Nocturnal radiation cooling tests

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Abstract

The sun radiates heat to earth in the day. At night the reverse happens when the warmer earth radiates heat to the cold night sky. Roofs of buildings radiate heat day and night at a rate of up to 75 watts per square meter. 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 as roofs can experience a temperature drop of 6 to 20°C below ambient.

Cooling a building by long-wave radiation to the night sky has long been identified as a potentially productive means to reduce space cooling energy in buildings but the technology has not been commercially available. A series of tests have been completed at Canada’s National Solar Test Facility and data shows that it is possible cool air a few degrees below ambient from sunset to sunrise using a perforated metal panel system mounted onto a sky facing surface.

This paper will summarize the night cooling tests, compare the data with published material from ASHRAE and suggest methods for utilizing nocturnal radiation to cool buildings.

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1. Background

Roofs of buildings radiate heat day and night. During the day, this is offset by solar radiation gains on the roofs; however, at night this heat loss has the ability to cool air. Cooling a building by long-wave radiation to the night sky has long been identified as a potentially productive means to reduce space cooling energy in buildings but the technology has not been commercially available.

The ASHRAE Handbook (2011) [1] explains cooling by nocturnal radiation under the solar heating category and states “Radiative building cooling has not been fully developed.” Radiation cooling to the night sky is based on the principle of heat loss by long-wave radiation from a warm surface (roof) to
another body at a lower temperature (sky). The referenced work from ASHRAE was actually done decades ago but its data only covered the USA and no other countries. Figure 1 shows that a roof facing the night sky can be significantly colder than the surrounding air temperature, from 6°C to 22°C colder.

![Average Monthly Sky Temperature Depression (Tair – Tsky) for July, °C (Adapted from Martin and Berdahl 1984) (ASHRAE Handbook 2011)](image)

Work done by Danny Parker of the Florida Solar Energy Center in 2005-2008 confirms that it is possible to cool a test house from sunset to sunrise by nocturnal radiation cooling. On a clear night, a typical sky-facing surface can cool at a rate of about 75 W/m² [3]. One limiting factor is the dew point which explains why a dry climate can achieve cooler night temperatures than humid climates such as those in Florida. When the dew point is reached, heat can be added to the surrounding air. Parker’s Florida tests had night surface temperatures of approximately 2°C below ambient which is not as low as those reported in the ASHRAE Handbook.

The transpired unglazed perforated metal solar collector called SolarWall®, developed by Conserval Engineering, has unique features that may make it suitable for collecting cool night air. Features include its ability to control the amount of ambient air passing through a large surface with precisely the same volume for each square meter whether the roof is 10 m² or 1000 m². A properly designed perforated solar panel draws the external heat boundary layer through each perforation and into the air cavity with minimal or no effect from wind. It was thought that the same principle that applies to solar heating could apply to the cold boundary layer on roofs. Given that solar efficiencies of 80% have been well established for heating, it is reasonable to assume that similar high heat transfer efficiencies may be possible for cooling. Without perforations, the external heat or cold boundary layer is not transferred to the ventilation air stream and can be dispersed by surface wind.
2. Description of work

Conserval’s initial work was to confirm whether a metal surface facing the night sky would experience temperatures similar to those shown in figure 1. The average night surface temperatures in July around the Great Lakes region are shown as 10°C below ambient. Conserval is located in this area with offices in Toronto Canada (on Lake Ontario) and Buffalo NY (on Lake Eire). The first experiment involved taking infrared images of a piece of a transpired collector in Toronto during a night in July.

With ambient air at 14.6°C, figure 2 shows the temperature of the metal surface ranged from 3.9 to 5.3°C which is approximately 10°C below ambient and agrees with the number shown in figure 1 for the same geographical area.

The next step was to determine whether the cold metal surface had the ability to cool air below ambient and over what period of time.

3. Tests at NSTF

Canada’s National Solar Test Facility (NSTF) is located near Toronto and it was decided to have NSTF conduct the tests to determine the volume of air that could be cooled at night and measure the temperature drop from ambient. Natural Resources Canada’s Active Solar Thermal group owns NSTF which is operated by Exova. NRCan covered the costs to perform the night cooling tests.

NSTF is currently the only testing laboratory in the world capable of testing ambient air solar collectors to the CSA F378.2 test standard and is the same facility that has tested and certified the performance of Conserval’s various transpired solar collectors over the past twenty years.

It was decided to first determine the amount of cooling that may be possible from conventional transpired solar panels facing the sky. Conserval’s engineers installed a test array consisting of transpired solar collectors mounted onto four solar duct modules with a total surface area of 8 m x 1.22 m = 9.76 m². The SolarDuct system is the same type that would be installed on a flat roof for solar heating purposes.
These were installed outdoors on the pavement at an angle of 30 degrees from the horizontal. NSTF installed temperature sensors on the array, connected the night cooling array to one of their calibrated solar fans and operated the system for several nights in September 2008.

The best results from the 2008 series of tests are shown in figure 3 which show an average of 2.8°C of cooling from 1 hour after sunset to 1 hour before sunrise. What is also interesting is that the cooling begins approximately half an hour before sunset and continues to just after sunrise. Other nights produced cooling in the range of 1 to 2.5°C below ambient.

It was thought that lowering the air flow would produce a larger temperature drop but tests performed at lower air flows did not generate the desired results.

Further work on the night cooling was delayed until the summer of 2009 and due to technical difficulties, actual testing did not resume until May 2010. As these were outdoor tests, it was decided to wait until the summer cooling season began to provide data that would be more typical of the climate where the technology would be deployed.

![Conservol Night Cooling 08:08-0256](image)

Fig. 3. Monitored night temperatures show air cooled by average of 2.8°C below ambient at flow rate of 36 m3/h.m2 (2.0 cfm/ft2)

A new test panel was designed and built to accommodate a wider range of air flows. The panel was approximately 100 square feet (9.5 m²) with a fan delivering from 50 cfm to 200 cfm of air to accommodate flow rates between 0.5 to 2 cfm/ft². (note that Imperial units were used for this series of tests) The night cooling tests were repeated over a period of a few weeks in July 2010. Figure 4 illustrates the amount of cooling below ambient for an air volume of 100 cfm which equates to 1 cfm/ft² of surface area. The air was cooled from 3 to 4.7°C below ambient beginning shortly after sunset until approximately 23:30. From midnight to 6 am, the amount of cooling was less and in the range of 2 to 3°C.
below ambient even though the sky temperature had decreased after midnight. This phenomenon was repeated on several other nights beginning at around midnight.

The data clearly shows that the transpired collector can cool air below ambient from just before sunset to shortly after sunrise on most clear nights. The variables affecting the cooling are still not fully understood as the amount of cooling did vary from night to night as well as from hour to hour even with clear nights.

The initial set of tests at a flow rate of 2 cfm/ft² delivered cool air at 2.8°C below ambient. When the flow rate was cut in half for the second set of tests, the maximum cooling was 4.7°C below ambient. The cooling did not extent throughout the night and the reasons for this are not understood at this time. One possible reason is that the dew point was reached and as moisture condensed out, it accumulated in the collector and began to add heat to the air stream.
4. Conclusions

The infrared photo confirms that on clear nights a metal roof can be approximately 10°C cooler than ambient temperature in the Great Lakes region which agrees with the ASHRAE information adapted from the 1984 Martin and Berdahl data.

The tests confirmed that nocturnal radiation cooling can cool ambient air for use in a building by as much as 4.7°C below ambient when using a transpired solar collector oriented towards a clear night sky.

A roof mounted transpired solar collector can be modified to cool buildings at night in the summer by connecting it to ventilation fans that provide both heating and cooling for a building. (see fig. 5)

The testing program generated a number of unanswered questions:
- What caused the temperature to increase around midnight on a few of the nights?
- Does condensation influence the amount of cooling?
- How does one measure cooling efficiency?
- Is consistent cooling of 4.7°C or more possible over an entire night?
- Assuming that some moisture does condense out from the air stream, is this a benefit for HVAC units operating an economizer cycle?
- How does one evaluate the improvement in conditioned air?
- How does one estimate the potential cooling benefit using a solar simulation or other program?
- Where can one obtain night cooling data for other countries similar to the USA Martin and Berdahl data?
These tests have shown that night radiation cooling has the ability to cool air and thus buildings but the design tools to predict and evaluate the amount of cooling are severely lacking.

**Recommendations**

Solar heating design parameters and simulation models are well defined, but the same cannot be said for the night cooling benefit. There has been very little progress in the past three decades on night cooling performance measurement, design tools and general awareness of the cooling concept. There is a huge gap in night cooling knowledge compared with daytime solar heating. The solar research community has an opportunity to correct this knowledge imbalance by developing design tools to assist the engineers and architects who may wish to incorporate night cooling into their buildings.

The cooling energy may be approximately one tenth of the solar heating energy, however, the PV industry and in particular the thin film industry has been able to provide reliable products which deliver energy in the range of 50 watts per square meter and which is equivalent to the energy range production for night cooling. It therefore makes sense to at least investigate this renewable cooling energy source especially if it can work in conjunction with solar heating equipment.

When a building is solar heated with the transpired solar collector, the preheated air enters the building’s ventilation system via rooftop HVAC units or dedicated air makeup fans. If these same heaters, fans and air conditioning units can be used for cooling, then nocturnal radiation cooling could be included with minimal additional cost and with only minor design and control programming changes necessary.

Night cooling panels are roof mounted to face the night sky but the cooling benefit is not just limited to night time. The addition of another surface on the roof with a vented air cavity means that the main roof is now shaded and not subjected to the daytime solar gains as solar heat does not reach the main roof. Further research is needed to quantify the daytime passive cooling benefit which may be higher than the night cooling.

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**References**

