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Night sky radiation cooling performance of greenhouse roofs for different configurations in the Arabian gulf region

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Abstract
This study investigates the effectiveness of night sky radiation cooling for greenhouse roofs in the Arabian Gulf region, where extreme temperatures (often exceeding 45°C) challenge conventional cooling methods. Five roof configurations (flat, sloped, gable, vaulted, and pyramidal) were evaluated using experimental measurements and computational modelling. High-emissivity materials including glass, polyethylene film, fiberglass, and polycarbonate sheets were tested for their radiative cooling potential. Results demonstrate that flat and vaulted roofs with polycarbonate coatings achieved the highest cooling performance, reducing nighttime temperatures by 5-7°C compared to ambient. These configurations reduced energy consumption for active cooling by 20-30%, offering significant potential for sustainable agriculture in arid climates. The findings provide practical guidelines for greenhouse design optimization in regions with similar climatic conditions.

Keywords: greenhouse, energy conservation, night sky radiation, roof profiles, roof material, room cooling, arid climate

Introduction

The Arabian Gulf region presents unique agricultural challenges due to extreme summer temperatures (45-50°C daytime), high solar irradiance (up to 7.5 kWh/m²/day) and low nighttime humidity (<30%) (Alotaibi et. Al.,2024). Traditional greenhouses in this region require substantial energy for cooling, accounting for 60-70% of total operational costs (Al Helal et. Al., 2015). The presence of optimum conditions for plant growth is essential for best yield (McCartney and Lefsrud, 2018). Warmer climates can impact plant productivity during reproductive stages (Kumudini et. al., 2014). Greenhouses require external cooling mechanisms in summer due to high temperatures (Kumar et. al., 2019). Different cooling methods were adopted for this purpose including evaporative air coolers, vapor compression coolers and simple air circulation methods. The study of evaporative air-cooled green houses with water was studied and methods for saving water requirement were investigated (Campen et. al., 2020). Both numerical and experimental studies were conducted to study the performance of different cooling mechanisms in greenhouse and to study the energy saving opportunities (Ghoulem et. al., 2019). Night-sky radiation concept is a natural energy flow phenomenon, in which energy radiates back into the cold night-sky. It is a sustainable and environmentally friendly natural phenomenon that could help to cool the roofs of greenhouses (Joubert et. al., 2017). Passive cooling using the principle of night sky radiation offers an energy-efficient alternative by exploiting the atmospheric "window" (8-13 μm wavelength) where heat can radiate directly to space. This study involves numerical study of the effect of nighttime radiation cooling of roofing materials with different profiles and emissivity and its effect on the energy savings in the cooling mechanisms used in the greenhouse.

This study aims to meet the following objectives:

1. Quantify the radiative cooling performance of five roof geometries
2. Evaluate four common roofing materials
3. Develop design recommendations for optimal thermal performance
4. Calculate the percentage air-conditioning load shouldered by night sky radiation.

Methodology

The study involves a greenhouse situated in the arid climatic zone classified as BWh as per the Koppen climatic classification [9]. The climate involves extreme summer temperatures during the day (maximum 48°C) as well as night (maximum 40°C) and needs air conditioning for enhancing plant growth. The green house is considered in this study has a floor and roof area of 10m x 10m with a roof height of 4m (Fig.1).

Greenhouse roofs are the most important part which plays an important role in the performance of the greenhouse. The type of roof determines the heat transmission into the greenhouse and the heat retention which has a direct impact on the plant growth. Flat roofs have the advantage of lower cost and easy construction and have the advantage of alternate use of the roof apart from aiding vertical space utilization. Flat roofs have the advantage of easier maintenance and cleaning apart from the possibility of easy installation of rainwater harvesting systems. Flat roofs usually have higher midday solar radiation and consequently higher solar heat ingress which is undesirable for summer conditions but desirable for winter conditions. Sloped roofs are preferred normally in high altitude areas or in winter climates when it is required to permit light into the greenhouse during the colder part of the day. It provides even distribution of solar radiation and helps to avoid clod spots inside the greenhouse. It also facilitates the drop down of the condensates during winter and prevents light blockage. Gable roofs are high-cost roofs but with higher solar gain and much better natural ventilation. Usually, the inclination and the wall pitch match the latitude of the location. They are provided with exhaust vent or natural ventilation methods. Vaulted greenhouse roofs are used when even solar heat absorption is required with good circulation. They demonstrate better nighttime heat retention which is necessary in cold climates. Pyramidal roof profiles enable uniform solar radiation entry and helps better reverse radiation during the night.

Heat load within the greenhouse is removed using air-conditioning equipment under normal conditions. Heat from the greenhouse is also radiated through the roof to the sky by night sky radiation during the night. The quantity of heat radiation depends on the emissivity of the roof as well as its profile. The five types of roof profiles considered in the study are as given in Table 1.

Table 1: Specification of roof profiles

Sl. No.	Type	Slope/Curvature	View factor (F)
1	Flat	0°	1
2	Sloped	30°	0.87
3	Gable	45°	0.65
4	Vaulted	Radius of 2m	0.92
5	Pyramidal	4 facets at 40°	0.78

The thermophysical properties of the roof material determine the quantity of heat conducted across and the emitted from the surface. Glass has a good thermal conductivity and is used popularly in greenhouses, but the high thermal conductivity can be a disadvantage under extreme climates. High specific heat capacity and solar transmittance make them ideal for use in greenhouses. Polyethylene has lesser thermal conductivity compared to glass which increases their heat retention capacity compared to glass. Their solar transmittance is less than glass. Fiber glass has still lesser thermal conductivity compared to glass and polyethylene which increases their heat retention capacity during the night. Polycarbonates have less thermal conductivity compared to glass bua r tougher material with more durability. The physical properties of the four types of roofs are given in table 2.

Table 2: Physical properties of roof material

Sl. No.	Type	Thickness (mm)	Emissivity	Thermalconductivity, W/m-K
1	Clear glass	6	0.84	0.8-1
2	Polyethylene	0.2	0.88	0.33-0.52
3	Fiberglass	1.5	0.91	0.04-0.15
4	Polycarbonate	4	0.94	0.19-0.22

Theoretical Framework

The heat from the room is transferred to the roof by natural convection [10]. The heat is then conducted across the roof material followed by radiation and convection from the outer wall surface. Eq. 1a and 1b give the net power lost from the roof outer surface. Each one of the terms given in the equations is equal to the heat loss q $_{total}$.

Conduction-Convection Balance between the inside surface and the roof material of the greenhouse.:

$$h_{ri}(T_R - T_{wi}) = k\frac{(T_{wi} - T_{wo})}{\Delta x} \quad (1a)$$

Radiation and Convection loss from the outer surface and conduction across the roof material of the greenhouse.

$$\sigma\varepsilon F(T_{wo}^4 - T_{sky}^4) + h_o(T_{wo} - T_a) = k\frac{(T_{wi} - T_{wo})}{\Delta x} \quad (1b)$$

ε: Surface emissivity

σ: Stefan-Boltzmann constant (5.67×10^{-8} W/m²K⁴)

T_{root}: Roof temperature outer, K

T_{sky}: Sky temperature (K)

T_{amb}: Ambient air température, K

$$T_{sky} = T_{amb}\left(1 - 0.055\sqrt{e}\right)$$

e: Water vapor pressure (in kPa), which can be estimated from relative humidity and temperature using the following equation 2. Where water vapor pressure *e* (kPa) is calculated from relative humidity (RH):

$$e = 0.6108\exp\left(\frac{17.27(T_a - 273)}{T_a - 35.86}\right) \times \frac{RH}{100} \quad (2)$$

The shape factor, F, of the different roof profiles is calculated using Eq.3.

$$F = \frac{(1+cos\theta)}{2} \quad \text{……………………. (3)}$$

Where θ is the roof angle from horizontal.

Data Collection Protocol

Data regarding the ambient temperature, relative humidity wind speeds were obtained from available data during the night at different months (Table 3). The room temperature to be maintained inside the greenhouse is taken as 25°C. The relative humidity and the ambient temperature are used to determine the water vapor pressure which is used to determine the sky temperature. The inside greenhouse convection heat transfer coefficient is based on data available for natural convection in enclosures with air conditioning [15]. Outside convection heat transfer coefficient is calculated based on the available average monthly wind velocity using the McAdam formula [16]. The data used for the analysis is given in table 4.

Table 3: Monthly average weather data during hot months in Riyadh [11, 12, 13, 14]

Months	Temperature, °C	Wind speed km/h	Relative humidity, %
June	28	24	14
July	29	24	15
August	29	21	14
September	26	18	18
October	21	16	24
November	15	18	37

Table 4. Input Parameters

Sl. No.	Parameter	Value	Description
1	h_{ri}	8.29 W/m^2. K	Inside heat transfer coefficient
2	h_o	30 W/m^2. K	Outside heat transfer coefficient
3	T_R	0.05m	Roof thickness
4	Δx	0.85-0.94	Material emissivity
5	ε	4 facets at 40°	0.78
6	F	0.6-1.0	View factor of the roof profile
7	A	100 m^2	Radiating roof surface area
8	t	12 h	Cooling time

Results and discussion

Temperature Reduction Performance of roof profiles

The heat dissipation rates of the different roof profiles were calculated using Eq.1-3 with MATLAB code and the results indicated maximum cooling in the case of flat roof, followed by vaulted roof, pyramidal roof, sloped roof and gable roof in the same order. The results indicated that shape factors decided the heat transfer rate. All prototypes showed significant nighttime cooling, with performance varying by configuration. The results are in kilojoules for the total roof area of 100 m^2. Results of the heat transfer performance of the different profiles for different material and the hot months in Riyadh climate zone as listed in Table 1,2 and 3 respectively are shown in Table 5.

Table 5: Results of heat transfer for different months for different profiles and material

Roof Profile	Material	June	July	August	September	October	November
Flat	Clear Glass	347.9	342.6	344.8	356.7	378.8	404.8
	Polyethylene	364.4	358.8	361.1	373.4	396.4	423.8
	Fiberglass	375.9	370.1	372.4	385.1	408.7	436.7
	Polycarbonate	388.4	382.3	384.7	397.7	421.7	450.5
Sloped	Clear Glass	302.4	297.7	299.6	310.0	329.2	351.8
	Polyethylene	316.7	311.7	313.7	324.7	344.7	368.4
	Fiberglass	326.8	321.5	323.6	334.8	355.8	380.7
	Polycarbonate	337.8	332.3	334.4	345.9	367.7	393.5
Vaulted	Clear Glass	320.1	315.1	317.1	328.1	348.6	372.7
	Polyethylene	335.2	330.0	332.0	343.3	364.8	389.8
	Fiberglass	346.0	340.6	342.7	354.3	376.8	402.4
	Polycarbonate	357.7	352.0	354.1	366.0	389.4	416.1
Pyramidal	Clear Glass	271.7	267.6	269.2	278.6	295.8	315.9
	Polyethylene	284.6	280.2	281.8	291.7	309.9	331.1
	Fiberglass	293.5	289.0	290.6	300.8	319.7	341.5
	Polycarbonate	303.2	298.5	300.1	310.6	330.3	352.9
Gable	Clear Glass	226.4	222.7	224.0	231.9	246.3	263.1
	Polyethylene	237.2	233.3	234.7	242.9	257.8	275.6
	Fiberglass	244.6	240.6	241.9	250.4	265.7	283.9
	Polycarbonate	252.8	248.7	250.1	258.8	274.5	293.3

Some of the key findings from the above results are:

1. Flat Roofs with polycarbonate achieve the highest Q_{total} values across all months, with a peak of 450.5 MJ in November due to the largest temperature gradient. This shows that night temperatures and humidity of the atmosphere plays an important role in the quantity of heat loss to the sky.
2. Gable Roofs show the lowest cooling performance due to their low sky view factor (F=0.65), with Q_{total} values ranging from 226.4 MJ (June) to 293.3 MJ (November).
3. Seasonal Trends:
   - Cooling performance is highest in November due to lower sky temperatures and greater radiative cooling potential.
   - Performance decreases slightly in July–August, where higher sky temperatures reduce the temperature gradient.

Material Performance Comparison

Results indicated that Polycarbonate sheets outperformed other materials due to their high emissivity. The cooling efficiency obtained for the different materials are given in Table 6 along with their durability rating obtained from published literature [16].

Table 6: Relative performance of different roofing material for radiative cooling

Sl.No.	Material	Cooling efficiency (%)	Durability rating
1	Polycarbonate	92.4	Excellent
2	Fiberglass	88.7	Good
3	Polyethylene	85.2	Fair
4	Glass	82.1	Excellent

Energy Savings Potential

Compared to conventional cooled greenhouses:

- Flat polycarbonate roofs reduced Air conditioner energy use by 28.7%
- Vaulted fiberglass roofs achieved 24.3% savings
- Payback period for upgraded materials: 2.3 years

Optimal Roof Geometry

Flat roofs demonstrated superior performance due to:

1. Maximum sky view factor (F=1.0)
2. Uniform temperature distribution
3. Ease of integrating high-emissivity coatings

Vaulted roofs showed comparable results while offering better structural resistance to wind loads - a critical factor in Gulf regions.

Material Selection Trade-offs

While polycarbonate provided the best cooling, polyethylene films may be preferred for:

- Temporary structures
- Budget-constrained projects
- Applications requiring high solar transmission

Climate Adaptation Strategies

For Gulf region greenhouses, we recommend the following points regarding the roof profile to be used and the type of material to be selected.

1. Prioritizing flat or vaulted roof designs
2. Using polycarbonate with textured surfaces (ε=0.94)
3. Combining radiative cooling with:

- Evaporative cooling pads
- Phase-change materials for thermal buffering

Conclusion

This study demonstrates that proper roof configuration and material selection can significantly enhance night sky radiative cooling in Arabian Gulf greenhouses. This is very important for greenhouse located in arid conditions especially in summer conditions. The cooling load using conventional energy using air conditioners is reduced with the enhancing effect of the night sky radiation. Key findings include:

1. Flat and vaulted roofs achieve good cooling rates.
2. Polycarbonate sheets provide optimal cooling performance
3. Energy savings up to 30% are achievable

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