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Theoretical investigation of Nocturnal cooling potential for Composite type climate of Punjab, India

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Abstract: *Air-conditioning is increasingly used to attain thermal comfort. It is highly energy intensive and there is a need to develop alternative low-energy means to achieve comfort. Radiative cooling is a passive technique to exchange heat with large sink such as sky. It reduces the electricity requirements, which normally be generated through fossil fuels, in order to run the active cooling systems. A theoretical model has been proposed to evaluate the radiative cooling potential for composite type climate of Punjab, India. Various correlations are given to evaluate the sky temperature.*

It is found that the there is a huge scope in reducing the energy requirements for cooling purposes. Average radiative cooling power of 65 W/m^2 is achieved in the months March, April and May whereas 30 % drop in cooling power is obtained in the wet months(July-Sep).The maximum temperature difference between the ambient and sky is found to be 15°C. Radiative cooling system has a potential of reducing the power consumption up to 14% for the space cooling purposes.

1. INTRODUCTION

The requirement of energy efficient cooling and heating systems is at their peak now days as these systems consumes intensive amount of energy. The cooling systems consume more energy as compared to heating systems & it has become the major energy consuming medium of the modern world. The predominant reasons for exploring alternatives & efficient cooling systems are global warming due to the emissions of carbon dioxide (CO_2) and hydro fluorocarbons (HFCs) used in refrigeration & air conditioning, depletion of non-renewable energy resources & demand of less polluting cooling systems. There is an urgent need of developing cooling systems which consumes less or no conventional energy source. However, we cannot fully replace conventional energy with Renewable or Alternative form of energy but efforts should be made to reduce its consumption. In this regard, Radiative cooling can be the cost effective technique to reduce the energy consumption in cooling systems. It is a passive technique to exchange heat with large sink such as sky. The radiative cooling techniques are mainly based on the principle of heat transfer by emission of long-wave radiation from a high temperature body to a lower one. This type of radiative heat transfer takes place significantly between earth and sky during night. This occurs due to the transmission of earth radiation to the sky during nights along with the emission of atmospheric radiation due to the water vapor, carbon dioxide and ozone layer. It reduces the electricity requirements, which normally be generated through fossil fuels, in order to run the active cooling systems

Al-Nimr et al.[1] presented a mathematical model describing the performance of a modified Australian cooling system. Golaka et al.[2] used the Computational fluid dynamics (CFD) to visualize the effect of wind shield height on the airflow pattern over the radiative surface. They found that a low wind shield slightly increased the convective heat transfer coefficient, but higher wind shields reduces the convection heat transfer . Farahani et al.[3] investigated the performance of the two-stage system of nocturnal radiative and indirect evaporative cooling in the city of Tehran. Ali[4] examined the feasibility of implementing desiccant enhanced nocturnal radiative cooling-solar collector system for air comfort application in hot arid areas of Upper Egypt. He has also presented a mathematical model to analyze the heat and mass transfer of the proposed system during adsorption and regeneration. Bagiorgas et al.[5] calculated the dynamic thermal performance of the system during summer months by using an accurate mathematical model, based on the heat transferred from the air circulating inside the radiator to the ambient air. Garcia[6] assessed the suitability of some standard methods to estimate the value of sky equivalent temperature, a simplified index aiming to better represent the thermal losses of the ecosystems to a nocturnal and cloud free atmosphere. Hanif et al.[7] determined the potential of radiative cooling for hot and humid climate of Malaysia.

In this paper, a theoretical model is presented to predict the potential of radiative cooling for a composite type climate of Punjab. Composite climate means a combination of severe winter, summer and rainy season throughout the year. The Punjab climate is divided into four seasons namely winter followed by spring followed by summer and monsson. The cooling requirements for the North Indian climatic conditions are from the month of March to October. The months from November to February are pretty chilled and don't required cooling in these months. So, in this paper, only eight months are considered to evaluate the radiative cooling potential. An effort is made to evaluate the performance of radiator exchanging heat with nocturnal sky during these months.

2. METHODOLOGY

Certain climatic parameters are required to build a mathematical model for evaluating the radiative cooling potential. The most important parameters are ambient temperature, Relative humidity or dew point temperature. Then the sky temperature will be calculated for evaluating the cooling power. Ludhiana is situated at latitude of 30.91' N and 75.85' E the monthly metrological data is obtained from the Agricultural meteorology department of Punjab Agricultural University, Ludhiana.

In this research a commercial flat plate radiator with area $6m^2$ is considered .The radiator will lose heat predominately due to radiation heat exchange between the radiator and nocturnal sky. In addition, there will be heat loss due to water evaporation, convective heat losses and negligible conductive losses between the surface and surroundings. In this paper an open uncovered radiator is considered. Mathematically,

$$Q_{total} = Q_{Rad} + Q_{conv} + Q_{cond}$$

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2.1 Heat Loss due to Convection (Q_{conv})

There are convective heat losses from the radiator surface with surroundings.

$$Q_{conv} = h_{conv} A_s \left(T_s - T_a\right)$$

If T_s < Ta and wind speed V < 0.076 m/s [8]
h_{conv} =0.79 W/m^2 K

If T_s > Ta and wind speed V < 0.45 m/s [8]
h_{conv} =3.5 W/m^2 K

Duffie and Bechman [9] suggested the following relationship

$$h_{conv} = \frac{(0.86\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.333})k_a}{L}$$ where characteristic length, $L=\frac{4\times A_S}{P_e}$ and $\mathrm{Re} = \frac{VL}{\nu}$

2.2 Heat Loss due to Radiation (Q_{Rad})

Radiation heat losses occurred due to heat exchange between radiator surface and cool sky. It provides a huge scope to reduce the temperature of working fluid air/ water which will further be used to reduce the cooling load requirements. The magnitude of heat flux is given by

$$Q_{Rad} = A\times\varepsilon\sigma(T_s^{\,4} - T_{sky}^{4})$$

where T_s is the temperature of radiator and usually equal to the ambient temperature. Various correlations have been given in the literature to calculate the sky temperature T_{sky} [16].

$$T_{sky} = T_a \times \varepsilon_{sky}^{0.25}$$

$$T_{sky} = 0.0552\times T_a^{1.5} \text{ [10]}$$

The next step is to calculate the sky emissivity using formulations provided by previous researchers. Generally, all these relationships are valid for clear sky conditions.

$$\varepsilon_{sky} = 0.66 + 0.4P_a^{0.5} \quad \text{[11]}$$

$$\varepsilon_{sky} = 0.787 + 0.0028T_{dp} \quad \text{[13]}$$

Based on the measured data in three US cities, Berdahl and Fromberg's suggested the correlation

$$\varepsilon_{sky} = 0.741 + 0.0062T_{dp} \text{ [14]}$$

Based on the monthly averaged sky measurement in six US cities, Berdahl and Martin's formulated the relationship

$$\varepsilon_{sky} = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right) + 0.73\left(\frac{T_{dp}}{100}\right)^2 \quad \text{[12]}$$

Where P_a is the vapor pressure (millibars) and T_{dp} is dew point temperature (°C).In the above two equations there is very small diurnal correction was suggested for a particular time of the day. The radiative heat transfer decreases with increases in dew point temperature, opaque sky cover, and ambient air temperature.

The dew point temperature (°C) is computed as a function of ambient air temperature (T_a) and relative humidity (RH), using the expression given by Murray [15].

$$T_{dp} = 237.3\left(\frac{\ln RH + a.b}{\left(a - \ln RH\right) + a.b}\right)$$

where $0 \le RH \le 1$; a=17.269; b=$\frac{T_a}{T_a + 237.3}$ There are also various formulations suggested for cloud cover by various researchers.

3. RESULTS AND DISCUSSIONS

The metrological data for the whole year is taken from Agro metrological department of Punjab Agricultural University, Ludhiana, (30.91'N). The data contains elaborative parameters like daily maximum/minimum ambient temperature, maximum/minimum relative humidity, rainfall, wind speed and evaporation. In order to calculate the radiative cooling potential, the important parameters are ambient temperature and relative humidity. Using these parameters dew point temperature is calculated which will be used to calculate the sky temperature. From the sky temperature, the cooling power has been calculated.

Table 1: Ambient temperature, dew point temperature and sky temperature for Ludhiana, Punjab(2013).

Months	T_a (°C)	T_{dp} (°C)	T_{sky} (°C)
Mar	13.2	12.3	-1.2
April	18.3	11.6	3.3
May	23	12	8
Jun	27.2	22.8	17.5
Jul	27.7	24.3	18.7
Aug	26.4	24.4	17.5
Sep	23.5	21.4	13.2
Oct	20.2	18.7	8.7

In the figure 1, variation of cooling power with the difference of ambient temperature and sky temperature is presented. The cooling power is directly proportional to the temperature difference between ambient and sky. Maximum cooling power 69.5 W/m^2 is calculated at a temperature difference of 15°C. Cooling power and temperature difference is correlated with a straight line equation with slope 3.86.Cooling power decreases in the wet months because of high relative humidy. While calculating the radiative cooling power; the temperature of radiatior is taken nearly equal to ambient temperature. Therefore, convective heat exchange is neglected.

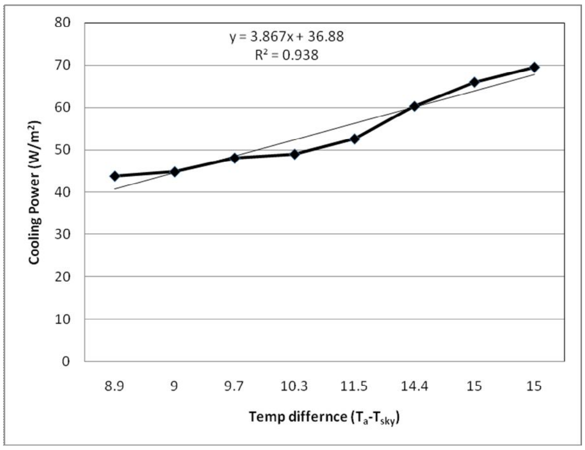

Figure 1. Cooling power variation with temperatre differnce (T_a-T_{sky})

3.1 Radiative cooling potential

The objective of the study is to evaluate the radiative cooling potential for Punjab climatic conditions. The sky emissivity is calculated using Berdahl and Frombergy's correlation. It is found that the emissivity of sky varies from 0.8 to 0.89 from the months March to October. The sky temperature is -1.2 °C in the month of March and attains a maximum value of 18.8 °C in the rainy month of July as shown in the figure 2.

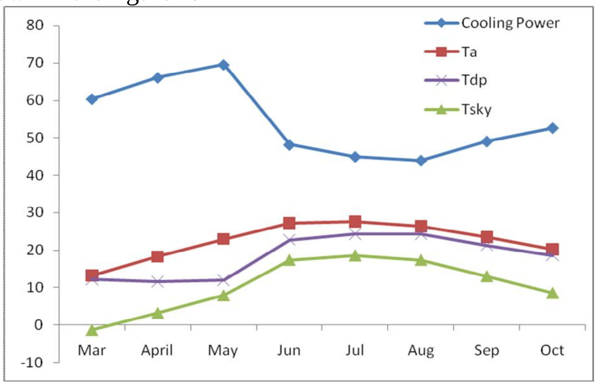

Figure 2. Annual variation of cooling power, ambient tempertaure,dew point tempertaure and sky tempertaure

3.2 Energy saving Potential

The important parameters required to calculate the radiative cooling power are dew point temperature and ambient temperature. In this research, a standard flat plate radiator without glazing is considered. Then the percentage of radiative cooling power contribution for cooling purposes is determined. It will calculate how much the radiative cooling system can reduce energy consumption. An air-conditioner consuming 1Kwh is considered to evaluate the potential energy saving.

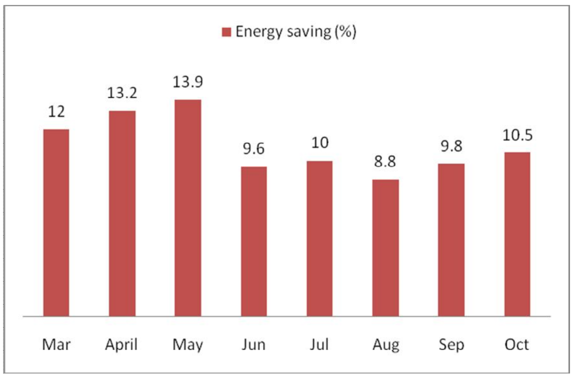

Figure 3. Percentage of energy savings in various months

Since radiative cooling is active in the nights only from 10PM to 6AM (8 hrs), a cooling system can save up to 14 % of energy required for space cooling purposes. In this calculation it is considered that air conditioner is working full 24hrs a day.

Since, there is huge difference in the ambient temperature and sky temperature in the months of March, April and May. So, radiative cooling power is more and hence energy saving potential is highest in these months as shown in figure 3.The minimum energy saving of 8.8 % is achieved in the month of August.

4. CONCLUSION

A theoretical model has been proposed to evaluate the radiative cooling potential for composite type climate of Punjab, India. Various correlations are given to evaluate the sky temperature.

It is found that the there is a huge scope in reducing the energy requirements for cooling purposes. Average radiative cooling power of 65 W/m^2 can be obtained during the months March, April and May whereas cooling power in the wet months(July-Sep) is dropped by 30 %.The maximum temperature difference between the ambient and sky is found to be 15°C. Radiative cooling system has a potential of reducing the power consumption up to 14% for the space cooling purposes.

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