An experimental evaluation of Nocturnal Cooling System- Case Study

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Abstract:
Nocturnal Cooling is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower temperature In many Indian locations, the available night cooling exceeds the residential nighttime cooling loads and in moderate climates such as Bangalore may be considerably in excess of total daily cooling requirements.

Careful examination of air conditioner operation in Bangalore shows that night sky radiation could substantially reduce cooling needs. Over a 10-hour night, theoretically night sky radiation amounts to about 250 – 2450 Wh/m if all could be effectively utilized. However, that is not easily achieved. Various physical limitations (e.g. air flow pattern under the radiator, fan power, convection and roof conductance) limit what can be utilized, so that perhaps half of the potential rate of cooling can be practically obtained. However, passive systems with additional systems such as ETS (Earth Tunnel Cooling Systems), Air washers (ECS), Stack effect with turbo-ventilation system-22combined will achieve net cooling rates of 4 - 5 W/m . With a four floor 200 m of roof in a typical home that adds up to a nearly free cooling rate of 500 - 1000 Watts (1700 - 3,400 Btu/hr).

In addition, the system offers enticing potential for low energy humidification. Materials placed in the attic, may absorb humidity from the interior during night cooling while exhausting moisture during daytime solar heating. An experimental evaluation has been conducted on a night sky cooling system designed to substantially reduce space cooling needs in homes in Bangalore climates. The system uses a sealed attic covered by a highly conductive metal roof (a roof integrated radiator) which is selectively linked by air flow to the main zone with the attic zone to provide cooling − largely during nighttime hours. Available house mass is used to store sensible cooling. Currently, the system's capability for solar dehumidification with minimal electricity input was demonstrated.

Keywords: Nocturnal Cooling, Sky Radiator, Night Radiation.

1. INTRODUCTION

The increasing of air temperature appearing in the global warming needs the air conditioner for living in the hot humid climate area. Non-greenhouse gases emitting is required in the process of the air conditioning system while the system consumes a lot of electrical power that the power plant pollutes the environments and affects to the global temperature increasing indeed. Therefore, the environmentally friendly air conditioning systems and renewable energy consumption are required. The nocturnal radiative cooling is an alternative method to be used for air conditioning system. It's not only less energy consumption but also non-greenhouse gases emitting. The cooling of the atmosphere due to infrared emission to space depends on the radiative and thermal properties of the atmosphere and of the Earth surface.

The average nocturnal air temperature in Bangalore is about 23^{O}C. This temperature would be suitable for the nocturnal cooling which was less studied in India. A experimental study of radiant cooling in an experimental room under the dry climate of Bangalore were done comparing the results from the experiments, while the feasibility study of desiccant air-conditioning system by conducting an experimental analysis to investigate the performance and energy saving in the air-conditioning system was studied.

2. DESCRIPTION OF THE NIGHT-COOL CONCEPT

We propose an innovative night cooling system consisting of a metal roof serving as a large area, low mass highly conductive radiator (see Figure below). The metal roof could be used at night during fall, autumn and acceptable summer periods to perform sensible cooling. It could also be used for heating during winter daytime operation where heating of the metal roof could be used to heat the home during midday and late afternoon hours when weather conditions were beneficial.

A recurring problem with night sky radiation cooling concepts have been that they have typically required exotic building configurations. These have included very expensive “roof ponds” or, at the very least, movable roof insulation with massive roofs so that heat is not gained during daytime hours (Hay, 1978; Fairey, et. al., 1990). The key element of the described configuration is that rather than using movable insulation with a massive roof or roof ponds, the insulation is installed conventionally on the ceiling. The operation of the system is detailed in the attached schematic.

Figure 3. Schematic of *NightCool* concept.

1. White metal roof on metal battens (no decking). Both sides are surfaced for high emissivity. A temperature probe measures roof underside temperature. 2. Small capacity dehumidifer (such as Whirlpool AD40DBK); operates only during evening hours when thermostat and roof temperature monitor calls for cooling and attic relative humidity is greater than 55%. 3. Baffled inlet frill from attic for nighttime operation. 4. Room return inlet (for daytime operation). Closed by damper at night when temperature conditions are met. 5. Thermostat (compares roof surface temperature and setting to determine vapor compression vs. nighttime cooling operation). 6. Variable speed air handler fan with electronically commutated motor.	7. Vapor compression air conditioner cooling coil. 8. Interior duct system with supply outlet. 9. Interior room air return to attic during evening hours when Night Cool is activated. 10. Roofline drip collection system with drain. 11. Ceiling return for NightCool operation mode. 12. Attic air connects to cool roof for nocturnal cooling. 13. R-20 ceiling insulation. 14. Sealed attic construction with top plate baffles (tested and sealed system). 15. Air conditioner outdoor unit (condenser). 16. Concrete interior walls (thermal mass for sensible cool storage). 17. Tile floor (add thermal mass).

During the day, the building is de-coupled from the roof and heat gain to the attic space is minimized by the white reflective metal roof. At this time the space is conventionally cooled with a down-sized air conditioner. However, at night as the interior surface of the metal roof in the attic space falls two degrees below the desired interior thermostat set point, the return air for the air conditioner is channeled through the attic space by way of electrically controlled louvers with the variable speed fan. The warm air from the interior then goes to the attic and warms the interior side of the metal roof which then radiates the heat away to the night sky.
As increased cooling is required, the air handler fan speed is increased. If the interior air temperature does not cool sufficiently or the relative humidity is not kept within bounds (<55% RH) the compressor is energized to supplement the sky radiation cooling. However, by midnight on clear nights, the temperature of the metal will have dropped sufficiently to begin to dehumidify the air introduced to the attic. The collected moisture on the underside of the roof will then drain to collection points at either side of the eaves so that the home can be dehumidified during evening hours by way of the operation of the blower fan (200-300 W). Also, if temperature conditions are satisfied, but relative humidity is not, a dedicated attic dehumidifier is energized. The massive construction of the home interior (tile floor and concrete interior walls) will store sensible cooling to reduce space conditioning needs during the following day.

3. THE NOCTURNAL RADIATIVE COOLING

During the night, the upper earth layer cools because of infrared radiation loss from the earth's surface. This radiation loss is the difference between the Stefan-Boltzmann radiation from the earth's surface and the radiation from the atmosphere, which depends on air temperature, water vapor content, carbon dioxide and ozone concentrations, and cloudiness. Since the ratios of carbon dioxide and ozone in the atmosphere are usually constant, the intensity of night radiation loss depends on mostly on water vapor content and air temperature. Heat exchanging of the adjacent air and earth surface is also dominated by convection and conduction. When the air temperature and humidity are low, and the sky is clear, radiative heat loss from the earth surface is very high.
An amount of radiative cooling depends on the characteristic of the sky radiation and the characteristic of the radiating surface described as equation

$$q_r = \varepsilon_r(\sigma T_r^4 - \varepsilon_s \sigma T_a^4),$$

where T_r is the sky temperature and T_a is the ambient temperature. ε_r is the atmospheric emissivity and ε_s is the surface emissivity. σ is the Stefan-Boltzmann's constant. The first term may be either directly measured or estimated from meteorological data and the second term may be from determined experimentally using appropriate equipment. The atmospheric emissivity is sensitive with the sky conditions and height (H) expression by [6]

$$\varepsilon_r = 0.1216\, e^{-0.00012H} - 1. \qquad \text{(H in meter)}$$

According to the temperature decreasing linearly in the low atmosphere (up to 11 km), the sky temperature (T_r) can be estimated by [7] $T_r = T(h = 0) - \gamma h$, (degree Celsius)

where the temperature gradient γ is about 6.5 ^oC/km.
Radiator efficiency (η) is defined as the ratio of the actual radiative cooling rate of a surface (q_{out}) over some idealized cooling rate (q_{in}):

$$\eta = q_{out}/q_{in}.$$

Where $q_{in} = (1 - \varepsilon_s)\sigma T_a^4$ and

$$q_{out} = mc(T_{inlet} - T_{outlet}).$$

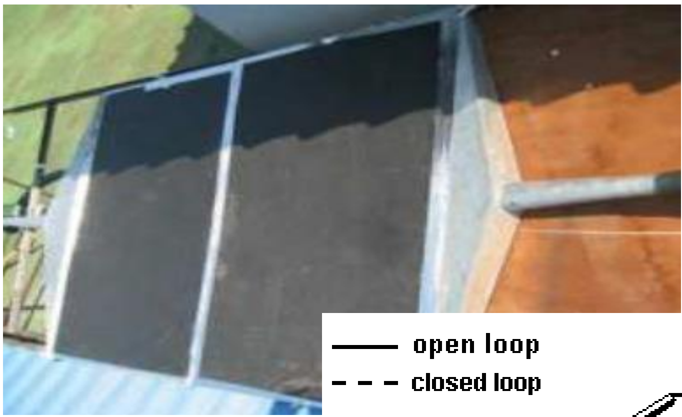
m is the flow rate. c is the heat capacity of the working fluid (for air = 1.0035 kJ/kg.K), while $T_{inlet} - T_{outlet}$

is the temperature difference passing through the radiator.

4. THE EXPERIMENTS AND RESULTS

The experiments were performed under the moderate weather conditions of Bangalore as the hot humid climate during May to June. A house model with dimensions of 2m×2m×2.5m has volume about 10.0 m^3 was constructed to use in the experiments located in north Bangalore- . The sky radiator was the aluminum foil painted black

Fig. 1 The model used in the experiments.



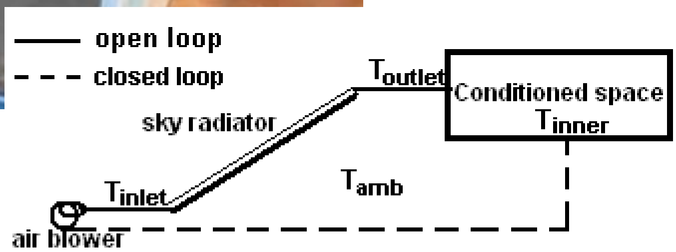


Fig. 2 The schematic diagram of the experimental measurements.

The air used as the working fluid flows beneath the radiative plate into the house conducted by the insulated air ducts. The sky radiator inclines of 17^o to the horizontal (as the located latitude), even though, its nocturnal radiation is not effected [8]. A low electrical power air blower was installed to circulate the air in the system (see Fig. 2).

A data logger was used for measuring the temperatures at inlet, outlet, room interior and ambient air. The temperature was measured every 5 minutes during nighttime at 6 pm to 6 am of the next day while the air velocity in air-duct was measured at the beginning and at the end of each experiment by an anemometer. The air flow rate was calculated by

Air flow rate = ρvA (kg/s)

where ρ = air density (approx. 1.12 kg/m^3 at 25 ^oC), v = air velocity (m/s), and A = cross sectional area of air flow path (m^2).

The results of the measuring is shown that the temperature of the radiative plate is approximately 19^oC, and the air temperature (inlet air temperature) is approximately 1.5^oC below ambient temperature, but the air temperature in the house model (in-house air temperature) is over ambient temperature according to its flow rate too low (about 0.0002 – 0.001 kg/s).

This temperature is obviously in the clear sky condition. The ambient temperature declines about 1 to

1.6°C/hour during the night in the clear sky condition depend on the wind speed and about 0.4°C/hour in the cloudy condition.

4. DISCUSSION AND CONCLUSION

The gap of ambient temperature and sky radiator temperature in the clear sky condition was bigger than that in the cloudy sky condition due to the effect of the protection of the infrared radiation. The slopes of ΔT versus the flow rates represent the radiative capability of the sky radiator (Fig. 9).

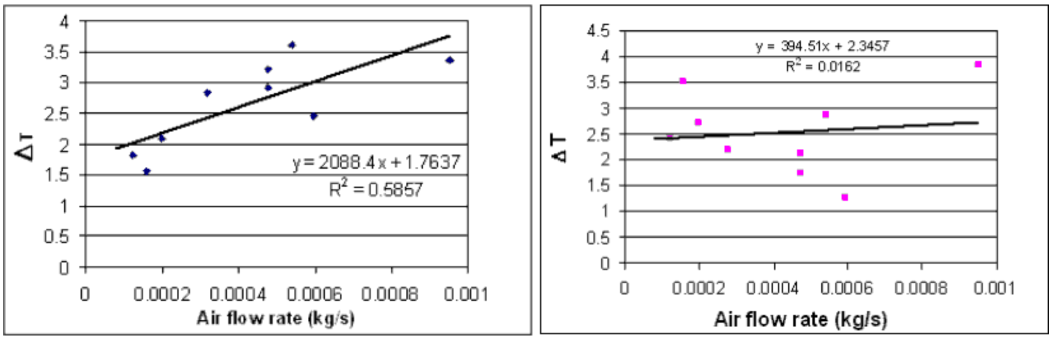


Fig. 9 The effect of the air flow rate to the averaged different temperatures (in Celsius) of inlet air and ambient temperatures in the clear sky condition (left) and in the cloudy sky condition (right).

The percentage efficiency of the sky radiator using air as working fluid seem to be low due to the air flow rate and the radiator area, especially in the cloudy sky condition. The inlet air temperature is still closed to the ambient temperature because of heat capacity of the air. Water can be used as the working fluid to maintain the inlet temperature below the ambient temperature corresponding to the sky radiator temperature [9]. Water can exchange the heat from the sky radiator better than that of air, so that the inlet temperature will be closed to the sky radiator temperature. But the experiment must be improved.
The experiment was performed in the sky condition of Bangalore to investigate the radiative cooling using air as working fluid. The inlet air temperature was below the ambient temperature by averaged of 2 - 3 oC, while the air temperature in the house model was above the ambient temperature by averaged of 1 – 2 oC. The radiative cooling using air as working fluid under clear sky condition can be made in North Bangalore according to the sky radiator temperature under the ambient temperature by averaged of 5 oC. The experiment should improve the sky radiator area and the air flow rate occurring to the cooling load of the house model.

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