NUMERICAL INVESTIGATION OF THE BENEFITS OF DAYTIME RADIATIVE SKY COOLING PANELS AS SUB-COOLER ON THE EFFICIENCY OF VAPOR COMPRESSION CYCLE COOLING SYSTEMS

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ABSTRACT

Radiative cooling is one solution to increase the energy efficiency of cooling systems, while mitigating the heat island effect and providing a passive solution for equitable access to cooling. Through a combination of high solar reflectivity (95%) and high infrared emissivity (90%), radiative coolers – when facing the sky – can passively reject heat to outer space and achieve sub-ambient temperatures, even when exposed to intense solar radiation. In the present study, an integration schemes involving radiative cooling panels as sub-coolers in vapor compression cycle (VCC) air conditioners is subject to numerical investigation. A water cooled loop in radiative sky cooling panels is used as a heat sink to absorb heat from the refrigerant through a heat exchanger placed after the air-cooled condensation. Numerical simulations show that integrating the water-cooled loop with radiative panels as sub-coolers in a small split-unit cooling device leads to an increase of up to 15% in the Energy Efficiency Ratio (EER) of the split unit, considering a typical meteorological year of a hot and arid region. In a context of global warming, an alternative is to couple existing air conditioners with radiative sky cooling loops as sub-coolers to increase the cooling capacity of the machines.

1 INTRODUCTION

Growing demand for air conditioning and cooling systems is one of the most alarming blind spots in today's energy debates. The International Energy Agency (2018) recently warned about a potentially dangerous "cold crunch" from the growth in cooling demand. The report revealed striking patterns: 10 new air conditioners sold every second for the next 30 years.

As the planet is getting warmer, cooling services are turning into an essential necessity for the health and well-being of the global population. In 2020, the total greenhouse gas (GHG) emissions related to refrigeration and space cooling was estimated to be 10% of worldwide emissions, and it is expected to increase significantly in the coming years (Dong et al., 2021). Another problem of the spreading out of air conditioners is that it is a major contributor to the urban heat island effect. In cities in which air conditioners are vastly implemented, space cooling can raise average exterior temperatures by more than 1°C (Salamanca et al., 2014). Given the forthcoming expansion in the space cooling demand and the potential drawbacks associated with it, active research is aimed at enhancing the efficiency of cooling machines. From thermodynamics, the efficiency of the Vapor Compression Cycle (VCC) air conditioners is dependent on the temperature of the refrigerant condensation: achieving lower condensation temperatures leads to an enhancement in the energy efficiency of the machine (Park et al., 2015). Another way to improve the Energy Efficiency Ratio (EER) of air conditioners is to sub-cool the refrigerant below the typical limit of air-cooled condensers (Pottker & Hrnjak, 2015). It would be particularly interesting to be able to passively sub-cool the refrigerant below the dry-bulb air temperatures with no evaporative water loss.

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Radiative sky cooling is an innovative process that enables cooling to sub-ambient temperatures passively and without water evaporation losses (Raman et al., 2014). By a combination of high infrared thermal emissivity and low solar absorptivity, a sky-facing object is able to reach sub-ambient temperature, even under direct sunlight (Fan & Li, 2022). The integration of sky radiative cooling materials and their large-scale deployment are ongoing research questions. For instance, fluid cooling panels featuring sky cooling materials on its surface has been used to cool water by up to 5°C below ambient under peak solar radiation of 850 W/m² (Goldstein et al., 2017). Injecting the sky cooled water into air conditioning systems can significantly improve the device efficiency (Chen et al., 2021).

In this paper, we numerically investigate the integration of a radiative sky cooling water loop operating as refrigerant sub-cooler of a VCC split unit air conditioner. Particularly, we focus on a use-case of hot and dry climate type, in which cooling demand is extremely high and cooling systems are quite inefficient. The paper aims to numerically demonstrate the significant performance improvements achievable by implementing radiative cooling panels as sub-coolers, enhancing the overall efficiency of split-unit cooling devices.

2 BACKGROUND

2.1 Daytime Radiative Cooling Materials

The Earth atmosphere is partially transparent to mid-infrared radiation (i.e., 8 to 13 µm), which is commonly referred to as the “atmospheric window”. A sky-facing object on Earth’s surface with a high emissivity in the mid-infrared wavelength range is able to radiate its heat through the atmosphere to the outer space (Fan & Li, 2022). Night-time radiative cooling integration in HVAC (Heating, Ventilation and Air Conditioning) systems has been studied for many decades. However, and because peak cooling demand frequently occur during the day, it is necessary to be able to achieve daytime radiative cooling and under direct sunlight.

Practically, to be able to perceive meaningful daytime radiative cooling, more than 94% of incoming sunlight must be reflected (Martin & Berdahl, 1984). This property needs to be coupled with a high and selective emissivity in the atmospheric window, so that emitted infrared radiation can leave the atmosphere and reach outer space (Raman et al., 2014). **Figure 1** illustrates the theoretically “ideal” spectral emissivity to achieve daytime radiative cooling combining both a low solar absorptivity and a selectively strong emissivity close to unity in the atmosphere window (8-13 µm) (Rephaeli et al., 2013).

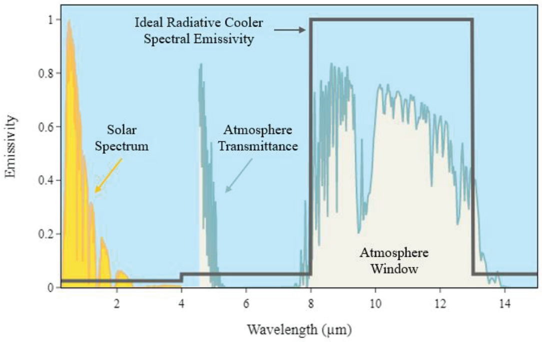

Figure 1: Ideal Emissivity Spectrum of a Daytime Radiative Cooling Material.

Daytime radiative cooling was experimentally demonstrated for the first time by Raman et al. (2014), who developed an innovative photonic material that satisfies the optical conditions required to achieve cooling during daylight hours. The structure achieved a temperature of 5°C below ambient temperature under 900 W/m² of direct sun radiation. After the initial experimental demonstration, daytime radiative cooling has emerged as a promising solution for many different applications.

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2.2 Water Loop Daytime Radiative Cooling Integration in HVAC Systems

In buildings, radiative sky cooling devices can be used as an auxiliary cold generation source that improves the efficiency of HVAC systems. Among the potential integration schemes, water-based radiative sky cooling systems produce the most energy savings (Zhao et al., 2019).

Wang et al. (2016) proposed a sky cooling water loop composed of a panel in which water is cooled before being stored in an insulated tank. Cooled water is used to pre-cool and assist a water chiller mounted to radiant-cooled offices. The introduced daytime radiative cooler could save up to 68% of cooling electricity compared to a typical variable air volume system. Similarly, Zhang et al. (2018) proposed to use radiative sky cooling water-loop to pre-cool air, thereby reducing the cooling load on the air conditioner. Numerical analysis of this integration scheme has demonstrated annual cooling electricity savings by between 26% and 46% in the United States compared to a split-unit standalone.

In hot climates, evaporative coolers (e.g. cooling towers) are used to lower the condensation temperature of VCC air conditioners by evaporating water into the ambient air (Goldstein et al., 2017). However, using evaporative cooling systems results in substantial water loss, which is a source of concern in water-stressed regions. Therefore, it would be interesting to couple evaporative cooling devices with radiative cooling panels. Katramiz et al. (2020) designed a cooling system composed of an indirect evaporative cooler along with water sky cooling panels. The designed system reduced the evaporative cooler water consumption by 44%. Also, the innovative system reduced the electricity consumption by 53% compared to a typical air conditioner in Kuwait.

2.3 Sub-Cooling in Vapor Compression Air Conditioners

Air conditioners that rely on VCC has significant thermodynamic losses as compared to an ideal reverse Carnot cycle. Sub-cooling is a technique used to mitigate those losses by cooling the saturated liquid refrigerant entering the expansion device at the condenser pressure (Pottker & Hrnjak, 2015). Indeed, sub-cooling the refrigerant increases the cooling capacity of the air conditioner as depicted in **Figure 2**. The enthalpy of the refrigerant is reduced after the expansion process, allowing it to absorb more heat from the cooled space at the same refrigerant flow rate. Therefore, the EER of the cooling system is increased. Sub-cooling has received particular attention as a way to enhance energy efficiency in VCC air conditioners (Park et al., 2015). Any available cold sink could be used to sub-cool the refrigerant.

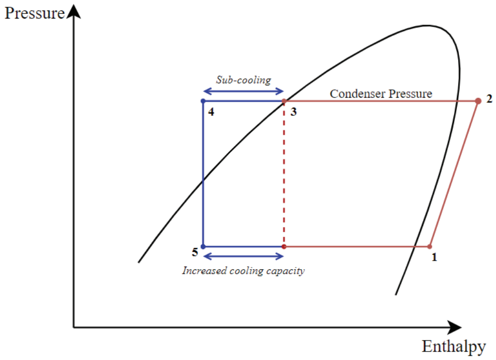

Figure 2: Typical pressure–enthalpy diagram of VCC with sub-cooling.

2.4 Daytime Radiative Sky Cooling as Sub-Cooler in VCC

Daytime radiative sky cooling emerges as a highly appealing method to passively sub-cool refrigerant beyond the air-cooled condenser, requiring no additional electrical input or water consumption.

Goldstein et al. (2017) were the first to propose to harness the cold of outer space in radiative water sky cooling panels to sub-cool the refrigerant as presented in **Figure 3**. Experimentally, water was sky cooled up to 5°C below the ambient temperature during daytime, with a net cooling heat flux of 70 W/m². Numerical analysis showed that the daytime radiative sky sub-cooler could save up to 21% of cooling electricity demand in a hot and dry climate. Experimental tests were conducted in September 2017, and up to 8°C of refrigerant sub-cooling was observed. Furthermore, refrigerant was cooled to sub-ambient temperature by the water radiative sky cooling loop (Goldstein, 2018).

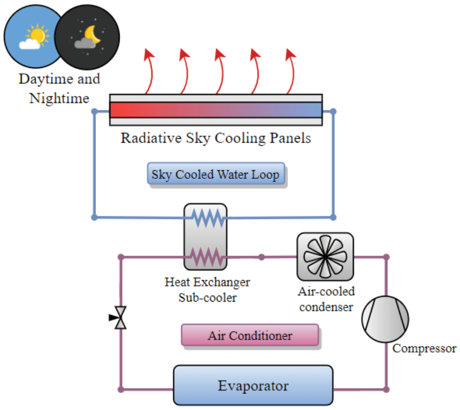

Figure 3: Radiative Sky Cooling Water Loop to Sub-Cool Refrigerant in Air Conditioner.

Recently, Zhao et al. (2019) proposed an innovative system capable of delivering day-and-night continuous cooling by separating daytime and nighttime radiative sky cooling operations. During the day, when the cooling load is high, the sky cooled water is used to sub-cool the refrigerant. However, during the night, the sky cooling energy is stored in a tank, which is retrieved during the day. Modeling results indicate that the system has the potential to provide cooling electricity savings ranging from 32 to 45% during the summer months in an office building located in the United States.

3 MODEL DESCRIPTION

The aim of this work is to numerically investigate the potential benefits of integrating a radiative sky-cooled water loop to sub-cool the refrigerant in a typical VCC air conditioner. Specifically, we examine three profits of radiative sky sub-cooling as sub-cooler: increasing overall energy efficiency, reducing the duration of air conditioning operation – and consequently decreasing AC electrical consumption – and minimizing the number of thermal discomfort hours. Therefore, a dynamic model of the system presented in **Figure 3** must be developed. This section outlines the completed modeling work.

3.1 Radiative Sky Cooling Panels Model

Consider a radiative sky cooling panel placed on Earth's surface. The radiative cooling panel undergoes four different heat transfer processes as seen in **Figure 4**. The net radiative cooling power $P_{net\ cool}$ generated at the surface of the sky cooler is given by equation (1) (Raman et al., 2014).

$$P_{net\ cool} = P_{rad} - P_{atm} - P_{sun} - P_{parasitic} \tag{1}$$

P_{rad} is the outgoing radiative power by the emitting surface, P_{atm} is the amount of infrared atmospheric radiation absorbed by the surface, P_{sun} is the solar irradiance absorbed by the radiative surface and $P_{parasitic}$ represents the parasitic heat gain due to conduction and convection from the surrounding air and external materials in contact with the panel.

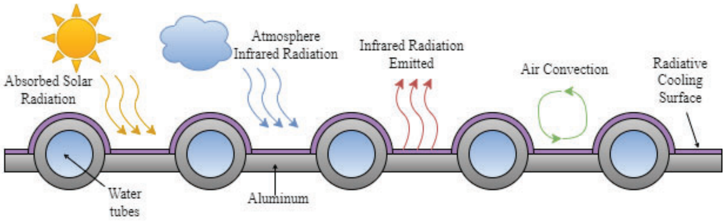

Figure 4: Heat Transfer Processes on a Radiative Cooling Surface.

The infrared radiative power emitted from the cooling panel depends on the surface temperature according to Planck's Law. Assuming a radiative cooler of surface area A, spectral emissivity ε(λ) and surface temperature T_S, equation (2) gives the power radiated out by the surface.

$$P_{rad}(T_S) = A \int \cos\theta \, d\Omega \int_0^{\infty} I_{Blackbody}(T_S, \lambda) \times \varepsilon(\lambda) \times d\lambda \tag{2}$$

$I_{Blackbody}$ is the function of spectral radiance of a pure blackbody at surface temperature T_S, and θ is the solid angle between the direction of the outgoing radiation and the normal to the surface. The solar power absorbed by the cooling panel is given by equation (3) (Rephaeli et al., 2013).

$$P_{sun} = A \times \overline{\alpha_{abs}} \times I_{sun} \tag{3}$$

$\overline{\alpha_{abs}}$ is the average solar absorptivity over the solar radiation spectrum, and I_{sun} is the global solar heat flux at the cooling panel surface. The atmosphere radiation P_{atm} absorbed by the sky cooling radiative surface is given by equation (4), considering that the atmosphere is at a uniform temperature of T_{amb} corresponding to the ambient air temperature (Raman et al., 2014).

$$P_{atm} = A \int \cos\theta \, d\Omega \int_0^{\infty} I_{BB} \; T_{amb}, \lambda \;\; \times \varepsilon \;\; \lambda \;\; \times \varepsilon_{atm} \;\; \lambda \;\; \times d\lambda \tag{4}$$

$\varepsilon_{atm} \;\; \lambda$ is the spectral atmosphere emissivity which depends on so the atmosphere composition and the meteorological conditions. MODTRAN software is used to predict the atmosphere emissivity. The parasitic heat transfer due to convection with the ambient air is given by equation (5).

$$P_{conv} = A \times h_c \times (T_{amb} - T_S) \tag{5}$$

T_{amb} is the ambient air temperature and T_S is the radiative cooling panel surface temperature. h_c is a combined non-radiative heat transfer coefficient that models the effect of the heating or cooling from convection with air flow over the radiative cooler.

The finite volume method is used to determine the evolution of water temperature inside the radiative sky cooling panel, as presented in **Figure 5**. Each water tube is divided into a fixed number of equal control volumes along the length of the tube. Considering a static system, the conservation of mass equation (6) and the conservation of energy equation (7) can be applied at each node of the cooler.

$$\dot{m}_{w_{i-1}} - \dot{m}_{w_i} = 0 \tag{6}$$

$$\dot{m}_{w_{i-1}} h_{w_{i-1}} - \dot{m}_{w_i} h_{w_i} - \sum Q_i = 0 \tag{7}$$

$\dot{m}_{w_i}$ and h_{w_i} are the water flow rate and the specific enthalpy at the ith node, respectively. Q_i represents the heat transfer leaving the control volume. Q_i depends on the temperature of the panel surface, which is calculated at each node by an energy balance considering the thermal resistance of tubes internal fluid convection, the conduction in the aluminum sheet and the heat transfer at the surface of the panel. The distance between 2 consecutive tubes is considered high enough to have a fin efficiency of 100%, and therefore we can neglect any temperature difference in the metal sheet between tubes.

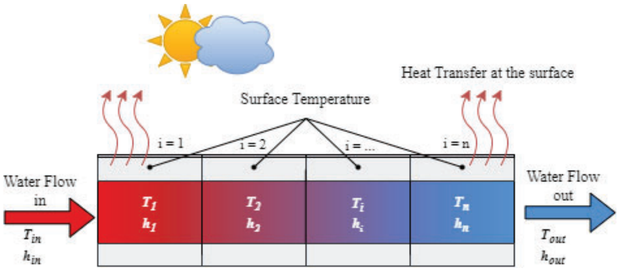

Figure 5: Finite Volume Discretization of a Radiative Sky Cooling Panel.

The exit temperature of water and the net cooling power at the panel surface can thus be precisely modeled when the radiative sky cooling panel is placed horizontally facing the sky, given the meteorological conditions and the inlet temperature of water.

3.2 Fixed Speed Air Conditioner Model

The work focused on the system performance of a split-unit air conditioner (AC). To better investigate the potential benefits of integrating a radiative sky cooling loop as sub-cooler, a commercially available AC with a fixed-speed compressor is modeled. Indeed, the fixed-speed compressor will operate at 100% of its capacity and will automatically start and stop to maintain the desired set-point temperature. The refrigerant has a constant volumetric flow rate determined by the size of the compressor. The AC can cool the room beyond the set-point temperature and then turn off until the room temperature rises above a certain threshold as seen in **Figure 6**.

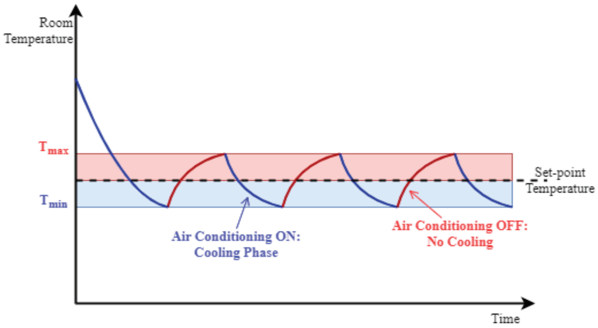

Figure 6: Functioning of Fixed Speed Compressor Air Conditioner.

The refrigerant is at the superheated state at the inlet of the compressor. Knowing the superheating degrees and the refrigerant low pressure, along with the compressor volumetric flowrate and volumetric efficiency, the mass flow rate of the refrigerant can be calculated by equation (8).

$$\dot{m}_r = \rho_r \times \Phi_r \times \eta_{vol} \tag{8}$$

$\dot{m}_r$ is the refrigerant mass flow rate, Φ_r the compressor fixed volumetric flow rate, and η_{vol} the compressor volumetric efficiency. The isentropic efficiency of the compressor is used to calculate the state of the refrigerant at the discharge state. The expansion process is considered isenthalpic. Energy balance and pinch analysis optimization are used on both the condenser and the evaporator to determine the optimal pressure stages. At the condenser side, the pinch is calculated considering the heat exchange between the refrigerant and the outside ambient air. On the evaporator side, the inside conditioned air is cooled down by the refrigerant, which must be superheated before re-entering the compressor. The sub-cooler heat exchanger that cools the refrigerant with the sky cooled water loop is modeled using the Number of Transfer Units (ε-NTU) method.

3.3 Building Model

To model the cooling cycle illustrated in **Figure 6**, a dynamic model of the room air temperature is required. The room characteristics are presented in **Table 1**.

Table 1. Modeled Room Characteristics.

	Value	**Units**
Room Dimensions	8x8x4	m
Wall Material	Concrete	-
Wall Thickness	0.2	m
Wall Solar Absorptivity	0.65	-
Convection Coefficient Outside	4	W/m^2.°C
Convection Coefficient Inside	0.75	W/m^2.°C
Ventilation	50	m^3/h

The convection coefficient outside is taken to be 4 W/m^2.K, which corresponds to a medium wind force outside the room (Zhao et al., 2019). Inside, the air is assumed to be stagnant, meaning natural convection predominates, resulting in a smaller convection coefficient. The room is considered to have an internal heat generation that is variable across the day, as presented in **Figure 7**.

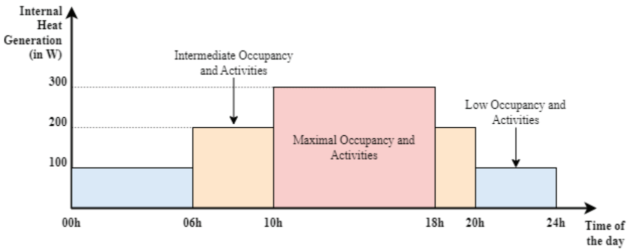

Figure 7: Internal Heat Generation Profile.

The inside air undergoes three different heat transfer: ventilation with the outside air at a fixed rate, convection with the inside wall surface, and cooling when the air conditioner is activated. The heat transfer equation of the air is given by equation (9).

$$\rho_{air} V_{air} c_{air} \frac{dT_{air}}{dt} = \sum Q_{air} , \qquad T_{air}(0) = T_{air}^{0} \tag{9}$$

ρ_{air} is the density of air, considered constant throughout the room, V_{air} the room volume, c_{air} the specific heat constant of air, and T_{air}^{0} is the initial room temperature. Q_{air} represents the thermal power transferred to the room or out of the room. The wall is divided into three nodes across its thickness, and Fourier's heat transfer equation is solved for each node. Therefore, there are a total of 4 nodes, resulting in a system of 4 heat transfer differential equations.

The system of differential equations is presented in equation (10).

$$C \times \dot{T} = A \times T + E \times S \tag{10}$$

C is the diagonal matrix of heat capacities, T is the discretized temperature vector, A is the square matrix containing the heat transfer coefficient between the nodes, E is the matrix containing the heat transfer coefficient with the external solicitations, and S is the vector of external solicitations. External solicitations include internal heat generation, outside ambient temperature, and solar irradiation. Solving the matrix system gives the temperature at each node, including internal and external wall surface temperatures and room air temperature. An exponential matrix explicit resolution scheme with a fixed time step is used to solve the system differential equation.

4 RESULTS AND DISCUSSIONS

As previously discussed, air conditioners tend to be inefficient in hotter climates, due to the high condensation pressure. However, recent studies suggest that radiative sky cooling is particularly interesting in hot climates because of the high transparence of the atmosphere (Feng et al., 2020). Therefore, we focus the study on the integration of sky cooling panels as sub-cooler in hot climates.

4.1 Location and Climatic Conditions

United Arab Emirates (UAE) is currently the world's 5th highest country in energy consumption per capita, where 36% of the electricity is used for cooling purposes (Salameh et al., 2020). Therefore, UAE is selected as the use case for the numerical investigation. Meteorological data with a resolution of one datum per hour have been collected from a weather station located in Abu Dhabi for the year 2021 using the Copernicus archives.

The typical weather in Abu Dhabi can be divided into 2 separate periods: a hot season and a mild season. During the hot season, the weather is extremely hot, with daytime temperatures reaching up to 45°C or even higher. Solar radiation is particularly intense, often exceeding 1000 W/m². Air conditioning is essential during this season to maintain indoor air temperatures at a vital level. The rest of the year, during the mild season, there are fewer extreme weather conditions, with daytime temperatures typically ranging between 20 and 35°C. However, solar radiation remains high, and air conditioning is often utilized to maintain a comfortable indoor environment.

4.2 System Description

A radiative cooling panel is designed based on the panels implemented by Goldstein et al. (2018) depicted in **Figure 8**. Each radiative panel has a surface area of 2 m². 4 radiative cooling panels are placed in parallel (total surface area of 8 m²) which is convenient to be placed on a building roof.

Each panel consists of 12 water tubes, each with an inlet diameter d_{in} of 1 cm and a thickness t of 0.3 cm. The water flow rate is constant and set to 1 kg/min in each panel. Node sensitivity analysis indicates that the optimal mesh size is 10 nodes per tube. The radiative surface material has a reflectivity of 97% in the solar spectrum and has an emissivity that is ideally selective in the mid-IR range (described in Section 2.1.).

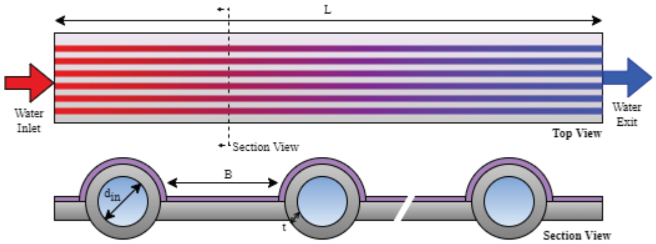

Figure 8: Sky Cooling Panel Geometry.

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A commercially available fixed speed air conditioner is modeled. The air conditioner is selected based on local recommendations, to maintain vital temperature inside the modeled room during peak hot days.

Table 2: Design Parameters for Fixed Speed Air Conditioner.

	Value	Units
Compressor Fixed Volumetric Flow Rate	1000	cm^3/s
Compressor Volumetric Efficiency	60%	-
Compressor Isentropic Efficiency	70%	-
Inside Air – Refrigerant Pinch	5	°C
Outside Air – Refrigerant Pinch	10	°C
Superheating	5	°C
Indoor Air Flow Rate	600	m^3/h
Air Flow on the Condenser	1000	m^3/h
Refrigerant	R410a	
Room Set-point Temperature	22	°C

The sub-cooler heat exchanger has a U_{HX} value of 540 W/m².K and a heat transfer area A_{HX} of 0.5 m². The selected refrigerant is R410a because it is the predominant refrigerant used in the UAE and to align with the experimental phase that will follow this work.

4.3 Results

First, we present key results for the capacity of the radiative cooling panels to sub-cool the refrigerant, along with the energy efficiency potential improvements. Simulation results are presented for a typical summer week in Abu Dhabi, UAE. **Figure 9** presents the temperature of the refrigerant before and after the sub-cooling heat exchanger.

Continuous sub-cooling is observable while the AC is turned on. The condensation temperature is typically much higher than the ambient temperature, and the water sub-cooling loop lowers the refrigerant temperature by an average of 6°C during the daytime and by up to 12°C during the nighttime. However, it is noteworthy that during the week, the refrigerant never reached a sub-ambient temperature. Radiative sky cooling panels have an average net cooling heat flux of 160 W/m² over the course of a week, with approximately 25% attributed to convection with air and 75% to radiation with the sky.

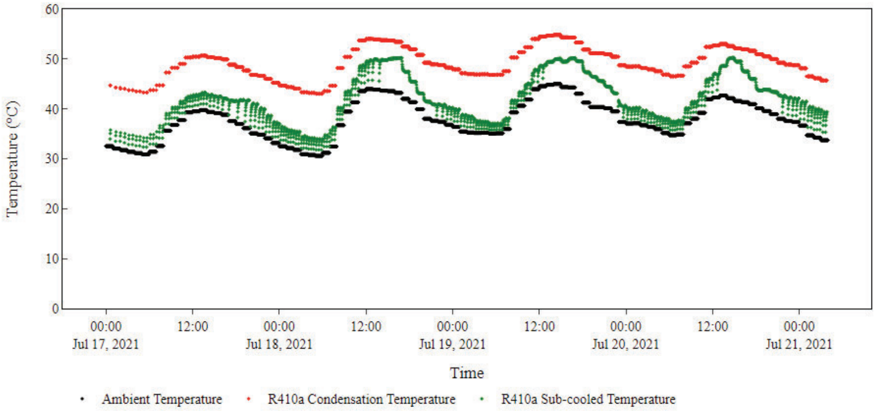

Figure 9: Refrigerant sub-cooling over 4 days in July.

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As previously discussed, sub-cooling the refrigerant leads to an increase in the cold produced on the evaporator heat exchanger inside the room. Therefore, the modified AC can reach the set-point faster. On average, throughout the hot season, the room equipped with an AC with the sub-cooler reaches the set-point around 10% faster than the commercial AC, as seen in **Figure 10**. This accelerated cooling translates to more frequent shutdowns of the air conditioner, leading to electricity savings.

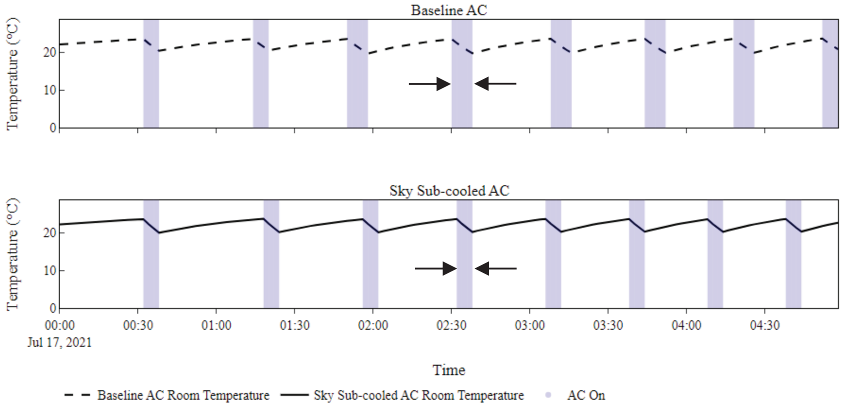

Figure 10: Sub-Cooled AC Reduced Cycling Duration.

Electricity cooling demand is reduced due to the enhanced cooling effect, as seen in **Figure 11**. Simulations for a typical summer week in Abu Dhabi show that the overall electrical consumption of the split-unit exhibits an 11.6% reduction in cooling electricity consumption by integrating the radiative sky sub-cooling water loop. In the mild season, the savings are approximately 9.4%.

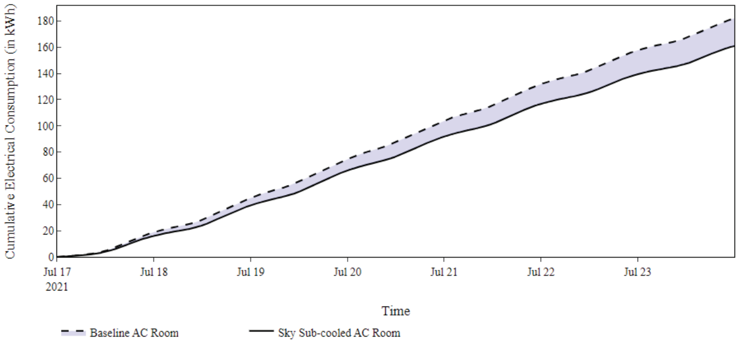

Figure 11: Cumulative Electrical Consumption of Split-unit during a Hot Week.

One additional potential benefit of integrating a radiative sky cooling sub-cooler is a reduction in the number of hours where the inside room temperature is outside the comfort thermal range. Indeed, with global warming, air conditioners need to provide a greater cooling load. Instead of replacing the whole machine, integrating a sky cooling sub-cooler could be a potential solution. During the hot season, the baseline AC operating independently can struggle to reach the set-point temperature of 22°C. This problem arises due to the fixed-speed split-unit's limited cooling capacity, which is insufficient to counterbalance the heat influx into the room. Consequently, the compressor continually cycles, leading to a significant surge in electrical consumption. However, upon integrating the sky sub-cooling loop, the air conditioner can maintain optimal operational conditions and achieve the desired set-point temperature, as depicted in **Figure 12**. This improvement is enabled by the additional cooling capacity supplied by the sub-cooling loop.

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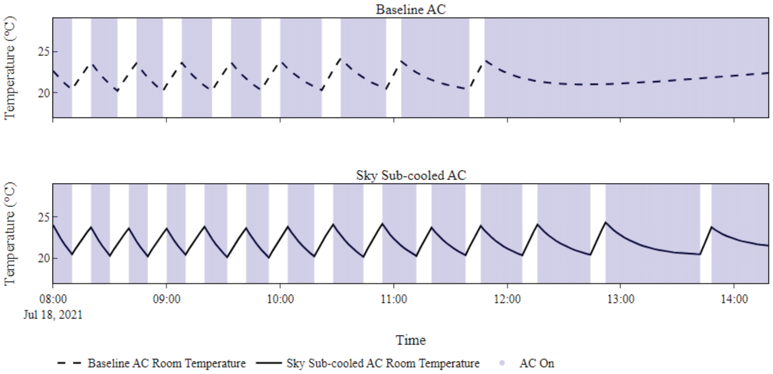

Figure 12: Sky Sub-cooled Air Conditioner Capability to Reach Set-point.

In more extreme conditions, the cooling device may struggle to maintain the room at a comfortable temperature. However, implementing a radiative sub-cooling loop can significantly mitigate such occurrences. For instance, simulations conducted show that the inside room temperature exceeded 25°C for a total of 27 hours in July. Following the integration of a radiative sky cooling loop, the number of hours with temperatures surpassing 25°C inside the room decreased to zero. Therefore, radiative sky sub-coolers are interesting to maintain comfortable temperatures, even during extremely hot weather conditions. **Table 3** presents a summary of the main advantages associated with incorporating a sky sub-cooling water loop into the performance of the air conditioner, as compared to the commercial baseline prototype.

Table 3: Results Summary of Sub-Cooling AC compared to Baseline AC.

	Hot Season	**Mild Season**
Cooling Electricity Consumption	-11.6%	-9.4%
Reduction in AC Working Time	-10.1%	-8.9%
Energy Efficiency Enhancement	+15.4%	+13.3%

5 Conclusion and Perspectives

In this paper, we conducted a numerical investigation into the potential benefits of integrating a radiative water sky-cooled loop as a sub-cooler in a typical vapor-compression cycle air conditioner. We selected a building in Abu Dhabi, UAE, as a use-case scenario. Numerical results reveal compelling insights into reducing cooling electricity consumption (around 10% savings over a year) and enhancing the energy efficiency of the cooling device. Notably, throughout the hot season, when air conditioning demand is remarkably high, we observed a significant 15% improvement in energy efficiency of the cooling machine.

Integrating a radiative sky cooling loop as a sub-cooler in a VCC system can yield additional benefits, such as reducing the time needed to reach the set-point temperature and consequently decreasing the overall air conditioner cycling time. This observation holds particular for enhancing cooling system capacity using existing components, thereby leading to a reduction in overall system costs. Moreover, over the course of a year, there is a significant reduction in the number of hours when the indoor temperature reaches unpleasant thermal conditions.

Furthermore, considering the anticipated rise in cooling demand due to global warming, it becomes imperative to address this challenge proactively. Instead of replacing all existing air conditioners to meet the escalating cooling demand, an interesting alternative is to couple existing air conditioners with

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radiative sky cooling loops as sub-coolers to augment the cooling capacity of the machines. Fortified by the positive outcomes of our study, we plan to implement an experimental apparatus in Abu Dhabi soon. This experimental setup aims to validate the numerical models and underscore the pivotal role of radiative cooling in revolutionizing the cooling sector.

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