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Free Subcooling with the Sky: Improving the efficiency of air conditioning systems

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ABSTRACT

Radiative sky cooling is a passive process that can be harnessed to subcool refrigerants in air conditioning and refrigeration systems, thereby increasing the cooling capacity of the refrigerant, and improving the underlying efficiency of the base cooling system. Here, we demonstrate the use of a radiative sky cooling-enabled passive fluid cooling panel. The panel's passive cooling capability is enabled by a multilayer optical film that enables the sky cooling effect 24-hours a day. The film is simultaneously a good reflector of solar energy and a strong emitter of infrared heat in the 8 to 13 micron wavelength range. Multiple such panels were built and then connected in a closed fluid loop to two 1-ton split air conditioning units in Davis, CA. The panels were used to subcool refrigerant out of the condenser by rejecting heat to the sky via a closed fluid loop. Refrigerant R410A was passed through a counterflow plate heat exchanger, where the cold fluid source was the circulating water/glycol solution in the panels. As much as 15˚F of additional subcooling was observed during the hottest time of the day. This resulted in calculated net efficiency improvements between 5 and 10%. The only added operating electricity required was to run a small circulating water pump, which consumed less than <1% of total compressor power.

1. INTRODUCTION

Improving the efficiency of vapor compression cycles is a topic of active research inquiry. From a thermodynamic point of view, one attractive way of improving the coefficient of performance (COP) of a vapor-compression cycle is to find mechanisms by which to maintain the condenser at a lower-temperature or sub-cool refrigerant leaving the condenser beyond what is possible with the condenser fans.. Both approaches will lead to an increased COP or greater amount of cooling for less electricity.

Subcooling in particular has been actively investigated as a means of improving the efficiency of vapor compression based cooling systems (Park et al., 2015; Thornton et al., 1992; Jensen et al., 2005; Pottker et al, 2012; Zhang, 2006). In refrigeration and air conditioning systems, subcooling occurs when the refrigerant is cooled below the saturated liquid temperature at the condenser pressure. By subcooling the refrigerant, the cooling capacity of the refrigerant is increased, as illustrated by the temperature-entropy diagram in Fig. 1. This, in turn, means that more cooling is achieved for the same work input to the compressors. As a result, the coefficient of performance (COP) of the system will increase: $COP = Q_{Cool} / (W_{fan} + W_{pumps} + W_{compressor})$, where Q_{Cool} is the cooling load, W_{fan} the energy consumed by the fan, W_{pumps} the energy consumed by pumps and $W_{compressor}$ the energy consumed by the compressor.

Nominally, for every additional 1°C of subcooling (at a fixed condenser pressure), the cooling capacity of the refrigerant increases by 1%. In most refrigeration systems, condensers are oversized to subcool the refrigerant between 2 to 5°C. Additional subcooling, greater than the 2 to 5°C, is desirable. However, it is not easy to achieve in practice because it requires an auxiliary refrigerant cooling system such as a secondary chiller or a cooling tower, where both systems have a high operating cost and result in marginal improvement for the added complexity and energy use. It would thus be very attractive to identify a means to passively subcool the refrigerant beyond what is possible in air-cooled system, as this would represent a way to meaningfully improve the COP of any A/C system without otherwise interfering in the system's operation and design.

Radiative sky cooling is a passive cooling technique that exploits a natural feature of Earth's atmosphere: it is partially transparent to electromagnetic radiation in the 8-13 micron wavelength range. This wavelength range overlaps with the thermal radiation emitted by objects at typical terrestrial temperatures (0-50°C). Thus, sky-facing surfaces at these temperatures emit more energy as thermal radiation to the sky than they receive back, and thereby cool themselves below air temperature. Everyday observations of this effect include the condensation of water on sky facing surfaces of a car in the morning, and the formation of frost on a roof before the air temperature drops below 0°C.

Previously, radiative sky cooling was only observed at night. Research on surfaces that cool to low temperatures using this effect was pursued from the 1970s onward (Catalanotti et al., 1975; Berdahl et al., 1983; Granqvist and Eriksson, 1991; Gentle and Smith, 2010), but has so far had a limited impact on building efficiency and cooling systems. A key reason limiting the technology's adoption was that radiative sky cooling was not accessible during the day, when cooling is most needed. In fact, this concept has historically been referred to as 'night sky cooling' or 'nocturnal cooling'.

In 2014, it was shown that specialized *nanophotonic* surfaces could passively cool up to 5˚C below air temperature, or more, even under direct sunlight (Raman et al., 2014; Rephaeli et al., 2013). These specialized surfaces were designed using optical and photonic principles to have a selective spectral emissivity, $\varepsilon(\lambda)$, that was high over infrared wavelengths, and low over solar wavelengths (Raman et al., 2014). The surfaces reflected 97% of incident sunlight and were strongly emissive of thermal radiation in the 8-13 micron range, where the atmosphere is transparent. These optical properties allow the surfaces to achieve the observed cooling effect, and to radiate and reject heat loads from other sources to below the air temperature. The results also highlighted that heat rejection capacities in excess of 100 W/m^2 were possible, 24 hours a day. More recently, fluid cooling panels that used these specialized surfaces were shown to cool fluids up to 5°C (9°F) below ambient air temperature 24 hours a day at varying flow rates (Goldstein et al., 2017). However, the direct use of radiative sky cooling to improve the efficiency of a vapor compression cycle has, to date, not been demonstrated.

In this paper, we demonstrate the use of radiative sky cooling-enabled fluid cooling panels operating as a secondary loop to subcool refrigerant leaving the condenser of a split air conditioning system. We integrate an array of fluid cooling panels, where the operating fluid is a mixture of propylene glycol and water, with a mini-split A/C system conditioning a space inside a shipping container at a test facility in Davis, CA. The mini-split system is modified so that a plate heat exchanger is added to the liquid line leaving the condenser; fluid cooled by the panels in a closed loop is used to subcool refrigerant further through this heat exchanger. The temperature and pressures of refrigerant and water-glycol is monitored and the added subcooling measured. The implied coefficient of performance improvement enabled by the subcooling is also calculated.

2. SYSTEM DESIGN & IMPLEMENTATION

2.1 System Design

The system architecture we designed and implemented is schematically shown in Figure 1. In this configuration, a plate heat exchanger was added after the condenser and a closed fluid loop will be used to remove heat from the refrigerant. By using a closed fluid loop to subcool the refrigerant indirectly (as opposed to flowing the refrigerant through the panels), minimal modifications to the core refrigeration system will be required. The added subcooling results in increased system capacity for the same amount of input compressor work, as can be seen in the Temperature-Entropy diagram of the modified cycle. This in turn results in the improved system COP.

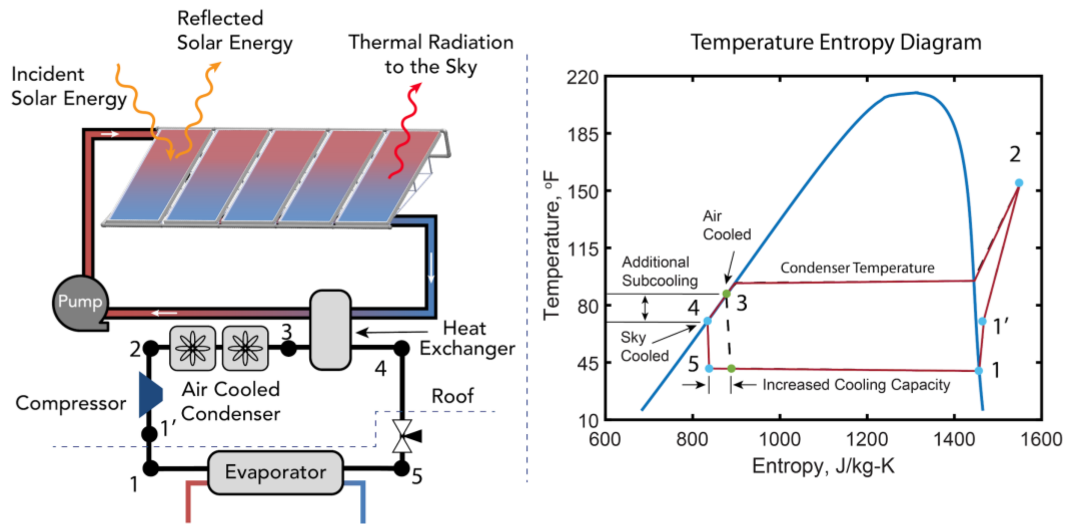

Figure 1: (left) system diagram of SkyCool panels integrated with a vapor compression system and (right) Temperature-entropy diagram of a vapor compression cycle with subcooling

2.2 Panel Fabrication and A/C System Modification

We fabricated 8 fluid cooling panels, each 3 ft. x 6 ft. in area, shown in Fig. 3. A specializing optical film was used as the top surface, above a flat heat-exchanging surface. The enclosure further consisted of polystyrene insulation and a top polyethylene glazing. A commercially available mini-split air conditioning (Amvent) charged with R410A was modified such that the liquid line leaving the condenser was connected in line to a brazed-plate heat exchanger (See Fig.3) .

2.3 Test-site description

Our demonstration site was located in Davis, CA, and testing occurred during the summer, fall and winter months of 2017. The deployments consisted the 8 fluid cooling panels connected in a closed, pressurized water/glycol hydronic loop to a plate heat exchanger. This plate heat exchanger then cooled refrigerant leaving the condenser of a split air conditioning system. A technical drawing of the hydronic loop and measurement points is shown on the right of Figure 2. Photos from the installation of the panels at the site are shown in Fig. 2. They are mounted to cinder blocks on the ground with conventional solar racking (Unirac). The hydronic loop (Fig. 4) is charged at a central pump station (Fig. 5) and typically maintained pressurized at 30-40 psi. A fluid pump from Taco is used to circulate a 5 to 10% water-glycol solution through the panels. The pump consumed less than 1% of total compressor power.

A 20 foot shipping container was rented and partitioned with heavy insulation to create two identical spaces that are conditioned by: 1) the aforementioned air conditioning system, and 2) an identical, un-modified version of the same air conditioning system to provide a baseline comparison. The installation of the container at the site, along with the evaporator units inside the container are shown in Fig. 3, along with other characteristics of the conditioned spaces.

Temperature and pressure readings are taken throughout the setup, both in the panel fluid loop and in the refrigerant lines. This includes all four ports in the heat exchanger and the condenser/ evaporator pressures of both the baseline and modified air conditioning systems. RTD probes are used for the temperature readings, and all measurements are centrally logged in a National Instruments data acquisition system.

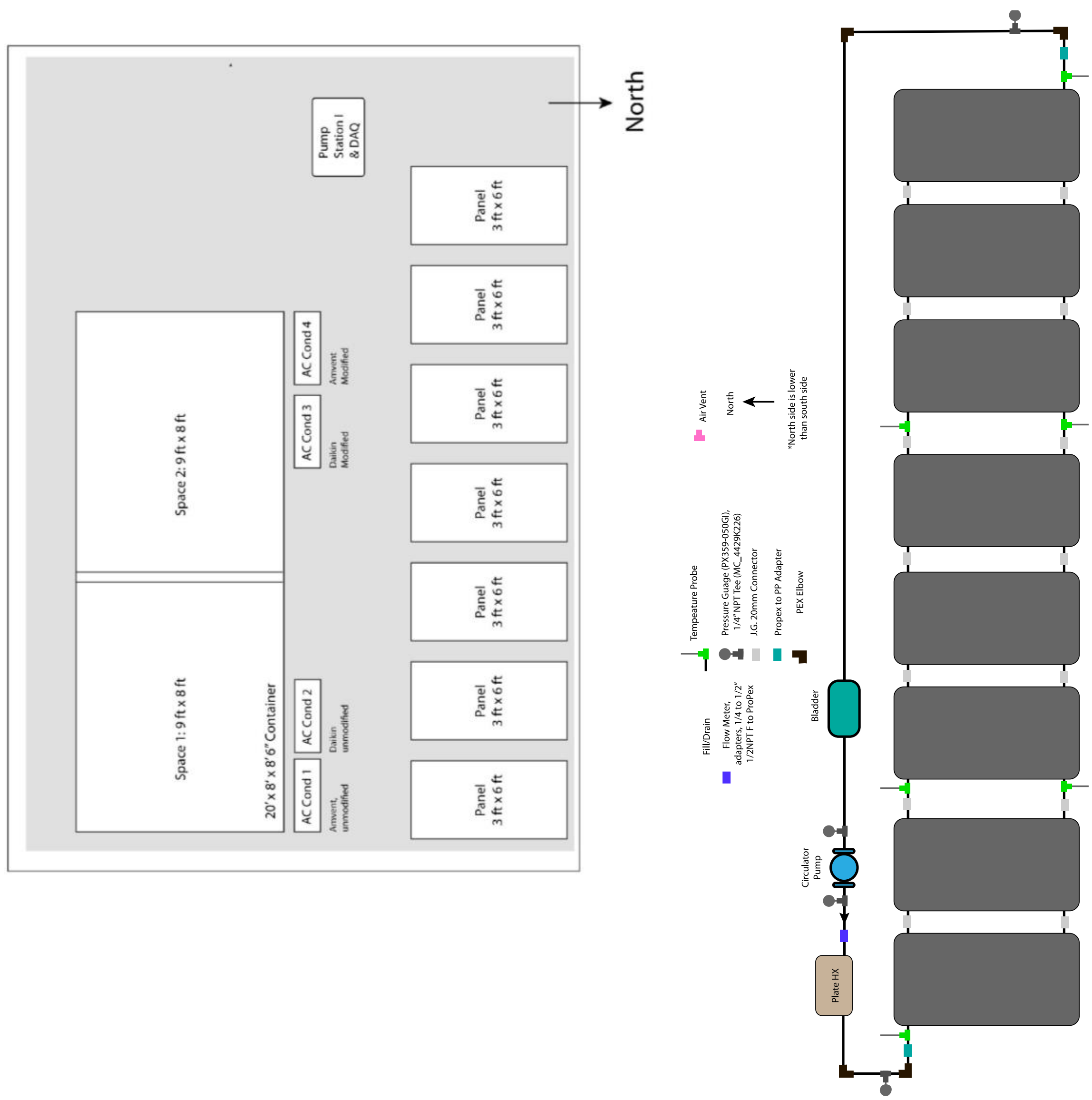

Figure 2: Diagram of site layout (left) and detailed technical schematic of the radiative cooling panel hydronic loop that is connected to the air conditioning systems.

Figure 3: Picture of the exterior of the container space cooled by the A/C units and the modified A/C units

3. RESULTS

We present here key results from the demonstration that show the subcooling capability of these panels in conjunction with split AC units, along with the COP improvements they enabled. First, we show data from continuous testing, where a large heat load was supplied to the conditioned space via a 1500 W space heater. Due to the heat load placed on the space, the A/C system is not able to reach its set-point after 11am and operates continuously. We present data from September 15, 2017, where subcooling of between 8-15°F (4-8°C) was measured, as shown in Figure 4. While the refrigerant is typically not cooled to below the ambient air temperature, at certain hours later in the day, we observe that it is in fact cooled to sub-ambient temperatures.

Next, we present 'on-off' testing of the system, where the pump circulating water-glycol through the panels is turned on and off in 30-minute cycles. This was done to clearly establish the efficiency benefit gained from the additional cooling provided by the panels. As can be seen in Figure 5, during 'on' periods, when water-glycol is circulating through the panels, refrigerant subcooling of 10-15°F is measured across the heat exchanger. When the pumps are turned off, as expected, no subcooling is measured. Thus the subcooling is clearly attributable to the fluid being circulated through the panels, and the additional cooling this brings to the overall systems

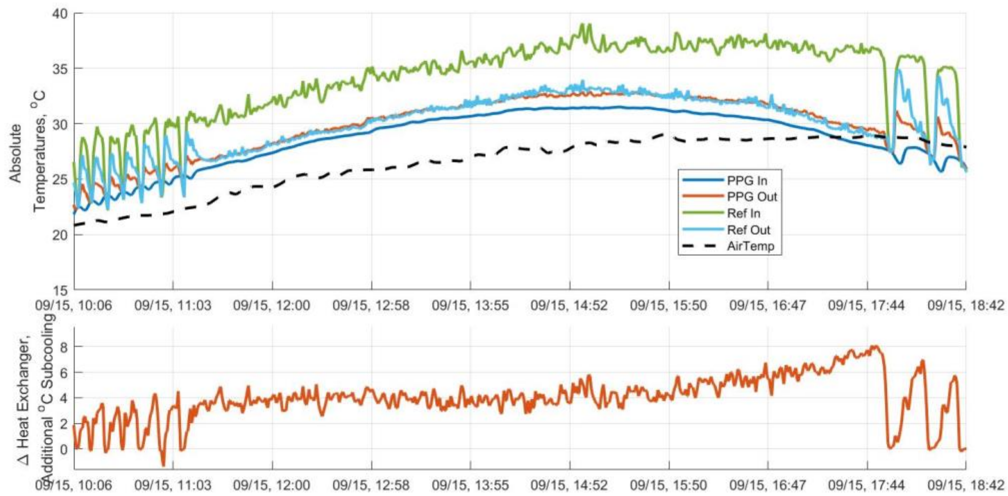

Figure 4: Continuous testing throughout the day with a constant heat load placed on the system. Refrigerant cooling of 4-8°C (8-12°F) is observed through the heat exchanger.

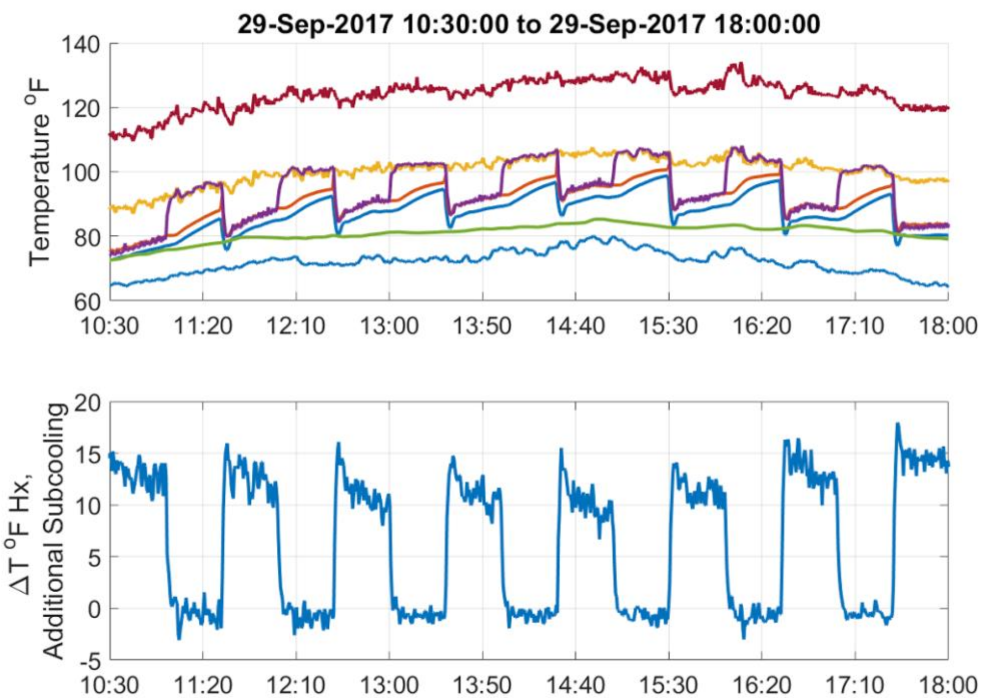

Figure 5: On/off testing of the fluid cooling panels in 30-min segments. Absolute temperatures are shown at top, (with ambient temperatures reaching 90°F), while the cooling of the refrigerant measured across the heat exchange shown in the bottom panel. Subcooling of nearly 15°F is observed during the 'on' periods in the middle of the day

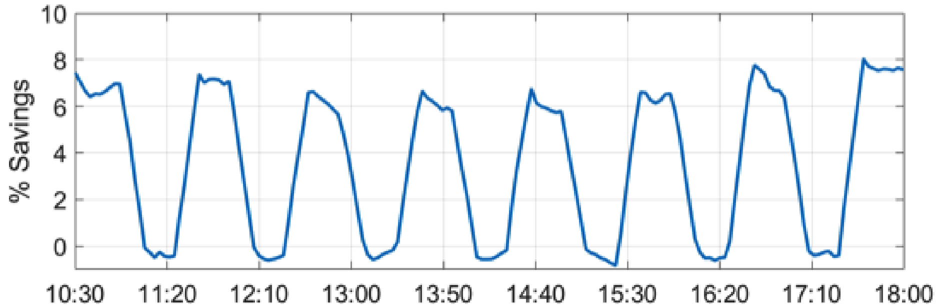

Figure 6: The data from Figure 5 is used in a vapor-compression system model to infer the COP improvement and energy savings possible due to the measured subcooling. Savings of 7-8% are seen during peak A/C use hours.

Finally, we calculate the improvement to the system's COP by using this subcooling information in a model of the vapor-compression system being tested. This model describes the expected improvement in system capacity, and hence improvement is system COP, with added subcooling. We emphasize here that the model takes as its input the *measured* subcooling, shown in Figure 5, to determine the expected energy savings. Remarkably, the 10-15°F subcooling measured should result in instantaneous energy savings of between 6-8% on this air conditioning system.

4. CONCLUSIONS

We have demonstrated a radiative sky cooling-enabled subcooling system that can increase the capacity of vapor compression systems as an add-on. This approach requires no water, and can be scaled with more or less panels depending on system size. It is also generically applicable to any vapor compression cycle, including lower-temperature refrigeration systems. The non-evaporative closed-loop and nearly passive nature of this approach to both subcooling and COP improvement offers a unique capability in the broader space of cooling technologies. As operators of air conditioning systems, chillers and refrigeration systems seek higher efficiencies, we believe this approach will offer an attractive method to gain efficiencies without having to make significant modifications to the underlying system.

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