11-2020

Remotely Accessible Laboratory for Teaching and Research on Solar Thermal Collectors

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REMOTELY ACCESSIBLE LABORATORY FOR TEACHING AND RESEARCH ON SOLAR THERMAL COLLECTORS

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This paper discusses a new test platform for evaluating the performance of solar thermal collectors that was recently designed and constructed on the roof of the Applied Energy Laboratory at Purdue University, located at 40.4 °N and 86.9 °W. The test platform is mainly used for teaching undergraduate students about applications of thermodynamics and renewable energy, but it can also be used for comparative evaluations of solar thermal collector designs according to an established test standard. The entire system is monitored and controlled by a web-based Building Automation System that automatically tracks and trends both weather data and the performance of individual solar collectors. The online data is particularly helpful for undergraduate education because large numbers of students, including international partners, can access real-time data to learn about solar energy applications. The weather at this location varies significantly by season, which has a substantial impact on the performance of the solar thermal collectors. ASHRAE designates this location as climate zone that experiences both hot, humid summers and cold, dry winters. The solar intensity also varies by season, with longer and more sunny days during the summer and shorter and more cloudy days during the winter. Not surprisingly, evaluations of solar collector performance vary seasonally too. Solar collector efficiency, the ratio of thermal energy collected to the solar energy available, varies from 10% to 80%. Solar energy factor, the ratio of thermal energy collected to the source energy (electricity) to circulate the fluid, varies from 10 to 150. Both performance terms (efficiency and energy factor) are needed to get a complete picture of solar collector performance.

Key Words: *Solar thermal energy, building automation, undergraduate education*

1. INTRODUCTION

The widespread use of computer controls for optimizing the efficiency of mechanical and electrical systems in commercial buildings has created a unique opportunity for conducting research and delivering lab-based distance education. Facility engineers routinely use Building Automation Systems (BAS) to access real-time performance data (e.g. chilled water pressure, temperature, and flow) over the Internet. This network capability has been applied in an educational setting to deliver laboratory experiments to large numbers of undergraduate students. This approach is particularly helpful for large laboratory installations where in-person access is limited. For example, solar collectors are frequently located on the roof of a building where access is limited due to safety concerns. A web-based BAS can provide data on solar collector performance and pictures of the equipment to explain how it operates (Hutzel, 2002).

Remotely accessed laboratory equipment has also been used to encourage international collaborations. A partnership with a university in Switzerland allowed Purdue University students to monitor the performance of a heat recovery system that is part of a large commercial air handling unit. The biggest challenge for this partnership was the large time difference between Switzerland and the U.S. Most of the laboratory work in the U.S. was in the middle of the night for our Swiss counterparts (Hutzel, 2005). There is the potential for using remotely access laboratory equipment to encourage new partnerships with our colleagues in Peru.

2 Applied Energy Laboratory

The Applied Energy Laboratory (AEL) located at 40.4 °N and 86.9 °W is a focal point for teaching and research at Purdue University for high performance buildings. The facility features a variety of HVAC equipment that are commonly found in commercial buildings. An air handler, chiller, and a heat recovery system showcase the kinds of technologies that students will encounter during their technical careers. The AEL also features a variety of solar energy installations that demonstrate technologies for achieving net zero energy buildings. An 8 kW photovoltaic array provides much of the AEL's electricity and helps showcase renewable energy technologies. There are also eight solar thermal collectors in the AEL, but they had to be replaced after 30 years of service. This paper documents the eight new collectors that were installed.

21 Solar Thermal Collectors

Figure 1 shows the new solar thermal test platform that was constructed on the roof of the Knoy Hall of Technology. Eight different solar collectors were installed side-by-side on a single large rack. The plumbing connections are designed so that it is relatively easy to swap out individual collectors to evaluate new collector designs. For purposes of comparison, the collectors have different fluids (air or glycol/water) and different absorber surfaces. Two were purchased from a commercial supplier and the other six were designed and built at Purdue University. The design work was completed by undergraduate students and the installation was made by the plumbing, sheet metal, and electrical shops at Purdue University.

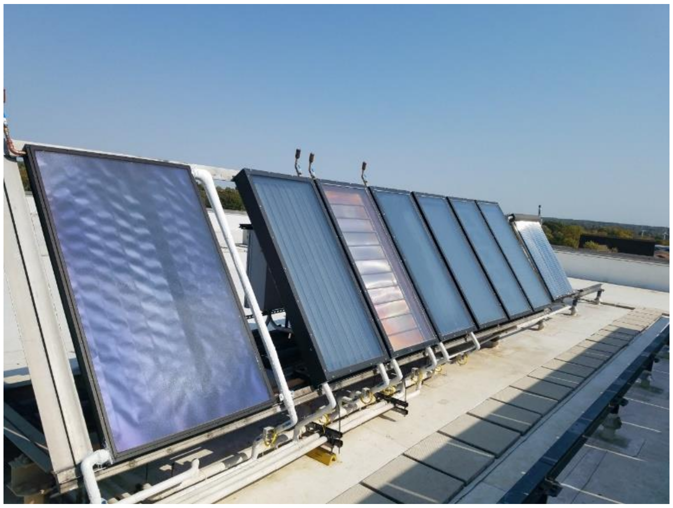

Figure 1: Eight solar thermal collectors were designed and installed on the roof

The weather at this location varies significantly by season, which has a substantial impact on the performance of the solar collectors. ASHRAE designates this location as a climate zone that experiences both hot, humid summers and cold, dry winters. The solar intensity also varies by season, with longer and more sunny days during the summer and shorter and more cloudy days during the winter. Unlike many geographic locations in Peru that are much closer to the equator, the sun is high overhead in the summer and much lower in the sky during the winter.

To optimize heat capture during cold weather, each collector is mounted at 57° with respect to horizontal. This is based on the rule of thumb shown in equation 1. Mounting a collector at its latitude plus 17° helps the sun's rays strike approximately perpendicular to the flat collector surface during cold winter weather, which increases the overall amount of radiation absorbed. The mounting angle of 57 is based on Purdue University's location at 40.4 °N latitude.

$$\textit{mounting angle with respect to horizontal for optimal winter heating} = \textit{latitude} + 17\ \textit{degrees} \qquad (1)$$

22 Web-based Monitoring System

A web-based Building Automation System (BAS) platform, more commonly found in large commercial buildings, monitors and controls all of the equipment in the Applied Energy Laboratory. The BAS communicates with a web server to provide full remote access to all of the sensors, actuators, and control logic for operating the equipment by computer, laptop, or even a smart phone. Passwords provide different levels of access to the website so students cannot make programming changes.

Figure 2 is one example of the graphic interface for assessing solar collector performance in real time. Weather information, including temperature, humidity, and solar intensity is available in the upper right side of the screen. Two pictures of the solar collectors, including physical dimensions, are provided so that students can see the characteristics of the collector they are evaluating. Figure 2 clearly shows the black "perforated x" configuration that enhances heat transfer for this air collector. The graphic interface also includes the air flow rate, inlet temperature, and outlet temperature for computing the heat rate.


Air Collector 2 - Perforated X

Current Outdoor Conditions:
Air RH: 30 %RH
Air Temp: 46 °F
Sun Intensity: 853 W/sq m

Temp. & Flow Conditions
Flow: 18 CFM
Temp in: 68 °F
Temp out: 133 °F

Fan Conditions
Fan Status: On

53 Degree Mounting Angle

Figure 2: Graphic interface for one solar thermal air collector

In addition to real-time data, the BAS also collects and stores data on solar collector performance at 15 minute intervals. Figure 3 shows a weeks' worth of trend data focusing on solar intensity as measured by a solar pyranometer in Watts/m^2. The data features a mix of sunny and cloudy days. A quick scan of this data allows students to pick an optimal solar day when the sun is shining. Evaluating solar collector performance on cloudy days is not reliable.

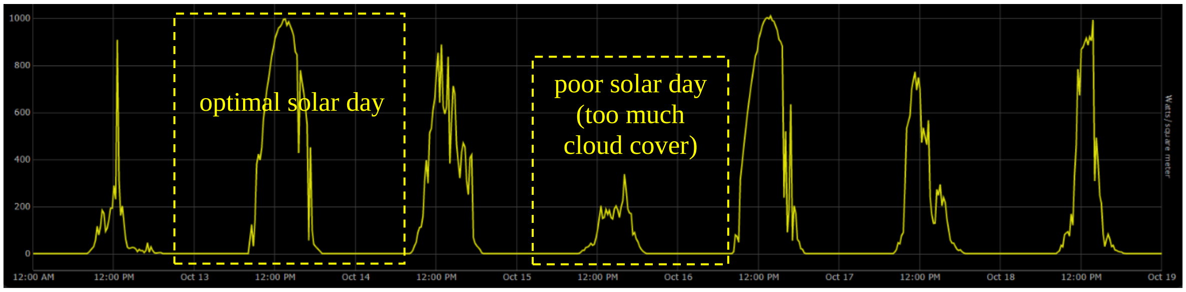

Figure 3: Graphic interface for one solar thermal air collector

Table 1 is a sample of a complete data set for a single solar collector in October of 2020. More than a month of data was considered before selecting this near-perfect day for evaluating the solar collectors. The data was automatically captured by the BAS at 15 minute intervals at a time that included peak sun intensity (~1,000 W/m^2) for the day in West Lafayette, IN. In addition to weather and solar panel performance, the power consumption of the circulating fan that pulls air through the solar thermal was also recorded.

Table 1: Performance data for one solar panel

Date & Time	Solar Intensity (W/m^2)	Outside Humidity (%)	Outside Temperature (°C / °F)	Fan Power (W)	Fan Flow (m^3/h / cfm)	Air Return Temperature (°C / °F)	Air Supply Temperature (°C / °F)	Heat Collected (W / Btu/hr)
10/13/2020 1:00:00PM	976	45	19.4 / 67	55	117 / 21	65.0 / 149	25.0 /77	430 / 1468
10/13/2020 1:15:00 PM	995	44	18.9 / 66	55	112 / 20	66.1 / 151	25.0 / 77	428 / 1463
10/13/2020 1:30:00 PM	997	40	19.4 / 67	55	112 / 20	66.7 / 152	25.0 / 77	438 / 1496
10/13/2020 1:45:00 PM	969	41	20.0 / 68	55	117 / 21	65.6 / 150	25.0 / 77	431 / 1472
10/13/2020 2:00:00 PM	985	41	20.6 / 69	55	108 / 19	65.6 / 150	25.6 / 78	400 / 1367

3. Solar Thermal Collector Performance

Students reference ASHRAE Standard 93-2010 “Methods of Testing to Determine the Thermal Performance of Solar Collectors” as the basis for their computations of solar collector performance. The standard helps ensure that their results are comparable to similar computations done at other locations. The test standard specifies weather conditions and the number and type of measurements needed. Several different computations are made.

3.1 Solar Efficiency

Students compute the *Solar Collector Efficiency* using equations 2, 3, and 4. Equation 2 shows that the basic efficiency computation compares the heat collected to the solar resource available. The value is expressed as a percent and by definition will always be less than 100%. Equation 3 shows that the numerator of equation 2 (heat collected) is computed from a sensible energy equation using the mass flow rate, the specific heat, and the temperature differential through the solar collector. The inputs to equation 3 differs by collector because some circulate air (an ideal gas) and others circulate a 50% glycol solution (a liquid). Equation 4 shows that the denominator of equation 2 (sun available) is computed by multiplying the solar intensity (W/m^2) by the surface area of one collector. The results of this computation for all eight solar collectors is presented later in this paper.

$$Solar\ Collector\ Efficiency = \frac{heat\ collected}{sun\ available} = \frac{\dot{Q}}{\dot{E}} \tag{2}$$

$$\dot{Q} = \dot{m} c_p \Delta T \tag{3}$$

$$\dot{E} = solar\ intensity\ x\ collector\ area \tag{4}$$

32 Solar Energy Factor

Students also compute the Solar Energy Factor (SEF) using equation 5. The SEF is a dimensionless number that should be significantly greater than 1 if the collectors are harvesting significant amounts of heat. Although it is not specifically called out in ASHRAE standard 93-10, the SEF is a helpful real-time indicator of solar collector performance. If the SEF drops below one, typically on cloudy days or during extremely cold weather, it is worthwhile to shut down the collectors.

$$Solar\ Energy\ Factor = \frac{heat\ collected}{electricity\ used} = \frac{\dot{Q}}{\dot{W}} \qquad (5)$$

The SEF equation compares the heat collected to the electricity used to circulate fluid through the active loop. The numerator for the SEF in equation 5 is computed using equations 2, 3, and 4. The denominator of the SEF in equation 5 is taken from sensors that measure the real time power consumption of the pumps for fans that circulate fluid through the active loop.

33 Solar Collector Performance

Figure 4 shows typical student results after they have evaluated collector efficiency (blue bars) and energy factor (orange bars) for all eight solar thermal collectors. Figure 3 is grouped into colored boxes to highlight important differences:

- The two collectors on the far left (blue box) were purchased from outside vendors who specialize in solar thermal collectors. The six other collectors were designed by Purdue University students. The commercial collectors generally outperform the collectors built at Purdue.
- The five collectors to the left (red box) circulate a glycol/water mix for freeze protection and the three collectors to the right (green box) circulate air. Glycol/water collectors outperform air collectors.

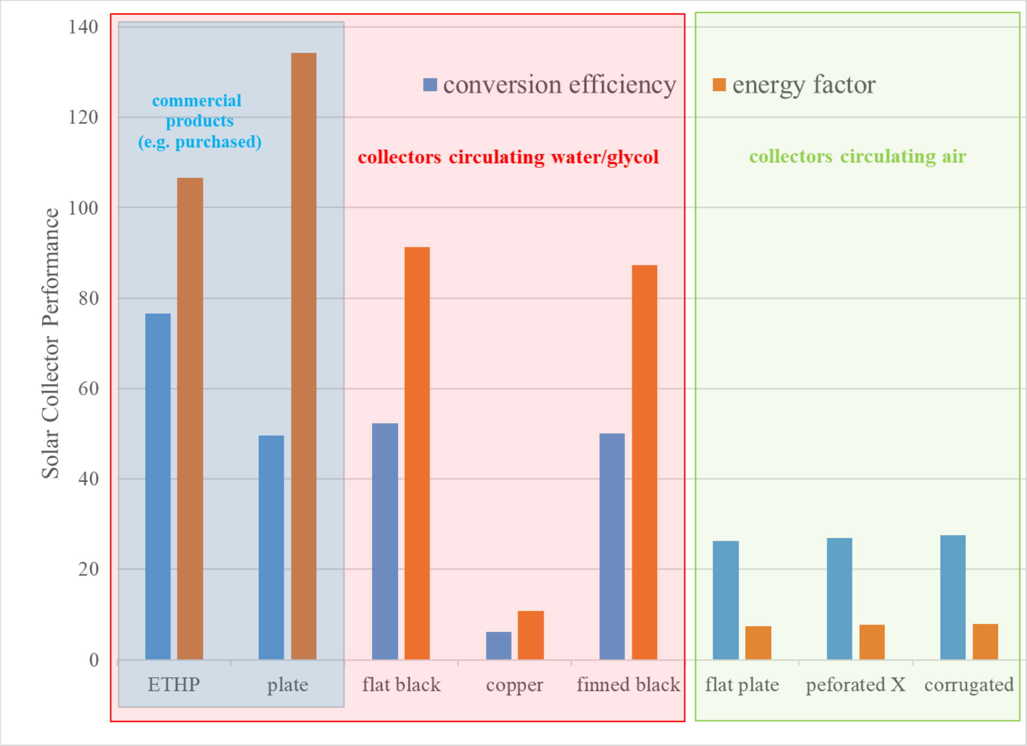

Figure 4: Performance comparison for eight solar thermal collectors

4. Conclusions

A test stand for comparing the performance of solar thermal collectors was recently installed at Purdue University in West Lafayette, IN. There are eight collectors in all, three circulate air and five circulate a glycol/water solution for freeze projection. The collectors have different sizes, colors, and configurations so that their performance varies. Using protocols from established test standards, undergraduate students compute both efficiency and energy factor and use that information to make generalizations about what characteristics are important for optimizing solar collector performance. Students generally report that glycol/water collectors outperform air collectors and that commercially available solar collectors generally outperform collectors that were designed by university students. The overall performance of the solar collectors varies by season, because Purdue University experiences cold/cloudy winter weather and warm/sunny summer weather.

The solar thermal collectors are monitored and controlled by a web-based Building Automation System that creates a unique opportunity for encouraging collaborations with international partners. Students and researchers from Peru can use the web-based platform to conduct the same solar energy experiments. Looking to the future, it may be possible to make similar installations at Peruvian universities to increase the opportunities for international exchange.

REFERENCES

Applied Energy Lab Building Automation System. WebCTRL: Solar PV Monitor. Retrieved from http://technrg1.ecn.purdue.edu/

ASHRAE Standard 93. (2014). Methods of Testing to Determine the Thermal Performance of Solar Collectors.

Hutzel, W. J., (2002). A remotely accessed HVAC laboratory for distance education, *International Journal of Engineering Education*, Vol 18, No 6, pp 711-716.

Hutzel, W. J. and Furter, R., (2005). International Partnership Using Remotely Accessed Labs. Proceedings of the 2005 Frontiers in Education Conference, American Society for Engineering Education, pp T4D-1- T4D-6.

Lotz, David, Hutzel, William, Arnett, William, Dunlap, Duane, and Foreman, Christopher (2016), Heat pump assisted solar thermal system, Proceedings of the 4th International High Performance Buildings Conference at Purdue, West Lafayette, IN, July 11-14, 9 p.