Efficient Solar Cooling

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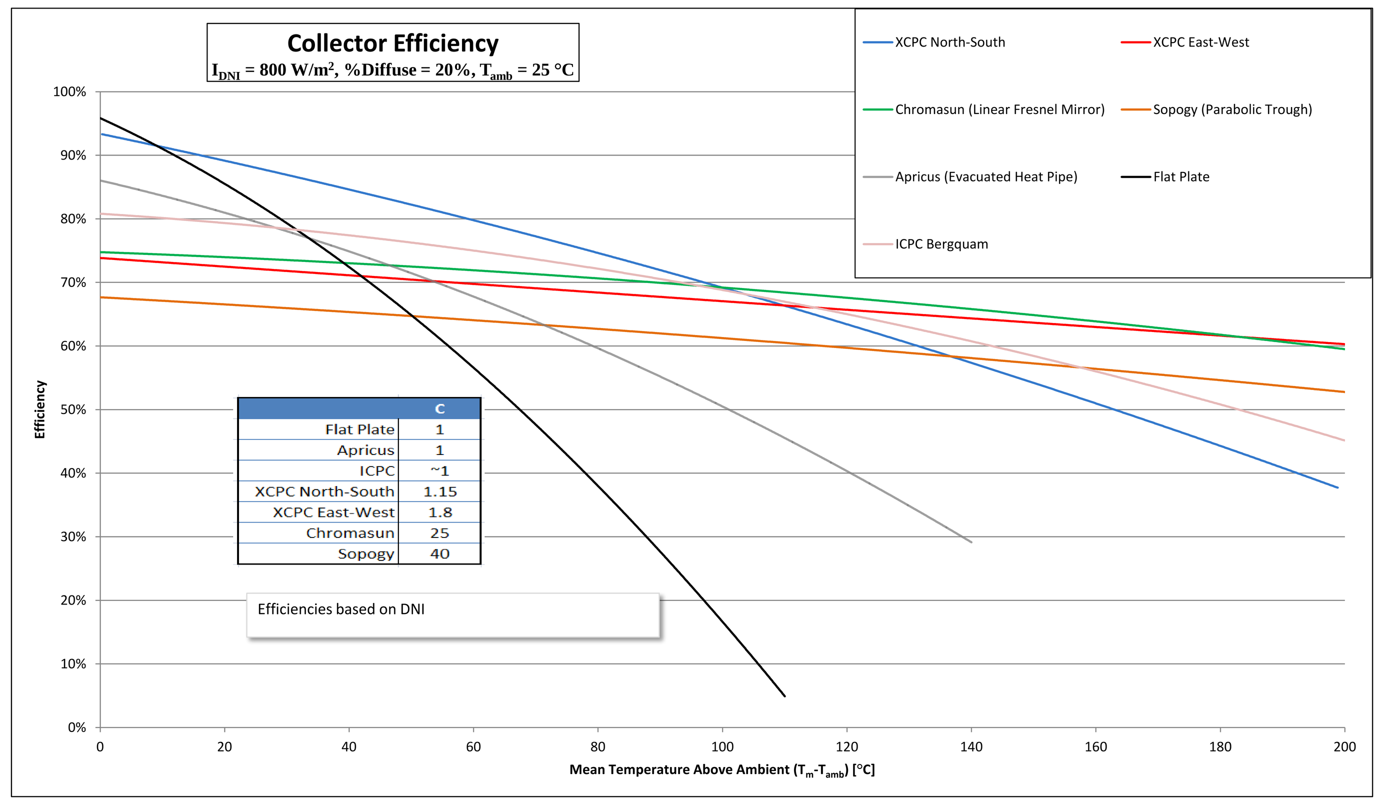
BACKGROUND

Solar cooling has long been a desired goal in utilizing the solar resource for the benefit of people. The reasons are intuitive; the resource is well-matched to the load (high cooling demand days are usually sunny days) and if deployed on a roof, solar radiation that would otherwise heat the building is instead diverted to cool the building.[1] However; the technical barriers to implementation are well-known. Efficient absorption cooling machines (double effect) require relatively high temperatures ~ 180° C which is well beyond the range of flat plate solar collectors, while tracking collectors are problematic for building applications. Moreover, absorption machines operate in a relatively narrow range of temperature and do not respond well to the natural variability of solar insolation.[2] Recently the availability of fixed, high temperature non-imaging collectors, and absorption chillers that are gas/solar hybrids have created a new paradigm in effective solar cooling.

Solar Collectors

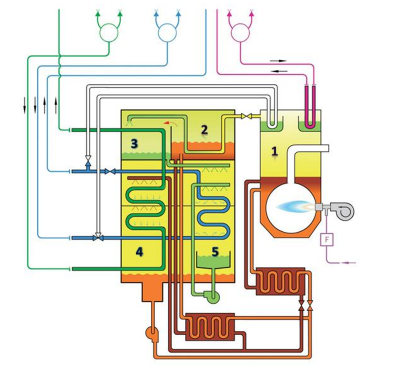
The collector configuration is an evacuated tube receiver matched to an external non-imaging reflector, typically referred to as an XCPC. The XCPC provides solar concentration without moving parts that can achieve operating temperatures up to 200°C. The design principle maximizes the probability that radiation starting at the receiver would be directed to a specific band in the sky we wish to accept. In our case "north-south orientation'' this band is 120 degrees in azimuth and 180 degrees in elevation. This corresponds to a nominal operational time period of eight hours a day with a concentration ratio of 1.18. The incidence angle modifier, IAM, was measured by positioning the collector due south and tilted to be normal to the sun at solar noon (no tracking) and recording the instantaneous thermal collector efficiency at a collector inlet temperature of 140 °C over the course of the day. In this measurement the instantaneous efficiency was based on the total insolation on the collector plane. The acceptance angle was measured as +/- 55°. The test used to determine the IAM chart and the acceptance angle can also be used to understand the collector's all-day performance. During the test, the collector performed within 90% of the nominal efficiency for roughly 7.3 hours. The thermal performance as a function of operating temperature is shown in the figure below. In the same figure, a selection of other thermal collectors are included, making the point that ours is the only fixed collector operating efficiently at 200°C. [3]



The Chiller

The cooling machine is a commercial 6.6 U.S. refrigeration ton double-effect lithium bromide chiller. It is a hybrid system that is powered by natural gas or solar thermal energy. To operate on solar energy the chiller requires 21 kWth energy at 175˚C. The following description is how this machine works.

When liquid evaporates, it absorbs heat from its surroundings. Water boils at 100° C under normal atmospheric pressure (760 mmHg), but it can also boil at very low temperatures under partial vacuum conditions. By creating a vacuum (6 mmHg pressure) in an airtight vessel, water can boil at 4°C. There is a Lithium Bromide, LiBr, solution as the absorbent, water as the refrigerant and natural gas or solar as the heating source. As the LiBr solution is deliquescent water absorbent, it can absorb surrounding vapor and maintain a low pressure condition in the evaporator. Chilled water at 14°C enters the copper tubes inside the evaporator and the refrigerant water at 4°C is sprayed on the outside of the tubes, under partial vacuum. The refrigerant water absorbs heat from the chilled water and evaporates, becomes vapor, thereby the chilled water temperature is reduced to 7°C. Concentrated LiBr solution in the absorber absorbs the refrigerant vapor and then transfers the heat from the vapor to the cooling water. The cooling water heat is released to the ambient air via the cooling tower. The diluted LiBr solution is pumped to the high temperature generator where it is reheated and refrigerant vapor evaporates from the solution making the solution concentrated. The concentrated solution repeats the absorbing process and the refrigerant vapor goes to the condenser where it is condensed and returns to the evaporator to begin the cycle again.



*Orange Liquid is LiBr + H_2O
*Green Liquid is H_20

High Temperature Generator
Low Temperature Generator
Condenser
Absorber
Evaporator
Green Loop is cooling water loop (goes to cooling tower)
Blue Loop is chilled water loop (goes to house AC system)
Purple Loop is hot water loop (goes to house hot water)

The System

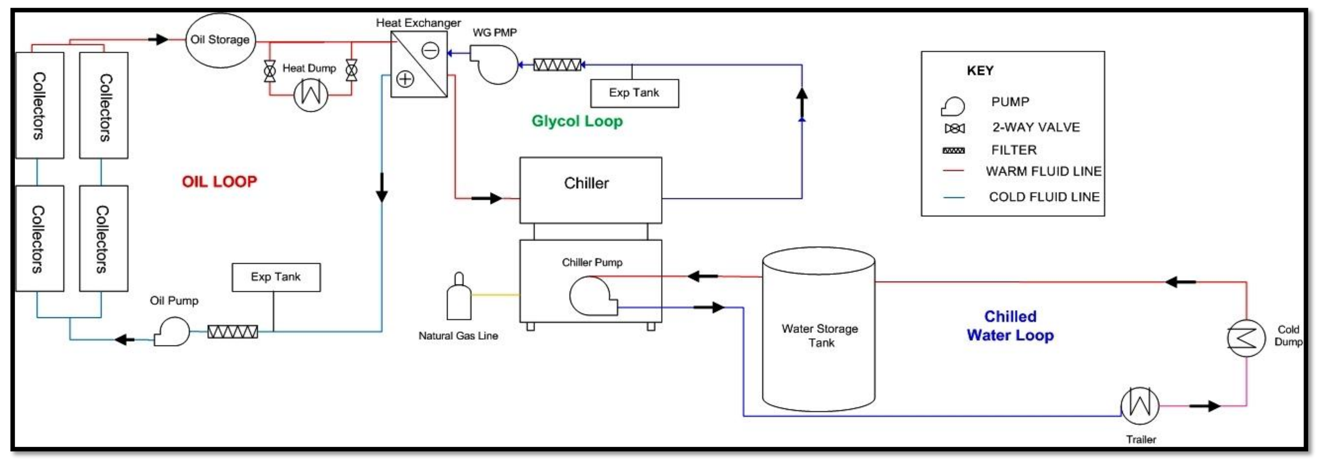
To power the double effect chiller we built a 21 kWth XCPC array, in north south orientation. The collectors are elevated 20° from the horizontal to favor summer operation and are orientated 14° west of south to favor operation later in the afternoon. The figure below is a process flow diagram of the solar cooling system. There are three loops in this system, referred to as: oil, glycol and water. The glycol loop was added to avoid potential contamination of the LiBr solution by oil.

The instantaneous solar thermal collector output power was calculated by equation

1: $\dot{Q}_{sc} = \dot{m}_{oil} C_{p_{oil}} \Delta T_{sc}$ The mass flow rate through the solar collectors was measured by a Coriolis flow meter, and the temperature difference is taken with two thermocouples placed at the input and output of the solar collectors. The available solar energy to the solar thermal collector system was calculated by equation 2: $\dot{Q}_{AVsc} = \Phi * A_{ap}$ There was a precision spectral pyronameter on the collector plane which measures $\frac{power}{area}$. Knowing this and the aperture area the available power to the solar thermal collector was calculated. The thermal efficiency of the collectors is: $\eta_{sc} = \frac{\dot{Q}_{sc}}{\dot{Q}_{AVsc}}$ The array performance is monitored by total insolation on the plane of the collector which is appropriate for natural variability of solar insolation. This is in contrast to individual collector testing where both direct and diffuse components are measured under stable, high insolation.[4] Conventionally a chiller's effectiveness is characterized by its coefficient of performance, COP. The COP is calculated by the following equation:

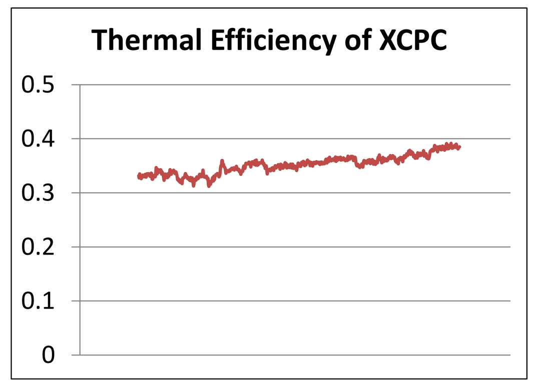
$$COP = \frac{Cooling\ Power\ Output\ of\ Chiller}{Solar\ Thermal\ Input\ to\ Chiller}$$

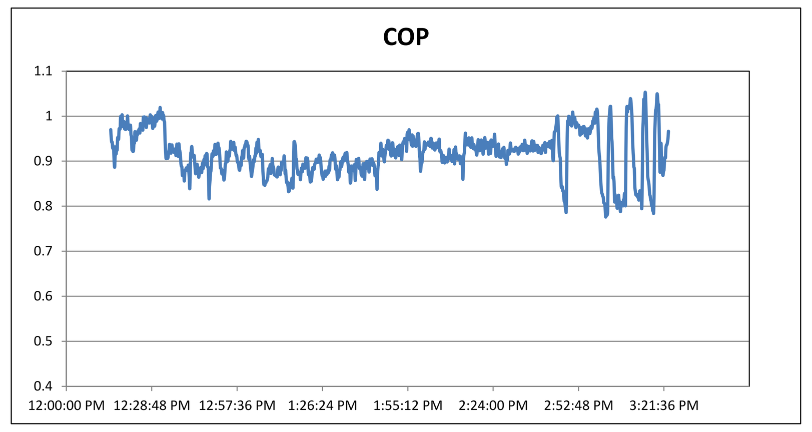
In our case the power input is the power provided directly by the collectors. This slightly de-rated the chiller performance by lumping in heat dissipation due to the glycol loop and heat exchanger. The power input to the chiller by solar energy is calculated by equation 1.In the natural gas mode the thermal input to the chiller is calculated by metering the natural gas consumption

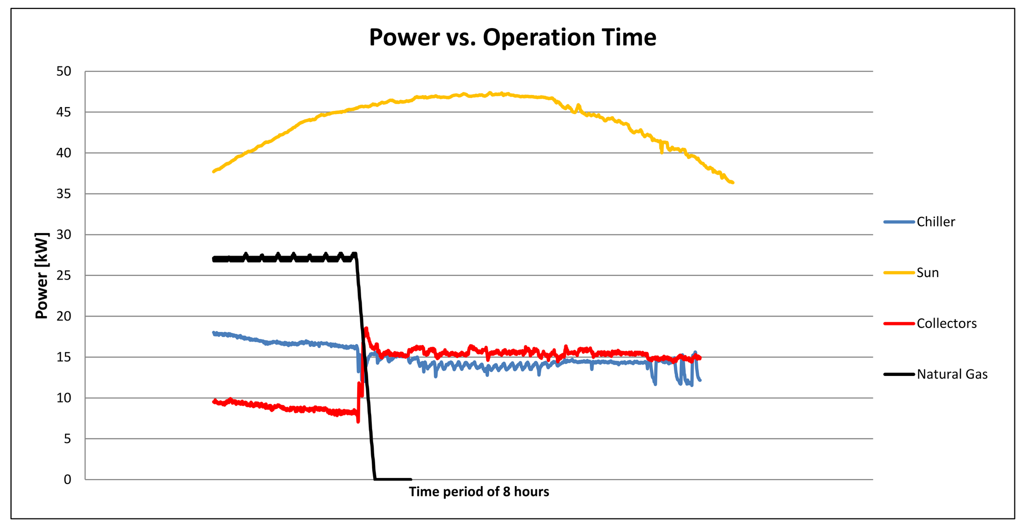


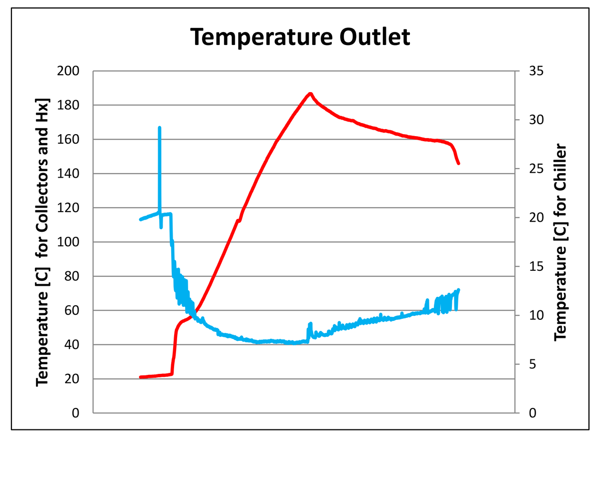
Results

The thermal efficiency of the xcpc is shown in a figure below and shows a daily thermal efficiency during operational temperatures, 180-160°C, which begins at 34% and grows to 40%. The thermal efficiency becomes higher during operation due to the entire system tending towards thermal equilibrium and reducing the heat loss. There are two critical variables to the chiller: The coefficient of performance, COP, and the outlet temperature of the chilled water. The double effect absorption chiller is designed to produce 7°C water at a rated COP of 1.1. The average COP that we measured was .9, and the average outlet temperature of the chilled water was 7°C. The outlet temperature graph and the COP graphs below represent this data. This proved to us that the double effect absorption chiller functioned very well with having the solar collectors as the power input. The power vs. operational time period shows that the non-tracking XCPC evacuated solar collector array at Castle Air Force Base provides enough energy for the double effect chiller to operate independent of natural gas. Through all of our experiments it has been observed that once the solar collectors provide enough energy at temperature the natural gas does not need to be turned on until evening. It has also been shown that despite fluctuations with the solar insolation the COP of the chiller is fairly constant.









CONCLUSIONS

On May 5th, 2011 the UC Merced solar cooling project was commissioned and by July 12th it became operational. The system starts on natural gas and once the solar reached operating temperature the chiller solely ran on solar energy for the remainder of the day. The chillers power output was consistent and actually attained a higher cop when running on solar.

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