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Evacuated-Tube Heat-Pipe Solar Collectors Applied to the Recirculation Loop in a Federal Building

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Evacuated-Tube Heat-Pipe Solar Collectors Applied to the Recirculation Loop in a Federal Building

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Abstract

This paper describes the design, simulation, construction and measured initial performance of a solar water heating system (a 360-tube evacuated-tube heat-pipe solar collector, 54 m^2 in gross area, 36 m^2 in net absorber area) installed at the top of the hot water recirculation loop in the Social Security Administration's (SSA) Mid-Atlantic Center in Philadelphia. When solar energy is available, water returning to the hot water storage tank is heated by the solar array. This new approach, in contrast to the more conventional approach of preheating incoming water, is made possible by the thermal diode effect of heat pipes and low heat loss from evacuated-tube solar collectors. The simplicity of this approach and its low installation costs make the deployment of solar energy in existing commercial buildings more attractive, especially where the roof is some distance away from the water heating system, which is often in the basement. Initial performance measurements of the system are reported.

Hourly simulation results estimate an annual energy delivery of 111 GJ/year of solar heat and an annual efficiency (based on the 54 m^2 gross area) of the solar collectors of 41%. For the entire system, including parasitic pump power, heat loss due to freeze protection and heat loss from connecting piping is estimated to be 34%. Annual average collector efficiency, based on a net aperture area of 36 m^2, is 61.5%, according to the hourly simulation.

Nomenclature

A_c = gross aperture area of solar array (m^2)
A_{loop} = surface area of building recirculation loop (m^2)
C = specific heat of water (kWh/kg°C)
G = solar irradiance in the plane of the array (W/m^2).
I_c = solar radiation in the plane of the array, totaled over a month (kWh/m^2/month)
I_{ave} = annual average daily solar radiation in the plane of the array (kWh/m^2/day)
I_{max} = maximum daily solar radiation in the sunniest summer month in the plane of the array (kWh/m^2/day)
L = daily energy requirement for heating water (kWh/day)
M = mass of hot water used daily (kg/day)
$Q_{collected}$ = annual heat collected by the solar collector from Equation 2 (GJ/year)
$Q_{delivered}$ = annual heat imparted to the recirculation loop after losses from connecting piping (GJ/year)
$Q_{freeze\ protection}$ = annual heat addition required to maintain system above 4°C (GJ/year)
T_a = ambient air temperature (°C)
T_{cold} = annual average mains water temperature (°C)
T_{hot} = temperature of the delivered hot water (°C)
T_{indoor} = temperature inside the building (°C)
T_m = mean collector temperature, $(T_{outlet}+T_{inlet})/2$ (°C)
U_{loop} = heat loss coefficient of recirculation loop (W/m^2°C)
$\eta_{collector}$ = efficiency of the solar collector (dimensionless)
η_{system} = efficiency of the solar system (dimensionless)

Figure 1. Photograph of the solar array on the southwest riser of the building recirculation loop on the Mid-Atlantic Social Security Center, Philadelphia, PA; another array on the northeast riser is identical in size and orientation.

Introduction

In 2002, the Mid-Atlantic Social Security Center in Philadelphia, PA (40^o N, 75^o W) switched to fuel oil for potable water heating because of high natural gas prices. The Center also began considering solar water heating (SWH) as a renewable energy alternative. Several offerors proposed flat-plate collectors and a design that would preheat cold incoming water before delivery to the building's existing hot water system. For the tall urban commercial building considered here (8 stories, 38 m), extensive piping would have been required to install a new preheat system, and it would have had to span the distance between the roof, where the collectors would be located, and the basement, where large solar preheat tanks would feed the existing boilers. A temperature-controlled valve would also be required to route water returning from the recirculation loop.

The SSA and the General Services Administration (GSA) selected the least expensive design that uses evacuated heat-pipe collectors in an alternative approach that avoids the additional tanks and piping required for a preheating system. Rather than preheating the water, the system reheats it. Reheating water that is returning in the recirculation loop would not be practical with flat-plate collectors, since their efficiency would be low at the loop's elevated temperatures. However, using evacuated-tube collectors with a sufficiently low loss coefficient makes it possible to add a solar system to the top of a recirculation loop and avoid the additional tanks and piping required for a solar preheat system. Pumps and controls are required to control heat collection as well as to avoid freezing and overheating. This reheating approach has been described in design guides such as the ASHRAE Active Solar Systems Design Manual [1], but it is not commonly employed and not described in the literature.

The Application: Commercial Building Recirculation Loop

The system can be used for cost-effective retrofits of solar water heating systems on existing commercial buildings. The U.S. Department of Energy reports that about 7% of the 17.5 quads/year used by commercial buildings (about 1.1 quad/year) are used for water heating [2]. Of this, 0.02 quad/year is currently supplied by solar water heating systems. In 2001, 26 manufacturers supplied 1.039 million m^2 (or approximately 4500 new systems) of solar collectors; of these, 1.003 million m^2 are unglazed swimming pool heaters. On average, water heating appears to be a small fraction of total energy use for commercial buildings. But for many other building types, water heating can be a large fraction of their total energy requirements. As Table 1 indicates, water heating is especially important in buildings used for health care, lodging, food service, education, and public order and safety [2]. The approach described in this paper is one way to facilitate the implementation of solar water heating in commercial buildings and thus to increase market penetration.

Table 1. Energy Intensity (in MJ per m^2 of floor space per year) in Different Types of Commercial Buildings for Water Heating and All Uses (space and water heating, lighting, cooling, other) [2]

Building Type	Water Heating	Total
Office	99	1027
Mercantile	58	790
Education	198	851
Health Care	715	2002
Lodging	583	1130
Public Assembly	199	927
Food Service	312	2738
Warehouse	23	499
Food sales	103	2295
Vacant	59	300
Public Safety	266	986
Other	174	1635
All Buildings	157 (13.7 kBtu/sf/year)	1027 (90.5 kBtu/sf/year)

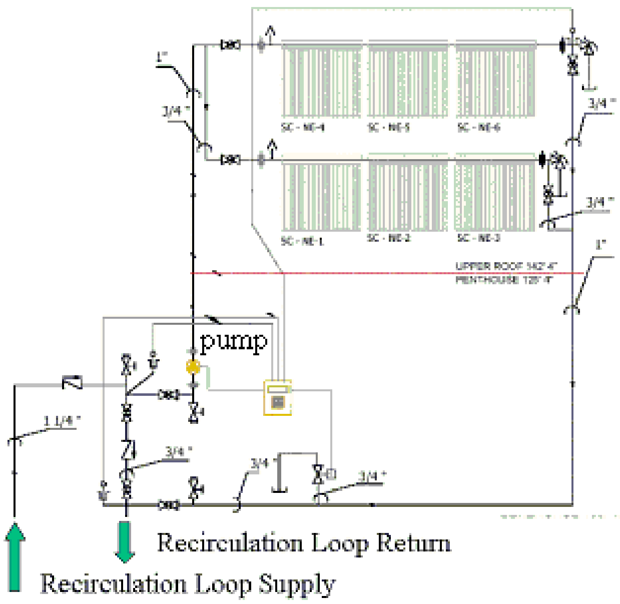

Figure 2. Schematic diagram of solar water heating system applied to commercial building recirculation loop, showing one of two identical systems on the Mid-Atlantic Social Security Center

Solar Water Heating System Description

The Mid-Atlantic SSA Center, like most large commercial buildings, has a recirculation loop that delivers hot water to all floors. In the mechanical penthouse on the 8th floor, the recirculation loop turns over and returns to the boiler for reheating. The selected design taps the loop at the 8th floor, diverts water that would otherwise be returning to the boiler, and passes it through a solar array if there is sufficient solar energy. Figure 2 is a schematic diagram of the system.

If no solar heat is available, potable hot water arrives at the top floor solar tap/bridge assembly after having been available to all the building's appliances and returns to the tanks and boilers in the basement for reheating, as it did before the installation of the solar system. If the temperature at the solar collector outlet exceeds the temperature in the recirculation loop by 4^{o}C, the solar pump turns on and water is routed through the headers of the heat-pipe collector solar array. Solar reheated water is then returned to the recirculation loop return, and subsequently to the tank and boiler system in the basement. Heating the tank in this way reduces the amount of fuel consumed by the boiler.

The solar collector system consists of 360 Thermomax evacuated heat-pipe tubes in two arrays. Each array is made up of six manifold units of 30 tubes each, for a total of 180 tubes per array. The total aperture area of both arrays is 53.9 m^2, including the space between tubes. The net absorber area is 36 m^2. One array injects heat into the recirculation loop return leg of a riser on the southwest side of the building, and an identical array serves the northeast riser. The collector arrays are mounted on the flat roof by using ballast blocks without roof penetrations. This is also made possible by the use of evacuated-tube collectors, since wind passing between the tubes exerts less of a sail effect force than that on a flat plate. For a 40 m/s wind, the uplift for each 30-tube collector array is 700 N, and the drag is 1190 N. In comparison, the maximum lift on a flat plate of the same size (4.5 m^2) is 5360 N, and the maximum drag is 8930 N.

The existing domestic water heating system delivers additional heating, if required. In this way, the existing hot water recirculation loop serves as the supply and return legs of the designed solar loop, and no additional piping or tanks are needed inside the building. While very simple in configuration, the design relies on active controls for freeze and overheat protection. A microprocessor solar controller determines the operation of the pump for energy collection and freeze protection and controls a drain dump solenoid valve for overheat protection.

Freeze protection is provided by monitoring the collector temperature (T_c). Regardless of the temperature difference (ΔT), the pump runs and circulates hot water through the array header when the collector temperature is below a programmable minimum temperature ($T_c < 4^oC$). The pump runs only briefly (30 m solar loop with a flow rate of 22 liters per minute results in less than 1 minute circulation time). This heating of the 15 m array header causes a measurable penalty under freezing conditions, but it is small in comparison to solar delivery. This is because the evacuated tubes are insulated well, and potable water flows only through the well-insulated array headers.

Overheating protection is also provided by active control plus the passive saturation of the heat pipe at very high temperatures. The maximum temperature of the solar loop return to the storage tank is coordinated in the following order: the circulating pump in the solar loop turns off at 80^{o}C (programmable); the solenoid valve discharges hot water to the drain line at 85^{o}C (programmable); snap discs in the heat-pipe header block the return of condensate at 120^{o}C; and the heat pipe reaches its saturation temperature at 150^{o}C. Because of the large thermal capacitance of the building recirculation loop and storage tanks, such overheating is expected to be rare. But it could occur when the recirculation loop is turned off.

Evacuated-Tube Solar Collectors

Reheating water in the recirculation loop, rather than preheating cold water, requires a collector with a very low loss coefficient. This is currently available only with evacuated-tube solar collectors, as opposed to flat-plate solar collectors. This project uses evacuated heat-pipe solar collectors, which consist of a heat pipe inside a vacuum-sealed tube, as shown in Figure 3. The air in each tube is evacuated to 10E-05 mbar, eliminating convection and conduction heat loss but allowing in the solar radiation. Test results from the Hochschul Rapperswil of Switzerland [4] lead to the following thermal performance equation:

η_{coll} = 0.84-2.02 (T_m-T_a)/G-0.0046G[(T_m-T_a)/G]**2 .   (1)

Tests conducted by the Florida Solar Energy Center [5] are in agreement:

$$\eta_{collector} = 0.82 - 2.19\ (T_m - T_a)/G \quad , \qquad (2)$$

where T_m is the mean collector temperature, (T_{outlet}+T_{inlet})/2 [°C], T_a is the ambient air temperature (°C), and G is the solar irradiance (W/m^2). Both of these equations are based on net absorber plate area rather than gross area. With this type of collector, the absorber area is 67% of the gross area. If gross area is used, the optical gain and thermal loss coefficients of Equation 2 would be 0.53 and –1.42 W/m^2°C, respectively.

Each tube contains a sealed copper pipe (heat pipe). The pipe is then continuously bonded to a selectively coated copper fin (absorber plate) that collects solar energy, converting it to heat. This energy is conducted to the heat pipe's working fluid, vaporizing it. The vapor rises into a condenser bulb at a higher elevation, and the condensate returns to the collector heat zone by gravity (without a capillary wick structure).

The selective coating has an absorbtivity in excess of 92% throughout the solar spectrum and an emissivity of less than 6% throughout the infrared spectrum (373 K). The coating is applied by a sputtering manufacturing process in a high-vacuum chamber and involves three stages: (1) a stabilizing layer of titanium (Ti); (2) reaction of the titanium with oxygen, creating a semiconductor layer to absorb radiation; and (3) an antireflection coating layer.

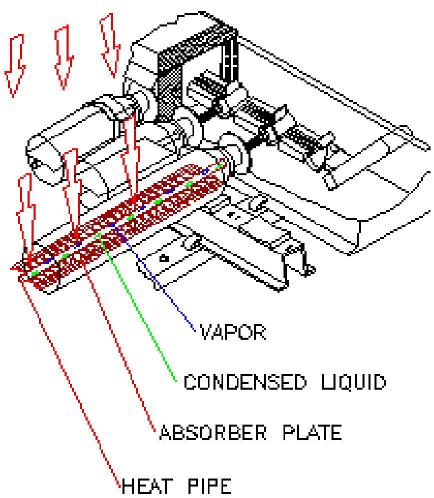

Figure 3. Components of an evacuated-tube heat-pipe solar collector

The tubes are mounted, with the condenser bulbs up, into a heat exchanger (manifold). The manifold is a shaped copper pipe that wraps around both sides of each condenser bulb. Potable water from the recirculation loop flows through the manifold and picks up heat from the condenser bulbs.

The maximum operating temperature of the heat pipe is the critical temperature of the dual-phase fluid, since no evaporation or condensation above the critical temperature is possible. The heat pipe also provides the system with a thermal diode function, so that when the sun is not shining, heat loss from the potable water is kept to a minimum. This occurs because heat is lost only from the header, not from the absorber surface of the array. The header is insulated with polyurethane foam to a U-value of 0.28 to 0.35 W/m K.

Within each condenser bulb, the maximum working temperature is controlled by means of memory-metal snap discs to a level below the critical temperature. The memory metal is programmed to change its shape at a preset temperature. This allows the condenser fluid to be retained inside the condenser. When the programmed temperature is reached, the memory-metal spring expands and pushes a plug against the neck of the heat pipe, blocking the return of the condensed fluid and stopping latent heat transfer. At temperatures below the maximum programmed limit, the spring contracts, allowing the condensed fluid to return to the lower section of the heat pipe. The solar heat from the absorber plate then causes the condensate to evaporate, transferring thermal energy to the condenser. The flexible neck system absorbs both thermal and mechanical shocks.

Initial Observed Operation of the System

System operation is demonstrated by the temperatures and system status illustrated in Figure 4. The data are collected with the recording capability of the system controller. The controller records data every 10 minutes and stores the data for up to two years before overwriting the old data with new. Figure 4 shows the measured collector outlet temperature, the temperature of water supplied by the recirculation loop (assumed constant at 50°C), the measured temperature of the water in the return leg of the recirculation loop, and the measured ambient temperature. The temperature in the return leg of the recirculation loop represents a mixture of water heated by the solar array and water bypassing the solar array through a check valve. (Some of the water in the recirculation loop might not pass through the solar array; this depends on the array flow rate induced by the pump). The ambient temperature reported for Philadelphia by the National Climatic Data Center [4] is also illustrated in Figure 4; it stays near 0°F for the entire day. Finally, Figure 4 also indicates the status of the system's energy collection: the status is 1 if the pump is on and the solar collector is hotter than the recirculation loop (for collecting energy as opposed to preventing freezing).

The collector temperature is observed to drop during the early morning hours until it reaches 4°C at 6:00 a.m., at which time the pump turns on and circulates hot water to the solar array. The temperature of the collector outlet is observed to increase in response to this deliberate circulation. The penalty for this nighttime heating can also be seen in Figure 4 as a decrease in the temperature of water being returned to the conditioned room for reheating. Some passive thermosyphoning appears to also heat the solar array header at night to an unknown degree. This natural circulation may be assisted by flow through the array header, which is induced by the consumption of hot water in the building. This effect is especially noticeable at about 6:30 a.m., when workday activities start. Sunrise occurs at 7:21 a..m. By 9 a.m., the array is hot enough for the pump to come on, and energy is delivered to the recirculation loop. The pump cycles a few times in the morning. By noon, the solar array is heating the recirculation loop continuously. The return to the boiler reaches a maximum temperature of 56°C from 12:30 to 2:50 p.m.

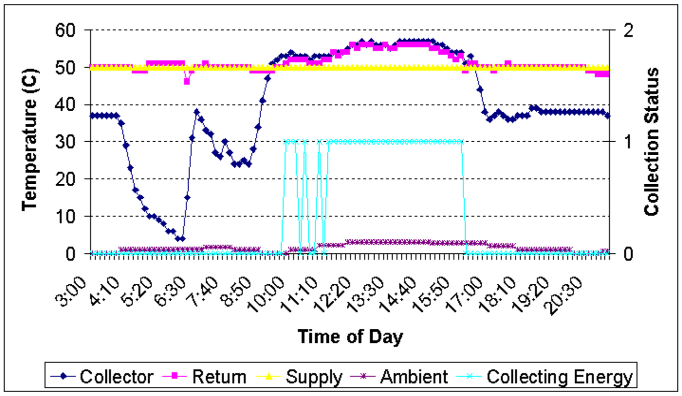

Figure 4. Collector temperature, recirculation loop supply temperature, return temperature, ambient temperature, and energy collection status (1 = collecting energy) throughout a selected day (January 10, 2004), illustrating the features of system performance

Solar Water Heating System Cost

The installed cost of the system is approximately $58,000. Of this total, 50% is associated with engineering and installation labor; 43% is for solar arrays and their mounting racks; and the remaining 7% represents plumbing supplies, pumps, data logger, and controller costs.

Savings Estimates

A computer program provided by the supplier estimates an annual delivery of 151 GJ/year for a 36 m^2 absorber area [6]. This method uses a monthly calculation that does not include heat loss from connecting piping or heat loss required for freeze protection.

To provide a more accurate estimate of annual energy delivery, an hourly simulation of the system was prepared. Delivered energy was calculated using Equation 2 for the collector performance; the incident angle modifier from the test report [4]; and heat loss from an insulated copper connecting pipe, 80 m long and 22 cm in diameter, with a heat loss coefficient of 28 W/°C. The heat required to maintain the array at 4°C (freeze protection) was calculated using both the heat loss from the piping and the collector header heat loss coefficient of 0.35 W/m°C, with a total header length of 30 m. The temperature of water delivered to the solar system by the recirculation loop was taken as 50°C for all hours of the year.

Typical Meteorological Year (TMY)2 weather data for Philadelphia were used in the simulation, which predicted that the pump runs 3,192 hours per year for a parasitic pump power of 654 kWh/year. Listed in Table 2 are solar energy incident on the collector (Ic); the heat collected annually by the solar collector, $Q_{collected}$; the annual heat imparted to the recirculation loop after losses from connecting piping, $Q_{delivered}$; the energy required to keep the system above 4°C, $Q_{freeze\ protection}$; and the system efficiency. Figure 5 presents these energy quantities on a monthly basis.

A simple hand calculation useful for estimating initial sizing and delivery may be devised using this value for efficiency. Flat-plate solar collector efficiency depends highly on ambient conditions. But for evacuated-tube collectors, low heat loss allows an approximation of constant efficiency for this simple hand calculation to be conservative and relatively accurate, depending wholly on the value stipulated for system efficiency.

The estimated energy use associated with hot water use is

$$L = M*C*(T_{hot} -T_{cold}) + U_{loop}A_{loop}(T_{hot}-T_{indoor}) , \quad (3)$$

where L = daily energy load (kWh/day), M is mass of hot water used daily (kg/day), C is the specific heat of water (0.001167 kWh/kg°C), $U_{loop}A_{loop}$ is the heat loss coefficient of the recirculation loop, and T_{indoor} is the temperature inside the building. T_{hot} is the temperature of the delivered hot water (°C), and T_{cold} is annual average mains water temperature (°C). The solar system sizing strategy in this case is to meet the load under the sunniest possible condition.

$$A_c = L/(\eta_{solar}*I_{max}) , \quad (4)$$

where η_{solar} is the efficiency of the solar system, and I_{max} is the maximum daily solar radiation occurring in the sunniest summer month (kWh/m^2/day). The estimate for annual heat energy delivery, $Q_{delivered}$, is based on the annual average daily solar radiation, I_{ave} (kWh/m^2/day).

$$Q_{delivered} = A_c*I_{ave}*\eta_{solar}*(365 \text{ days/yr}) . \quad (5)$$

For the system in Philadelphia, the following values apply: a daily hot water load at the SSA Center estimated at 3562 kg/day; a delivered hot water temperature of 50°C and annual average mains water temperature of 8.3°C; I_{max} of 5.5 kWh/m^2/day; and I_{ave} of 4.6 kWh/m^2/day. With these values and a system size of 54 m^2 gross area, annual energy delivery is estimated by Equation 5 at 111 GJ/year, the same as in the simulation, which calculated a 34% system efficiency. Note that this system efficiency, including all heat loss and parasitic power, is not to be compared with collector efficiency, which is 41% based on gross area, as estimated by the simulation.

Table 2. Results of the Hourly Simulation: Energy Incident on the Collector, Heat Captured by the Solar Collector, Heat Delivered to the Recirculation Loop, and Heat Loss Required for Freeze Protection (GJ/year)

Ic (GJ/year)	313
$Q_{collected}$ (GJ/year)	129
$Q_{delivered}$ (GJ/year)	111
$\eta_{collector}$	41%
$Q_{freeze\ protection}$ (GJ/year)	1.37
Pump energy (GJ/year)	2.35
η_{system}	34%

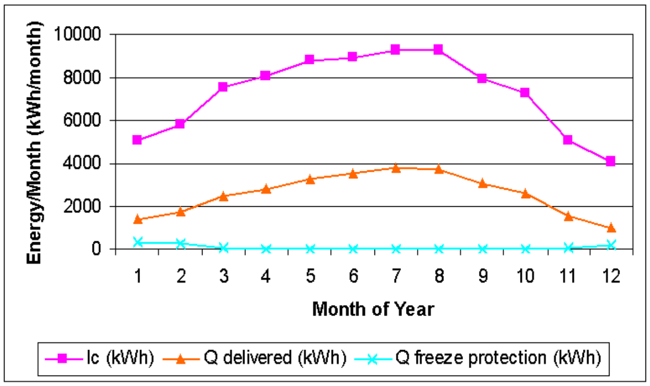

Figure 5. Simulated incident solar energy, delivered energy, and energy required for freeze protection per month

Conclusion

This paper describes a solar water heating system configuration that shows promise for reducing the cost and complexity of solar water heating on commercial buildings with a recirculation loop. The system relies on the diode function of heat pipe, the superior insulation of evacuated-tube collectors, and active controls for successful operation and protection from freezing and overheating. An hourly simulation predicts a system efficiency of 34% (based on gross area) for the building in Philadelphia. Initial observations of system performance indicate that the system operates as expected and returns water to the boiler about 5°C hotter than that supplied to the solar system. Project participants are pleased with the relative ease of implementing this type of system and with its initial performance. Long-term monitoring will assess the system's ability to operate and deliver savings under varying conditions.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
This paper describes the design, simulation, construction, and initial performance of a solar water heating system consisting of 360 evacuated-tube heat-pipe collectors with a gross area of 54 square meters and a net absorber area of 36 square meters. The collectors were installed at the top of the hot water recirculation loop in the Social Security Administration's Mid-Atlantic Center in Philadelphia. When solar energy is available, water returning to the hot water storage tank is heated by the solar collectors. This new approach, in contrast to the more conventional approach of preheating incoming water, is made possible by the thermal diode effect of heat pipes and low heat loss from evacuated-tube solar collectors. The simplicity of the approach and its low installation support the deployment of solar energy in existing commercial buildings, especially where the roof is some distance away from the water heating system, which is often in the basement. Initial performance measurements are reported.

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