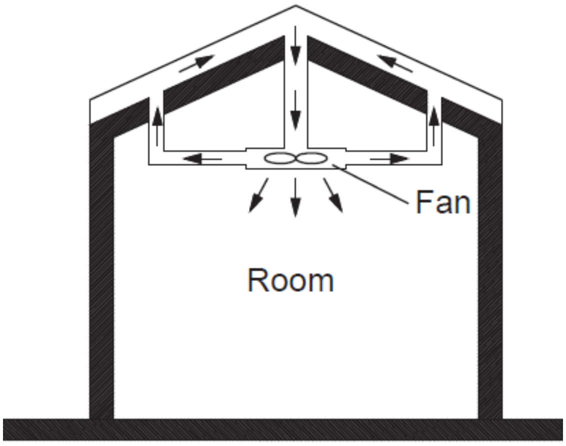


Figure 6. Schematic of air-based system [2]

The second implementation method is water-based system. This system utilizes water as working fluids for panel and cooler takes heat from input water and provides water with lower temperature in outlet. The cooled water is stored in the water tank. This method is appropriate to cooling tap water for building. Figure 7 illustrates the schematic of water-based system by K. Zhang [2].

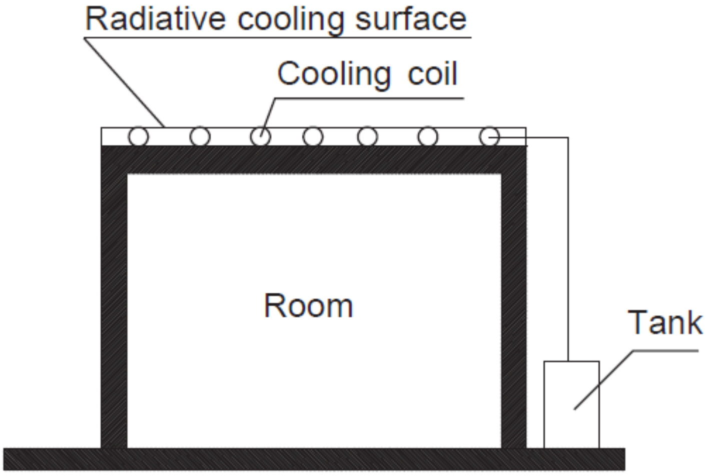


Figure 7. Schematic of water-based system [2]

The last implementation method is hybrid system. This system utilizes water as the working fluid of the cooling panel. Furthermore, it is combined with air flows by heat exchanger. Figure 8 illustrates the schematic of hybrid system by K. Zhang [2]. Cooling panel cools water and it is stored in cooling tower. Then, by using heat exchangers water to air, cooled air flows into room. As this system has the most complicated structure among the three methods, this system has the lowest efficiency. However, it can achieve consistent cooling operations for room cooling methods while air-based system can be limited due to inappropriate environmental conditions for passive radiative cooler.

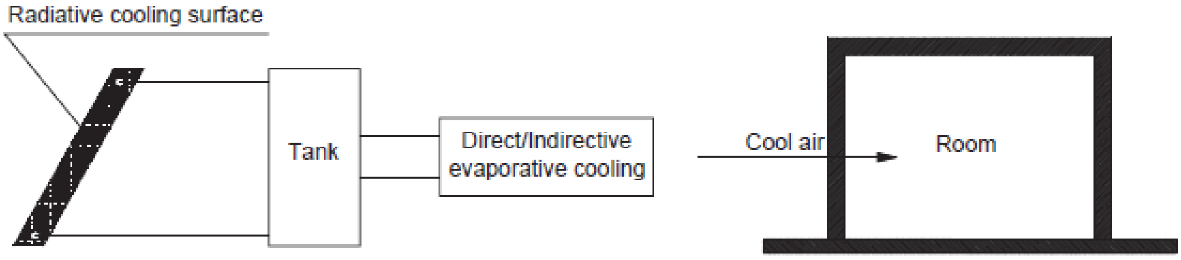


Figure 8. Schematic of hybrid system [2]

Analytical analysis is conducted for all the three methods mathematically. The purpose of the analysis is to identify the minimum area required to fulfill heat load, and corresponding flow requirements. All systems have different efficiencies, which are tabulated in Table 3. All the three systems have cooler efficiency, which considers energy loss from bottom surface of cooler to the top surface of cooler. This efficiency is estimated as 96.8% by D. Zhao [4]. While air-based system has relatively higher flow speed, water-based system has lower flow speed. So, panel efficiency, which considers energy leakage at the bottom of the panel, should be considered and it is estimated as 95%. Furthermore, energy leakage in the cooling tower will influence water-based and hybrid system. This is estimated as 90% by K. Zhang [2]. Lastly, hybrid system should consider one more efficiency term due to heat exchanger from water to air. As a heat exchanger efficiency, 75%, which is a typical counter flow heat exchanger efficiency argued by K. Ciraldo [5], is used.

Table 3. Efficiency for three systems

System	η_{cooler}	η_{panel}	$\eta_{HE,\ hybrid}$	η_{tower}	η_{total}
Air	0.968	N/A	N/A	N/A	**0.968**
Water	0.968	0.95	N/A	0.90	**0.82764**
Hybrid	0.968	0.95	0.75	0.90	**0.62073**

Figure 9 illustrates modeling for analytical analysis. A room with 20m^2 area is evaluated and unit heat load is 40W/m^2. 305K is considered as average summer daytime ambient temperature. dT is set as -3K as the cooler is integrated with fluids for building applications and it would be slightly lower than the ambient temperature. For this modeling, inlet fluid temperature is assumed to be equal to the ambient temperature and outlet fluid temperature is assumed to be equal to the surface temperature. So, the fluid is cooled by 3 degree by passive radiative cooling panel in this modeling. The pipe diameter for water and air is 0.05m and 0.2m respectively. These assumptions will be used to compute minimum area required to fulfill cooling load and corresponding flow conditions for three systems.

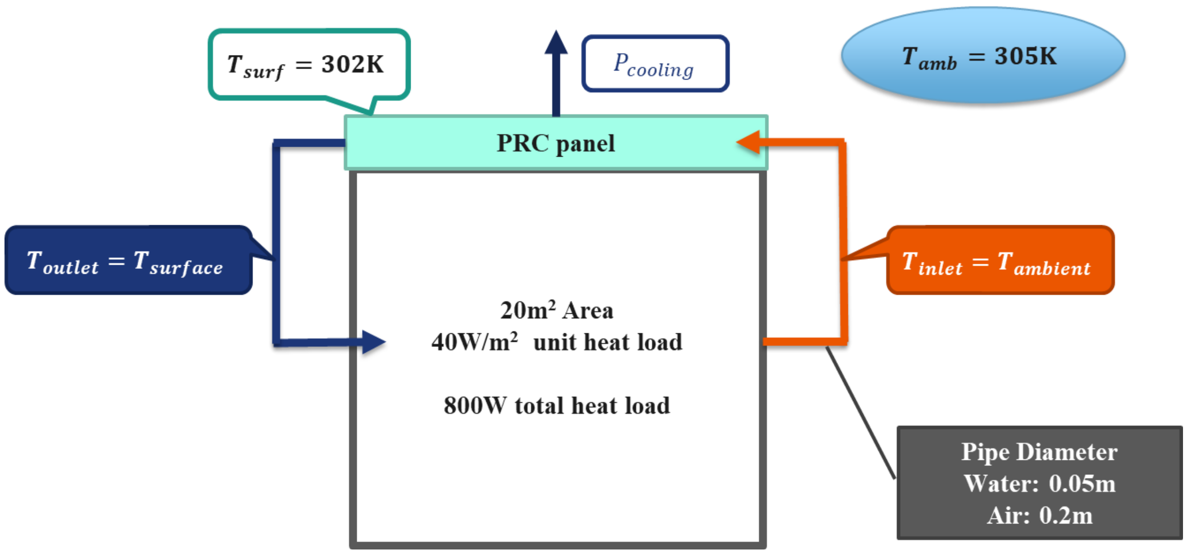


Figure 9. Schematic of modeling for analytical analysis

Analytical analysis is handled with following equations and the results will be discussed in later section.

$$P_{req} = \frac{P_{load}}{\eta_{total}} \tag{8}$$

$$A_{min} = \frac{P_{req}}{P_{cooling}} \tag{9}$$

$$\dot{m}(mass\ flow) = \frac{P_{req}}{c_p(T_{inlet} - T_{outlet})} \tag{10}$$

$$Q(volumetric\ flow) = \frac{\dot{m}}{\rho} \tag{11}$$

$$A = \frac{\pi (D_{pipe})^2}{4} \tag{12}$$

$$v\ (flow\ speed) = \frac{Q}{A} \tag{13}$$

5. Data analysis & Discussion

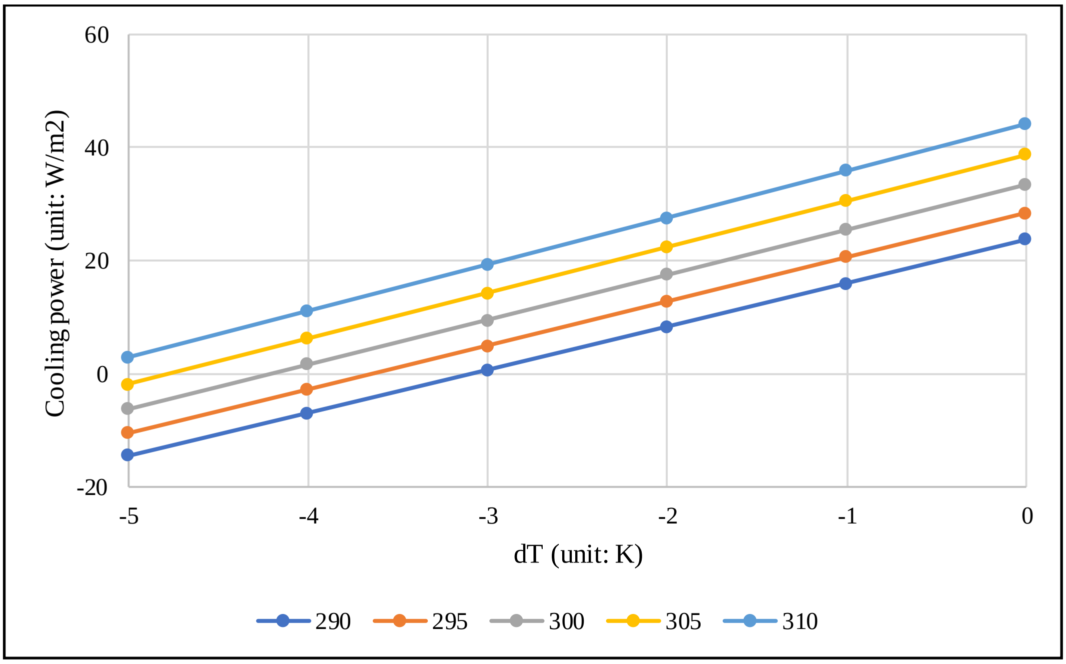
a. Cooling performance evaluation

Table 4 represents the results of cooling performance evaluation and data is plotted in Graph 1. Firstly, higher cooling power is achieved when the surface temperature is close to the ambient temperature. As the surface temperature decreases, the cooling power decreases, the maximum cooling can be achieved when the surface temperature is identical to the ambient temperature. In addition, passive radiative cooler could not function cooling at some points. This point is considered as steady-state surface temperature with given ambient temperature. The steady state surface temperature is computed by executing MATLAB code and tabulated in Table 5. Cooling power of passive radiative cooler would be zero at this point.

Secondly, it is observed that cooling power is higher at higher ambient temperature. While the maximum cooling power at 290K ambient temperature is 23.7429 W/m^2, the maximum cooling power at 310K is 44.2049 W/m^2. It is 86.18% greater than cooling power at 290K. The corresponding steady-state temperature also increases, and the gap between ambient temperature and steady-state temperature also increased as ambient temperature increases.

Table 4. Evaluation of unit cooling performance (unit: W/m^2)

dT (unit: K)	Ambient temperature (unit: K)				
	290	295	300	305	310
0	23.7429	28.4832	33.4717	38.7113	44.2049
-1	16.0384	20.631	25.4688	30.5549	35.8922
-2	8.3631	12.8086	17.4963	22.4295	27.6109
-3	0.7168	5.0158	9.5541	14.3348	19.361
-4	-6.9006	-2.7474	1.642	6.2709	11.1424
-5	-14.4891	-10.4812	-6.2401	-1.7625	2.955



Graph 1. Change in cooling power within different dT value

Table 5. Steady-state surface temperature

Ambient temperature (unit: K)	290	295	300	305	310
Steady-state surface temperature (unit: K)	286.9	291.35	295.79	300.22	304.63

b. Analytical analysis

The cooling power value with ambient temperature of 305K and dT of -3K, which is **14.3348 W/m^2**, is used for analytical analysis of three different systems as modelled in Figure 9. The computation is executed by input data and equations in Excel. Table 5 shows the results for three different implementations. For flow conditions, all systems provide acceptable flow condition requirements. However, it is observed that all the systems require larger area than the given area of modeling to fulfill the cooling requirement. So, passive radiative cooling cannot fulfill the cooling requirement by itself.

Air-based system seems the most efficient system as it uses cooled fluids directly. So, it has the least panel area required. Instead, it cannot store the cooled fluids. So, it has limited operation time. Hybrid system seems the least efficient system, but the air-cooling system can be utilized without time limitation as the cooled water will be stored in a cooling tower. Thus, cooling can be operated whenever it is needed. Lastly, water-based system seems more efficient than hybrid, but it is not good to be used as cooling system independently. Because water-based cooling shows not efficient cooling performance, it would be more appropriate to cool down tap water.

Table 6. Results of analytical analysis for three systems

	Air-based	Water-based	Hybrid
Minimum panel area (unit: m^2)	57.65	67.43	89.91
Mass flow rate (unit: kg/s)	0.2741	0.07697	0.1026
Volumetric flow rate (unit: m^3/s)	0.2238	7.720×10^{-5}	1.029×10^{-4}
Flow speed (unit: m/s)	7.124	0.03932	0.05243

6. Conclusion

This project developed a theoretical model of a passive radiative cooling technology and evaluated its performance on building applications. Evaluated cooling performance with inorganic cooling materials provides appropriate cooling power. The cooling power is enhanced when the surface temperature is close to the ambient temperature and higher performance could be expected in hot ambient temperature conditions. This cooling material will provide long-lasting cooling performance with higher durability.

From the analytical analysis, it is observed that passive radiative cooling system can achieve cooling that is required for real-life applications. However, they are not developed enough to be used as stand-alone as they occupy big spaces that are not available in standard buildings and houses. Instead, by combining it with current cooling systems, passive radiative cooler can help achieve a significant reduction in energy consumption. While air-based system can achieve the most efficient air-cooling for building applications with the simplest structure, this system cannot be operated in consistent manner. Water-based system and hybrid system have cooling tower which can store the cooled fluids and provide consistent cooling operations without conditional limitations. Water-based system would be more appropriate for tap water cooling and hybrid system would be applicable for room cooling applications for building.

Anyhow, passive radiative cooler has great potential to be an energy saving solution, and it is highly anticipated that with further technological improvements. Wind cover and shading are candidates which could improve the performance of passive radiative cooler. In the near future, passive radiative cooling can provide remarkable cooling performance with great sustainability. Passive radiative cooling, which will be a great environmentally friendly cooling methods for building applications, would be one more step to lead a sustainable world.

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