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A field investigation of passive radiative cooling under Hong Kong's climate

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ABSTRACT

This paper discusses the feasibility of cooling using radiation under Hong Kong's hot and humid climate. Three different designs of a passive radiative cooler were studied in this work. The three designs include non-vacuum, and vacuum with seven potassium chloride (KCl) IR-Pass windows as well as one system with a single KCl IR-Pass window. The coolers were examined during daytime and night time operation as well as under different sky conditions, such as clear, cloudy and partly cloudy. Investigation was mainly based on the temperature difference between the radiative cooler and ambient air. The experimental results showed that the passive radiative cooler with seven KCl windows and the cooler design without vacuum provided a satisfactory cooling effect at night (i.e. the ambient air temperature was reduced by about 6–7 °C), but the coolers could not produce a cooling effect during daytime under any of Hong Kong's weather conditions. The same results were obtained for the passive radiative cooler with the single KCl window during daytime operation. However, the cooling capacity of the passive radiative cooler design without vacuum under a clear night sky achieved 38 W/m^2.

1. Introduction

More than 30% of electricity consumption in the residential and commercial sectors is for space conditioning in Hong Kong [1]. Reducing the energy consumption for space conditioning is essential to develop energy-efficient buildings. Among the various techniques for space conditioning, passive radiative cooling is very attractive since it requires no electricity and is environmentally friendly [2–16]. Passive radiative cooling is a phenomenon utilizing the properties of the Earth's atmosphere that consists of many different gases, and each gas will absorb Electromagnetic (EM) radiation with specific wavelengths. Combining the absorption spectrum of the gases, there exists transparent windows, called atmospheric windows, where EM waves can pass through easily. Besides the window for visible light, there is also an infrared atmospheric window within the wavelength of 8–13 μm. The peak of the black-body spectrum of normal ambient temperature, about 300 K (27 °C), is also within this range. It means that an object under normal ambient temperature will emit EM radiation mainly within 8–13 μm and the EM radiation can pass freely through the atmosphere.

Radiation cooling to the night sky is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower temperature. Roofs of buildings radiate heat, day and night, at an average rate of up to 75 W/m^2 [15]. During the day, this is offset by solar radiation gains on the roof, however, at night, this heat loss has the ability to cool air or water as roofs can experience a temperature drop of 6–20 °C below ambient. The infrared atmospheric window is a path from the land-sea surface of Earth to space. At the scarcely absorbed continuum of wavelengths (8–13 μm), the radiation emitted by the Earth's surface into a dry atmosphere, and by the cloud tops, mostly passes unabsorbed through the atmosphere and is emitted directly to space. This is because the infrared absorptions of the principal natural greenhouse gases (CO_2 and H_2O) are outside of this range. The effect of this radiant heat leaving the surface of the Earth can easily be seen on some mornings after a clear night in temperate climates. A layer of frost will form on rooftops and on automobiles even though the outdoor air temperature is well above freezing. This frozen condensation is proof that the rooftops lost heat by radiation to the night sky faster than the surrounding warmer air could replace that

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heat by natural convection. The passive radiative cooling below ambient air temperature has been well-demonstrated at night [4–7,10,11,16].

In 1979, Michell and Biggs first investigated the cooling of small buildings at night by radiation loss to the sky [2]. They monitored the thermal performance of two huts: one roofed with galvanized steel decking painted white, while the other had aluminum decking to which aluminized 'Tedlar' sheet had been glued. It was found that the hut with the painted roof was cooled better than that with the 'Tedlar' covered roof. A cooling power of about 22 W/m^2 was achieved at a roof temperature of 5 °C with the ambient air temperature at 10 °C. In 1980, Granqvist and Hjortsberg produced a surface for efficient radiative cooling that consisted of 1.0 μm of silicon monoxide on aluminum. They envisaged that refrigeration to 40 K below the ambient appears to be possible under suitable climatic conditions [5]. One year later, they utilized the same infrared selective surface, and performed a practical test of radiative cooling under transparent polyethylene films in a polystyrene box. The test was conducted during clear nights. A cooling power of about 60 W/m^2 was achieved [6]. In 1984, Berdahl demonstrated that magnesium oxide in ceramic foam can be fabricated into a useful selective radiator which cools well below ambient temperature [8]. The MgO radiator cooled to 5 °C below the reference panel. In 1995, Nilsson and Niklasson prepared five different pigment materials, ZnS, ZnSe, TiO_2, ZrO_2 and ZnO. Simulation results showed that only ZnS could promote cooling of a black body radiator in an insulated box at noon under direct sunlight [12]. In 1993, Orel et al. developed an infrared selective radiator. A temperature difference of about 10 °C was obtained between the radiators and ambient air temperature [10]. They also found that the addition of a $BaSO_4$ extender dispersed in the paint increased the cooling performance of the painted radiators. In 2000, Khedari et al. studied the feasibility of cooling by using night radiation under Thailand's hot and humid climate [3]. The experimental results showed that the depression of different surface temperatures was in the range of 1–6 °C below ambient temperature under clear and cloudy skies. The temperature of different surfaces of roof radiators and ambient air was fairly close under rainy skies. Besides, they also found that the thermal emissivity of materials and water condensation on the radiator surface area are the two major factors affecting night radiation cooling. In 2009, Suryawanshi and Lin designed and developed a high-surface-emissivity "molecular fan" coating, consisting of an acrylate resin and carbon-based materials on aluminum panels [16]. The "molecular fan" nano-coating can act as a selective emitter and displayed an enhanced emissivity. The results showed that using 1wt% multi-wall carbon nanotube, the "molecular fan" coating on one side of the aluminum test panel lowered the equilibrium temperature of a heat sink by 17 °C. In 2010, Gentle and Smith demonstrated a mix of two resonant nanoparticles, SiO_2 and SiC [11]. They found that a mixture of SiC and SiO_2 nanoparticles yielded high performance cooling at low cost within a practical cooling rig.

By using photonic structures to selectively reflect and emit photons in different wavelength regimes, a net cooling effect can be achieved if the emission of infrared to outer space, whose radiation background temperature is about 2.7 K, exceeds the absorption of sunlight and environment thermal radiation. In other words, to realize net passive radiative cooling below ambient air temperature, strong reflection of sunlight and strong emission of thermal radiation with a wavelength within the atmospheric infrared window (8–13 microns) must be achieved simultaneously; however, it is extremely difficult to achieve using conventional optical coatings. Recent success in passive radiative cooling is attributed to the adoption of a multilayer photonic structure. By creating a subwavelength photonic structure, the spectral absorption, emission and transmission of photons can be controlled. It has been demonstrated in California (USA) that passive radiative cooling of 4.9 °C below ambient air temperature can be achieved under direct sunlight with a photonic radiative cooler consisting of a silicon substrate and a multilayer photonic structure, which shows a cooling capacity of 40.1 W/m^2 [17]. This promising result again excites the research interest in radiative cooling since passive radiative cooling no longer has to be limited to night operation. However, their design could be further optimized from a heat transfer perspective. It was predicted that the cooling performance can be improved by about four times if the non-radiative heat transfer coefficient is reduced to zero.

According to our knowledge, there is no field investigation of radiative cooling in Hong Kong. This paper is intended to make an initial feasibility study on how effective this technique would be under a sub-tropical sky. One major difference between California (USA) and Hong Kong is the humidity. Harrison [18] reported that the absolute humidity at ground level can strongly influence the radiation cooling effect of TiO_2 white paint. The performance of a photonic radiative cooler is also affected by humidity. Overall, this study aims to experimentally investigate the passive radiative cooler described in Ref. [17] with different thermal designs (i.e. vacuum and non-vacuum configurations) and test its cooling performance in the hot and humid environment of Hong Kong. It should be noted that the non-vacuum design of the passive radiative cooler indeed is the cooler described in Ref. [17], while the vacuum design configuration of the passive radiative cooler is our proposed design. Vacuum is a common method to eliminate conductive and convective heat transfer to the surrounding environment. This method is widely used in vacuum bottles, evacuated tube solar collectors, vacuum insulation panels, etc. The effect of different sky conditions on the cooling performance of the passive radiative cooler, such as clear, cloudy and partly cloudy, are studied. Lastly, some recommendations on how to further enhance the cooling performance of the passive radiative cooler are also addressed.

2. Experimental setup

As California's weather is totally different from Hong Kong's, it is necessary to assemble the same setup in Hong Kong so that a fair comparison can be made. Most importantly, the effect due to different weather conditions can be eliminated. Based on the design proposed in Ref. [17], an identical prototype was built as shown in Fig. 1. It should be noted that the passive radiative coolers used in this study and in Ref. [17] were all built by the same company (LGA THIN FILMSTM, Inc. Santa Clara, CA 95051) located in California (USA). Briefly, the photonic radiative cooler consists of seven alternate layers of hafnium dioxide (HfO_2) and silicon dioxide (SiO_2) of varying thicknesses, on top of 200 nm of silver (Ag), which are all deposited on a 200 mm silicon wafer [17]. The cooler can reflect 97% of incident sunlight, while at the same time, strongly and selectively emitting the thermal radiation heat in the atmospheric transparent window (8–13 μm). As a result, a cooling effect can be produced by the passive radiative cooler. Please refer to Ref. [17] for details about the exact thickness of each layer as well as the overall thermal design configuration of the passive radiative cooler.

Based on the simulation result published by Raman et al. [17], the passive radiative cooler can reduce the ambient air temperature by about 20 °C if both conductive and convective heat losses are negligible. In their experimental setup, the radiative cooler was suspended in a relatively well-sealed air pocket. However, it should be noted that no matter how well the air pocket is sealed, conductive and convective heat losses still exist. In order to

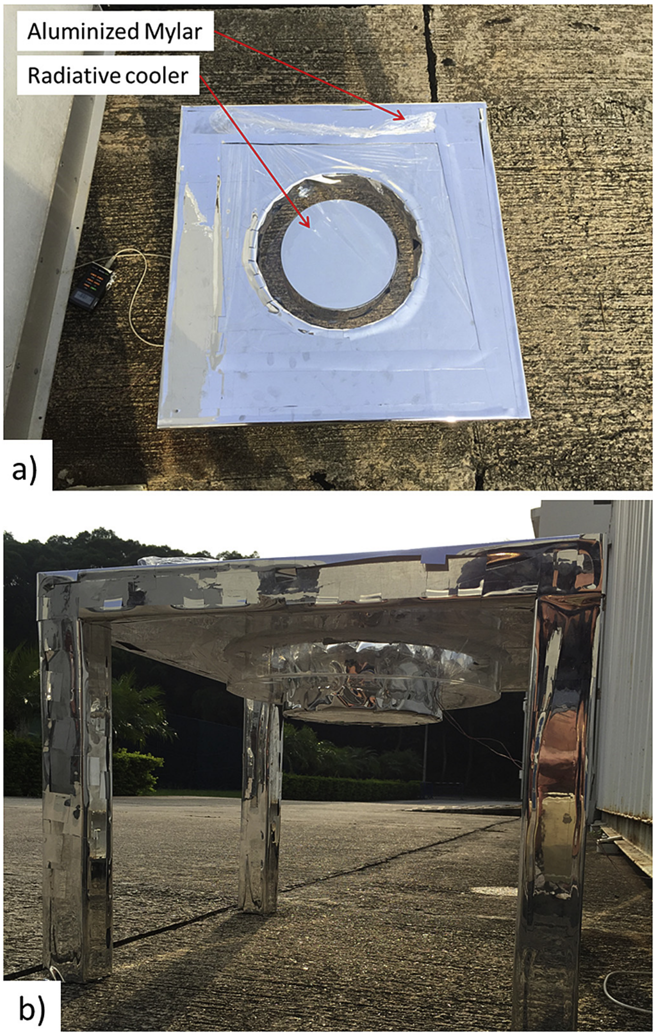

Fig. 1. A prototype of the passive radiative cooler with non-vacuum design built in Hong Kong (top view) [17].

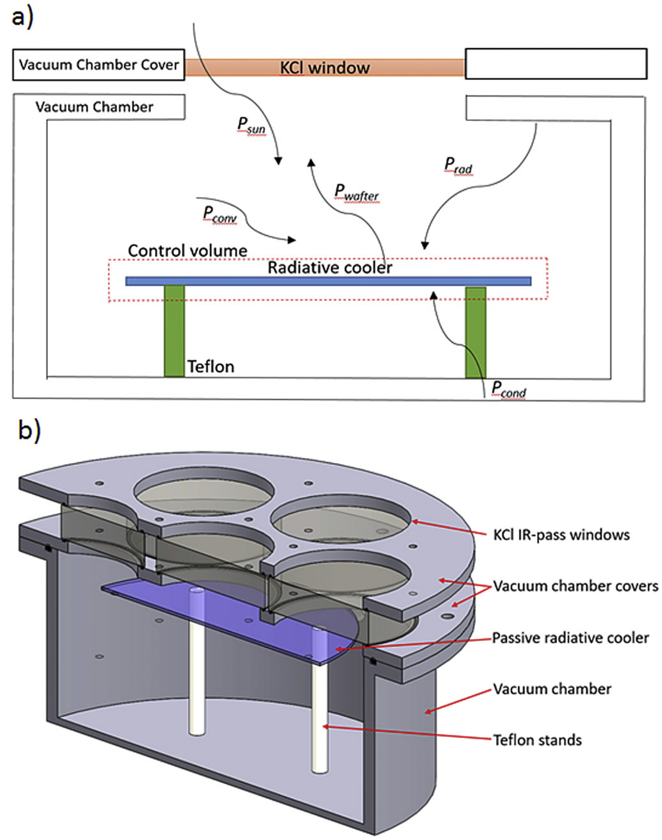

Fig. 2. a) Schematic diagram and b) drawing of the passive radiative cooler inside the vacuum chamber.

optimize the thermal performance of the passive radiative cooler by completely eliminating the heat loss due to conduction and convection, the vacuum technology is proposed in this study. The schematic diagram and drawing of the passive radiative cooler inside the vacuum chamber is shown in Fig. 2. The net cooling power P_{cool} of the radiative cooler (i.e. considering the passive radiative cooler as a control volume) is given by:

$$P_{cool} = P_{cooler} - P_{sun} - P_{rad} - P_{cond} - P_{conv}, \tag{1}$$

where P_{cooler} refers to the power generated by the passive radiative cooler (W); P_{sun} is the incident solar power absorbed by the structure (W); P_{rad} is the power gain due to radiation or the absorbed power due to incident thermal radiation from the vacuum chamber (W); P_{cond} is the power gain due to conduction or the adsorbed power from the vacuum chamber through conduction (W); P_{conv} is the power gain due to convection or the adsorbed power through convection inside the vacuum chamber (W). In order to enhance the net cooling power (P_{cool}), the values of P_{rad}, P_{cond} and P_{conv} should be as small as possible. In a vacuum condition, P_{conv} can be ignored since there is no medium for convection. Besides, P_{cond} is eliminated through support of the radiative cooler by four Teflon rods. Teflon is used because it has very low thermal conductivity of 0.25 W/mK. The location of the passive radiative cooler inside the vacuum chamber is also determined. Based on the average measured emissivity of the passive radiative cooler between 8 and 13 μm published by Raman et al. [17], the best location for the passive radiative cooler inside the vacuum chamber is about 15 mm below the vacuum cover edge since this can ensure that the angle of incidence is always between $-60°$ and $+60°$, leading to consistently having the largest emissivity value (~0.7). Fig. 3 shows the location of the passive radiative cooler inside the vacuum chamber.

Moreover, both the inner and outer walls of the vacuum chamber were covered by aluminum Mylar such that the radiation heat released by the passive radiative cooler will not be absorbed by the vacuum chamber. Similarly, the vacuum chamber will not absorb the thermal radiation heat from the sun (external heat source) as shown in Fig. 4. Fig. 4 shows a picture of our proposed design of the passive radiative cooler. It consists of one passive radiative cooler located inside a vacuum chamber. On the vacuum chamber cover are seven potassium chloride (KCl) IR-pass windows. KCl is chosen since the transmittance of the KCl crystal, in the range between 0.3 and 18 μm, is about 90%. The thermal radiation heat released by the passive radiative cooler can transmit to outer space through the KCl windows. Seven 100 mm diameter KCl windows are used instead of a single large window because of the low stiffness of KCl. The KCl windows used are 23 mm thick so as to withstand the force created by vacuum. During the experiment, the design of the setup has been revised by reducing the number of KCl IR-pass windows from seven to one, reducing the amount of solar heat being absorbed by the inner wall/components of the vacuum chamber, and improving the performance.

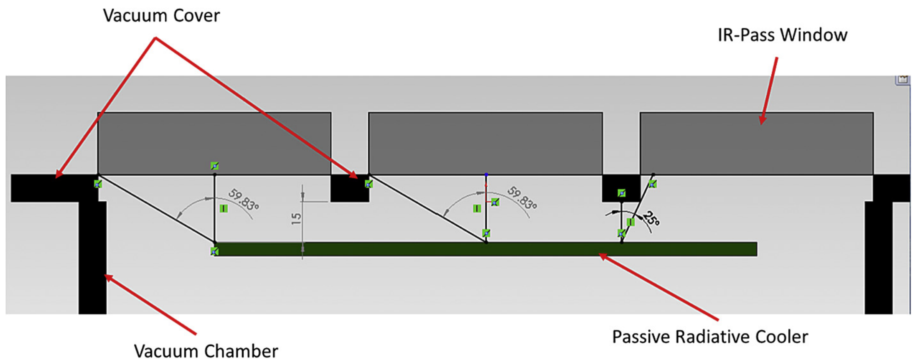

Fig. 3. The location of the passive radiative cooler inside the vacuum chamber.

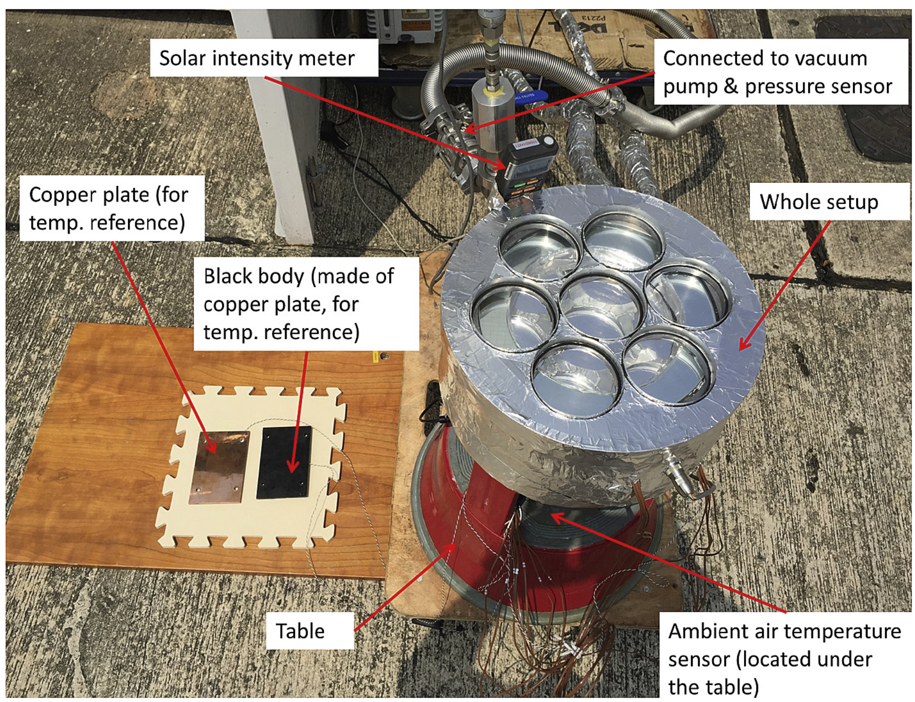

Fig. 4. A complete setup of our proposed passive radiative cooler with 7 KCl IR-pass windows.

The vacuum chamber is connected to a vacuum pump. A solar intensity meter and an ambient air temperature sensor are located near the setup. A polished copper plate and a black body (made of copper, but painted black) are placed next to the vacuum chamber. They are used as a temperature reference as well as for the temperature comparisons between the passive radiative cooler and ambient air temperature. All the temperatures were measured by T-type thermocouples and were recorded by a data acquisition device, National Instruments NI 9213, with an accuracy of ±0.02 °C. Three T-type thermocouples were directly pasted at different locations (i.e. center and two edges) on the rear side of the cooler. Only the temperature at the center point is presented in this work. In each experiment, the temperatures at various points were recorded every 5 s, while the solar intensity was recorded every 2 min. The solar intensity was measured by a Solar Power Meter, (Iso-Tech with the Model No. ISM410). The spectral response is 400–1100 nm with an accuracy of ±10 W/m^2. The ambient air temperature was measured by TSI 8552 Q-Trak Plus with an accuracy of ±0.6 °C. Measuring instruments were calibrated before performing the experiments.

3. Results and discussion

3.1. Two days' continuous operation

Fig. 5 shows a temperature profile of the non-vacuum design passive radiative cooler and the vacuum design with 7 KCl windows. The experiment started at 7 p.m. on 25 Nov 2015, and ran continuously for 2 days. The sky was very clear during the first night. Both coolers produced a cooling effect during the night time. The non-vacuum design lowered the ambient air temperature by about 7 °C during the first night, while the cooler with vacuum reduced the ambient air temperature by about 6 °C. It should be noted that the temperature of the polished copper plate as well as the black body was also lower than that of the ambient air temperature, but the temperature reduction was not significant. This again proved that the passive radiative cooler can provide a cooling effect at night in Hong Kong's climate.

However, during daytime operation (under direct sunlight), it was found that the non-vacuum cooler increased the ambient air temperature by about 8 °C, a similar temperature to that of the

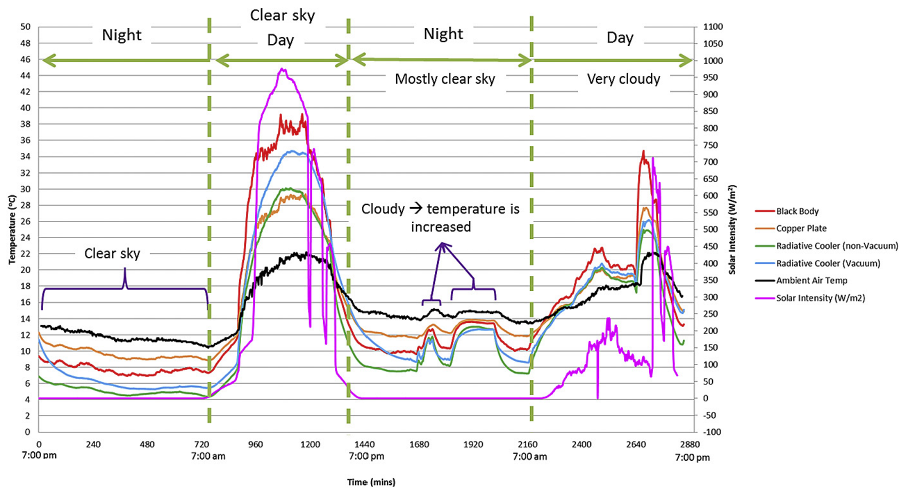

Fig. 5. Temperature profile of the passive radiative coolers with non-vacuum design and vacuum design with 7 KCl windows.

polished copper plate. Surprisingly, the results from the cooler with vacuum design were even worse, with the ambient air temperature increasing by about 12 °C. This significant increase in temperature may be because of a large amount of heat being absorbed by the inner wall/components of the vacuum chamber. With regard to this, the number of KCl windows should be revised in order to ensure that only the area from the passive radiative cooler is exposed to outer space. Fig. 6 shows the revised passive radiative cooler design. Only one KCl window is adopted, and the vacuum chamber cover is coated with a highly reflective aluminum Mylar, so that the whole vacuum chamber can be treated as a reflector, except for the central area of the cover that houses the KCl window. Fig. 7 shows the overall experimental setup of the passive radiative cooler design without vacuum as well as the vacuum design with the single KCl window during night time operation.

3.2. Daytime space cooling

After installing the single KCl window at the middle of the vacuum chamber cover, the test was conducted again and the result is shown in Fig. 8. Surprisingly, our proposed cooler showed an enhanced performance. Most importantly, it showed a better result than that of the non-vacuum design during daytime operation. Although the cooler's temperature is still about 1–2 °C higher than that of the ambient air, it should be noted that the exposure area of our cooler (100 mm in diameter) is much smaller than that of the non-vacuum design (200 mm in diameter), thus, the cooling power is smaller, limiting the temperature reduction. In other words, if the exposure area of our proposed cooler is the same as the non-vacuum device, it is believed that a cooling effect may be produced during daytime operation in Hong Kong's weather. As the single KCl window design showed a better cooling performance during daytime operation, the design will be used for the following tests.

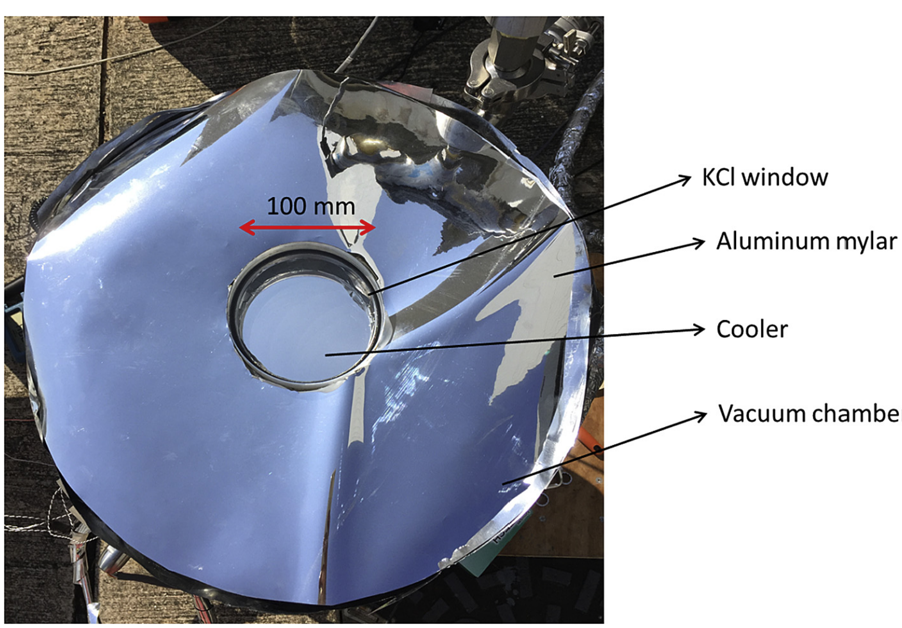

Fig. 6. A passive radiative cooler placed inside the vacuum chamber with a single KCl window.

Fig. 7. Overall experimental setup of the passive radiative coolers with non-vacuum design and vacuum design with a single KCl window during night time operation.

The non-vacuum cooler does not work in Hong Kong's weather during daytime operation. The cooler's temperature was about 6–7 °C higher than that of the ambient air. This result obtained is totally different compared to Ref. [17] (i.e. the cooler can cool the ambient air temperature by about 5 °C under direct sunlight). This is probably because the cooler works well in California's weather which is dry and cold, but not in Hong Kong's weather which is hot and humid. Harrison conducted a study on the effect of atmospheric humidity on radiation cooling [18]. It was shown that the radiative cooling performance of the TiO_2 white paint decreases with increasing absolute humidity, and weakly depends on the ambient temperature. The tests in Ref. [17] were conducted in mid-December 2013, where the ambient air temperature was about 17 °C and the absolute humidity about 10 g/m^3. In our study, the ambient air temperature was about 22 °C and the absolute humidity was up to 16 g/m^3. For the TiO_2 white paint, the radiation cooling was predicted to be 4 °C with absolute humidity at 10 g/m^3, and only about 2 °C with absolute humidity above 15 g/m^3 without direct sunlight. The cooling performance is reduced by half. This is because the presence of water vapor reduces the transparency of the atmosphere. Water vapor can absorb a large range of EM radiation and it is the main dominant greenhouse gas [19]. It is believed that the cooling performance of the photonic radiative cooler studied in this paper shall obey a similar trend as the TiO_2 paint, as both techniques utilized the 8–13 μm infrared atmospheric window.

3.3. Night time space cooling

Fig. 9 shows a temperature profile of the passive radiative cooler design without the vacuum and the design using a vacuum with the single KCl window under partly clear and partly cloudy weather conditions. It can be seen that the weather hugely affects the cooling performance. The temperature variation is very sensitive to the change of the weather. So, in order to achieve an excellent cooling performance, a clear sky is necessary.

In Fig. 10, it can be observed that a constant temperature difference of about 6 °C was achieved between the passive radiative cooler with non-vacuum design and ambient air temperature throughout the whole night operation (i.e. 6:00 p.m. to 7:00 a.m.). Regarding the passive radiative cooler design with vacuum and the single KCl window, a constant temperature difference of about 1 °C was obtained, the temperature difference being similar to the effect generated by the polished copper plate. Additionally, the black body can cool the ambient air temperature by about 2 °C during night time operation. This implies that the cooling effect generated by the black body is greater than the cooler and the polished copper plate. Thus, the cooling effect produced by the cooler design with vacuum and the single KCl window is not satisfactory during night time operation in Hong Kong's environment, even though it was tested under a very clear night sky. However, it should be noted that only 1 KCl window is utilized, thus the cooling effect is limited. Recalling the results from Fig. 5, our developed passive radiative cooler with 7 KCl windows can cool the ambient air temperature by about 6 °C during night time operation, which is about 5 times that of the cooler with 1 KCl window. On the other hand, it may be argued that nearly 20 °C below ambient can be achieved by the passive radiative cooler based on the results published by Ref. [17]. However, it should be noted that the result they obtained is through the simulation approach. Besides, the external effect is also different (i.e. California's weather vs. Hong Kong's weather). In Hong Kong's weather conditions, the passive radiative cooler (non-vacuum) can only produce the cooling effect during night time operation.

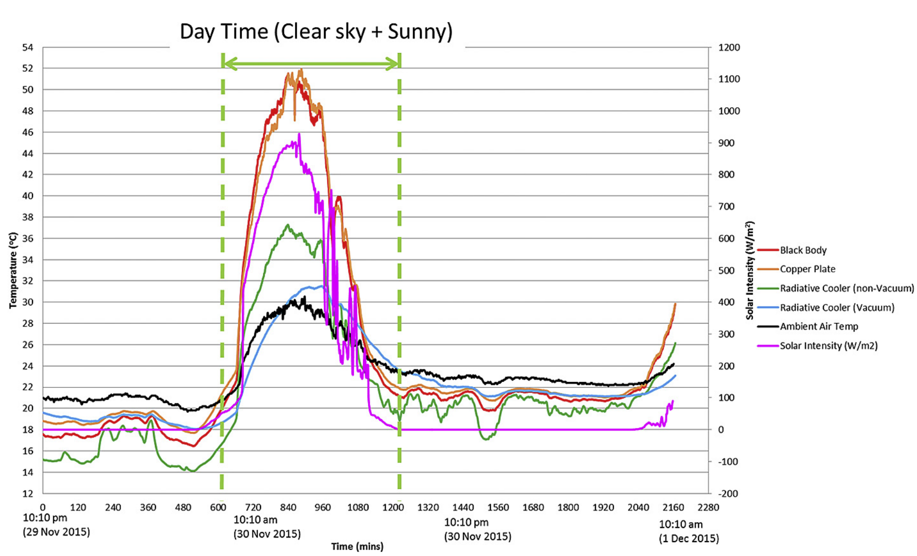

Fig. 8. Temperature profile of the passive radiative cooler with non-vacuum design and vacuum design with a single KCl window under a clear sky (daytime operation).

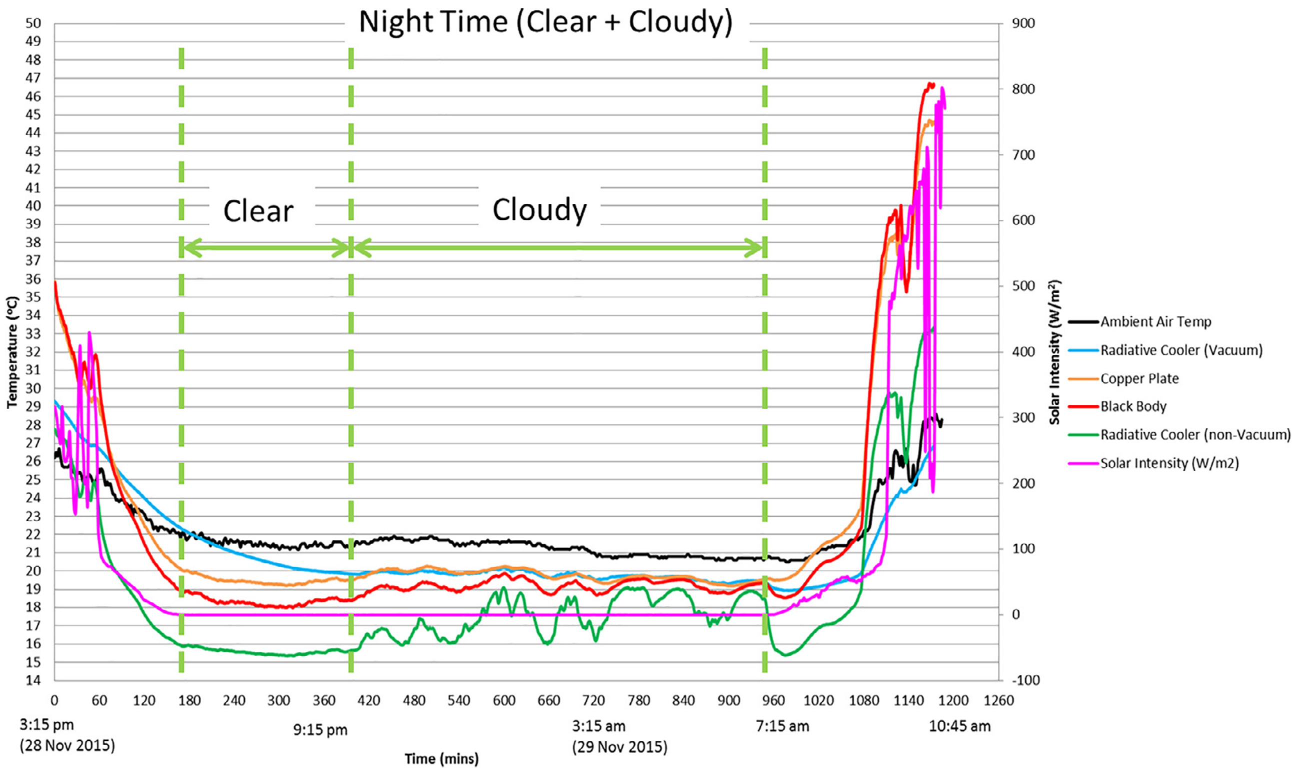

Fig. 9. Temperature profile of the passive radiative coolers under partly cloudy weather conditions.

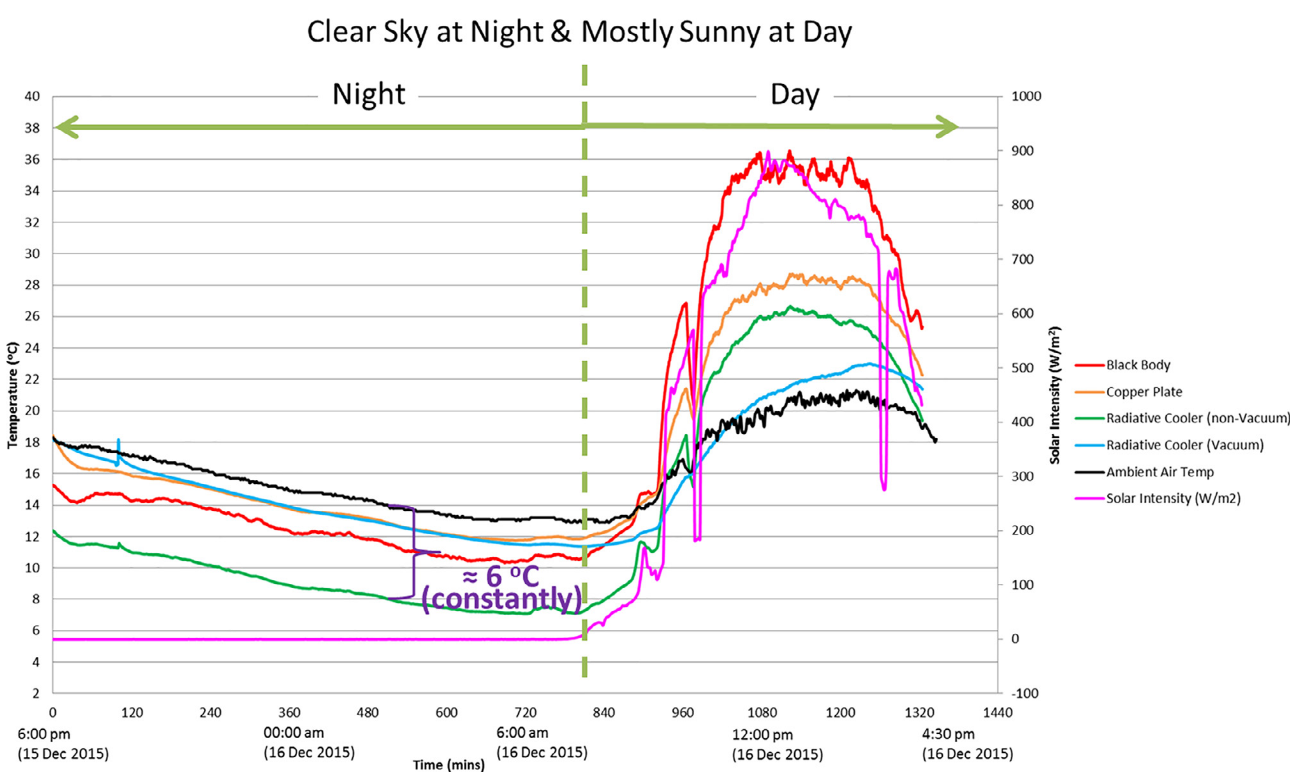

Fig. 10. Temperature profile of the passive radiative coolers under a clear night sky weather condition.

3.4. *Effect of clouds*

During December in Hong Kong, the weather condition was very cloudy for one day of the tests. All the coolers were barely able to cool the ambient air temperature during the night as shown in Fig. 11 since the long wavelength infra-red radiation was blocked by

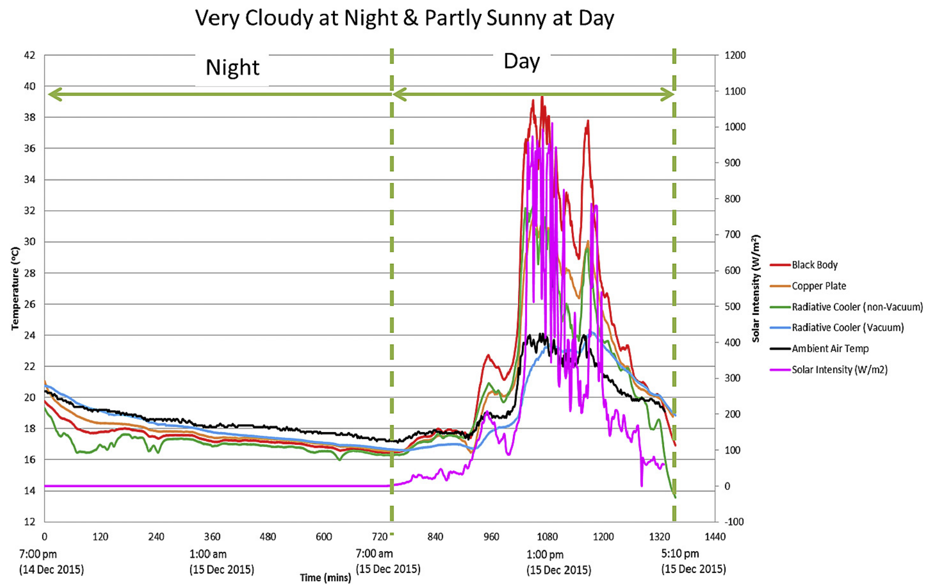

Fig. 11. Temperature profile of the passive radiative coolers under cloudy weather conditions.

the clouds, preventing emissions to outer space where the temperature is absolute zero. Overall, the cooling effect is limited during a cloudy day. This again proves that the passive radiative cooler depends hugely on the weather and requires a clear sky to provide a satisfactory cooling performance.

3.5. Cooling capacities estimation

The results of maximum temperature difference under different weather conditions with different design configurations have been discussed above, but there is an unknown: the cooling power. Therefore, in this section, the cooling capacity of the passive radiative cooler (non-vacuum) is investigated.

As the largest temperature difference obtained between the ambient air and cooler's temperature was achieved with the non-vacuum design during night time operation, the cooling power was estimated using the passive radiative cooler with non-vacuum design at night. A heater pad was pasted directly on the rear side of the passive radiative cooler. The cooling power is equal to the heating power of the heater pad while the temperature remains the same as the ambient air temperature. The power of the heater was recorded by a Digital Power Meter (YOKOGAWA with the Model No. WT210). Fig. 12 shows the temperature profile of the passive radiative coolers. The cooling capacity was estimated at 2:45 a.m. on 17 Dec. 2015. It can be seen that the temperature of the passive radiative cooler (non-vacuum) increased immediately at about 2:35 a.m. after the heater was switched on. The voltage of the heater pad was adjusted slightly to maintain the same ambient air temperature (please refer to Fig. 12). The voltage and the current of the heater pad were recorded simultaneously via a computer. By multiplying them together, the cooling power of the passive radiative cooler can be estimated. It is found that the passive radiative cooler with non-vacuum design achieved a cooling capacity of 1.2 W (38 W/m^2).

4. Recommendations

Although none of the coolers achieved a cooling effect during daytime operation in Hong Kong's climate, it is believed that the cooling performance of the photonic radiative cooler could be further enhanced through the following approaches.

4.1. Active guard cooler and radiation shields

In order to eliminate the power gain due to radiation or the absorbed power due to incident thermal radiation from the vacuum chamber (P_{rad}), an active guard cooler and radiation shield could be considered. As the vacuum chamber will be exposed to the atmospheric environment, its temperature will be equal to that of the outdoor temperature or even higher (i.e. 40 °C). An active guard cooler will absorb the thermal radiation heat from the vacuum chamber wall. If the temperature difference between the cooler and vacuum chamber wall is zero, there is no thermal radiation heat exchange. However, it is impossible or unrealistic to have a cold vacuum chamber wall where the temperature is the same as the cooler since it requires energy to cool the vacuum chamber. Thus, it is suggested that the temperature of the vacuum chamber wall is controlled by a water cooling tower, where the cooling water temperature is around 27 °C. This technology is named as an active guard cooler. In order to further reduce the radiation heat loss/gain, radiation shields are recommended to be installed.

4.2. A large ZnSe IR-Pass window

In this study, a KCl IR-pass window is utilized since it is low cost and the transmittance of the KCl crystal, in the range between 0.3 and 18 μm, is about 90%. As a result, the thermal radiation heat released by the passive radiative cooler can transmit to outer space through the KCl windows. However, KCl is a very brittle material and it dissolves in water. Other IR-pass windows could be considered as long as the transmittance is high in the wavelength of 8–13 μm, for example: ZnSe and KBr. ZnSe is a good choice since it is resistant to water (only slight degradation in water), but it is extremely expensive. In order to achieve the largest exposure area to outer space (i.e. the passive radiative cooler's diameter utilized in this study is about 200 mm), the IR-pass window's diameter should be larger than 200 mm. However, due to the brittleness of the KCl, the largest diameter for use in a vacuum application is about 100 mm, limiting the exposure area to outer space. Therefore, it is suggested that a ZnSe window is utilized since it is much stronger

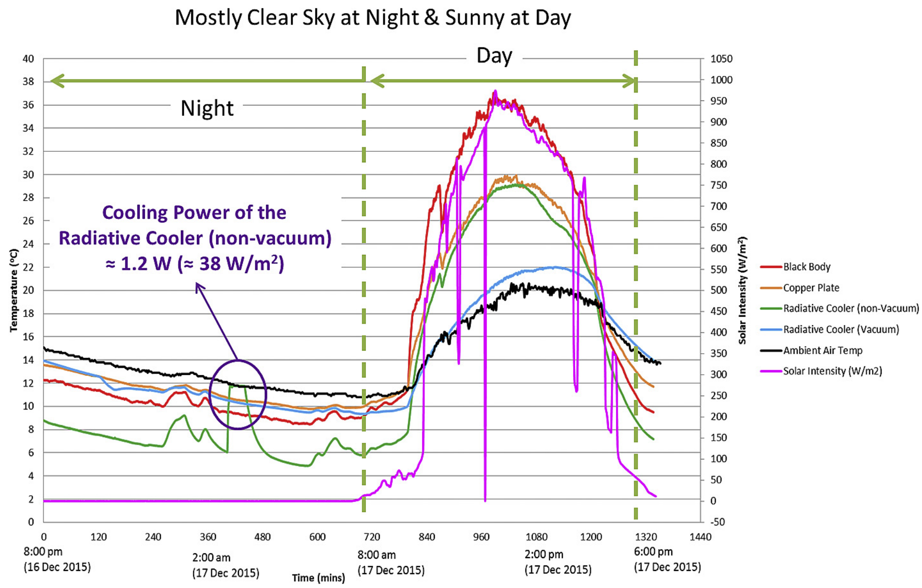

Fig. 12. Temperature profile of the passive radiative cooler with the purpose of estimating the cooling capacity.

than the KCl window in terms of the stiffness, allowing the middle exposure area of the vacuum chamber cover to be enlarged (i.e. greater than 100 mm), leading to enhance the cooling performance. In the long term, a ZnSe IR-pass window with a larger area should be considered.

4.3. Biomimetic coating

A recent article reported that the conspicuous silvery appearance of the Saharan silver ant is created by a dense array of uniquely shaped triangular hairs providing two thermoregulatory effects [20]. The reflectivity of the ant's body surface in the visible and near-infrared range of the spectrum is enhanced. In addition, the emissivity of the ant in the mid-infrared is also improved. This promising result could have a significant technological impact by inspiring the development of biomimetic coatings for passive radiative coolers.

5. Conclusions

In this study, we utilized the same passive radiative cooler based on Ref. [17], but with three different thermal designs, one identical to Ref. [17], while the other two are our proposed vacuum designs with different number of KCl windows. The experimental results showed that the passive radiative cooler with 7 KCl windows could only provide a satisfactory cooling effect at night, reducing the ambient air temperature by about 6 °C, while the passive radiative cooler with a single KCl window was only able to cool the ambient air temperature by about 1 °C. Regarding the daytime operation, the passive radiative cooler with 7 KCl windows increased the ambient air temperature by about 12 °C, about 6 times that of the cooler with the single KCl window. Neither passive radiative cooler with vacuum design was able to provide a cooling effect under direct sunlight.

It was found that the local weather plays a major role on the cooling performance of the passive radiative cooler. A clear sky can provide an extremely good cooling performance. The passive radiative cooler with non-vacuum design (Ref. [17]) can cool the ambient air temperature during night time (i.e. reducing the ambient air temperature by about 7 °C), but it cannot provide cooling effect during daytime under Hong Kong's weather conditions. This finding contradicts the results shown in Ref. [17] that the cooler lowers the ambient air temperature by about 5 °C under direct sunlight. This can be totally due to external factors (i.e. weather). The passive radiative cooler operates well in California's (USA) weather, but not in Hong Kong's weather. In short, the cooling performance of the passive radiative cooler with non-vacuum design at night is satisfactory, producing a cooling power of 1.2 W (i.e. 38 W/m^2) under a clear night sky in Hong Kong.

Overall, this initial study indicated that cooling by using night radiation technique seemed to be feasible in Hong Kong, but there remains much work to successfully produce the cooling effect under direct sunlight in Hong Kong's climate.

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