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# EVACUATED TUBE HEAT PIPE SOLAR COLLECTORS APPLIED TO RECIRCULATION LOOP IN A FEDERAL BUILDING (SSA PHILADELPHIA)

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## ABSTRACT

This paper describes design, simulation, construction and measured initial performance of a solar water heating system (360 Evacuated Heat-Pipe Collector tubes, 54 $m^2$ gross area, 36 $m^2$ net absorber area) installed at the top of the hot water recirculation loop in the Social Security Mid-Atlantic Center in Philadelphia. Water returning to the hot water storage tank is heated by the solar array when solar energy is available. This new approach, as opposed 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 makes the deployment of solar energy in existing commercial buildings more attractive, especially where the roof is far removed from the water heating system, which is often in the basement. Initial observed performance of the system is reported.

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

Keywords: solar water heating, recirculation loop, commercial building, evacuated tube solar collector

## 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/kgC)
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 4C (GJ/year)
$T_a$ = ambient air temperature ($^oC$)
$T_{cold}$ = annual average mains water temperature ($^oC$)
$T_{hot}$ = temperature of the delivered hot water ($^oC$)
$T_{indoor}$ = temperature inside the building ($^oC$)
$T_m$ = mean collector temperature, $(T_{outlet}+T_{inlet})/2$ ($^oC$)
$U_{loop}$ = heat loss coefficient of recirculation loop (W/m2C)
$?_{collector}$ = efficiency of the solar collector (dimensionless)
$?_{system}$ = 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. The other array on the northeast riser is identical in size and orientation.**

## INTRODUCTION

In 2002, high natural gas prices caused the Mid Atlantic Social Security Center in Philadelphia PA (40° N, 75° W) to switch to fuel oil for potable water heating and also to consider 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, 38m), this would have required extensive piping to install a new preheat system which would have to span the distance between the roof, where the collectors were to 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 GSA selected the least expensive design that uses evacuated heat pipe collectors in an alternative approach that avoided the additional tanks and piping required for a preheating system. Rather than preheating, the system reheats. Reheating water 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, by using evacuated tube collectors with a sufficiently low loss coefficient, it is possible to add a solar system to the top of a recirculation loop and avoid the additional tanks and piping required for a solar pre-heat 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 [1] but it is not commonly employed and not described in the literature.

## THE APPLICATION: COMMERCIAL BUILDING RECIRCULATION LOOP

The system described has application for the cost-effective retrofit of a solar water heating system onto an existing commercial building. The US Department of Energy [2] reports that about 7% of the 17.5 Quads/year used by commercial buildings (or 1.1 Quad/year) are used for water heating. Of this, 0.02 Quad/year is currently supplied by solar water heating systems. In 2001, 26 manufacturers supplied 1,039,000 m$^2$ of solar collectors, 1,003,000 m$^2$ of which is unglazed swimming pool heaters for approximately 4,500 new systems that year. For commercial buildings on average it seems that water heating is a small fraction of total energy use, but for many building types water heating can be a large fraction of total energy requirements. Table 1 indicates water heating is especially important in health care, lodging, food service, education, and public order and safety buildings [also from 2]. The approach described in this paper offers a means of facilitating implementation of solar water heating in commercial buildings, and thus increasing market penetration.

**Table 1. Energy Intensity (MJ per m2 of floor space per year) for different types of commercial buildings for water heating and total for all end uses (space heating, lighting, cooling, water heating, 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 (13.7kBtu/sf/year) | 1027 (90.5kBtu/sf/year) |

 

## SOLAR WATER HEATING SYSTEM DESCRIPTION

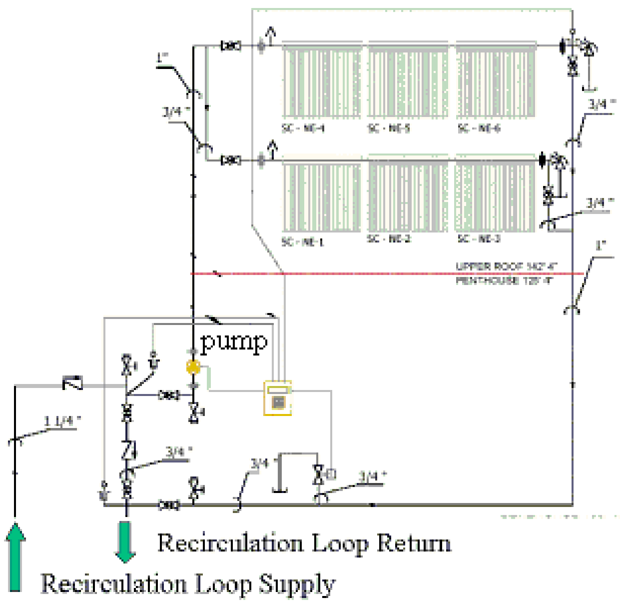


**Figure 2. Schematic diagram of solar water heating system applied to commercial building recirculation loop. This figure shows one of two identical systems on the Mid Atlantic Social Security Center.**

The SSA, like most large commercial buildings, has a hot water recirculation loop, which delivers hot water to all floors. In the mechanical penthouse on the 8-th floor, the recirculation loop turns over and returns to the boiler for reheating. The selected design taps the loop here at the 8-th floor, diverts water that would otherwise be returning to the boiler, and passes it through a solar array if solar energy is sufficient. Figure 2 illustrates 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 appliances and returns to the tanks and boilers in the basement for reheating, as it did prior to 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 re-heated water is then returned to the recirculation loop return, and subsequently to the tank and boiler system in the basement. By heating the tank in this way, the fuel consumed by the boiler is reduced.

The solar collector system consists of 360 Thermomax evacuated heat pipe tubes in 2 arrays. Each array is made up of six manifold units of 30 tubes each, 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 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 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 1190 N. By comparison, the maximum lift on a flat plate of the same size (4.5 m$^2$) is 5360 N and maximum drag is 8930 N.

The existing domestic water heating system delivers additional heating if required. In this way, the existing hot water re-circulation loop serves as supply and return legs of designed solar loop, without any additional piping or tanks 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 collector temperature ($T_c$). Regardless of the temperature difference (?T), the pump runs and circulates hot water through the array header when the collector temperature is below a programmable minimum temperature ($T_c$ < 4$^o$C). The pump runs only briefly (30m solar loop with a flow rate of 22 l/minute yields 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 compared to solar delivery because the evacuated tubes are well-insulated and potable water flows only through the well-insulated array headers.

Overheat 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 following order: circulating pump in solar loop turns off at 80 $^o$C (programmable); solenoid valve discharges hot water to drain line at 85 $^o$C (programmable); snap discs in heat pipe header block return of condensate 120 $^o$C; and heat-pipe reaches its saturation temperature at 150 $^o$C. Due to the large thermal capacitance of the building recirculation loop and storage tanks, such overheating is expected to be rare, but could occur when the recirculation loop is turned off.

## EVACUATED TUBE SOLAR COLLECTORS

Re-heating water in the re-circulation loop, rather than pre-heating cold water, requires a collector with a very low loss coefficient, currently available only with evacuated tube solar collectors (as opposed to flat plate solar collectors). This project uses evacuated heat pipe solar collectors consisting 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] leads to following thermal performance equation:

$$?_{coll} = 0.84\text{-}2.02\,(T_m\text{-}T_a)/G\text{-}0.0046G[(T_m\text{-}T_a)/G]\text{**}2 \qquad (1)$$

Tests conducted by Florida Solar Energy Center [5] agree:

$$?_{collector} = 0.82 - 2.19\,(T_m\text{-}T_a)/G \qquad (2)$$

Where $T_m$ is mean collector temperature, $(T_{outlet}+T_{inlet})/2$ [C], $T_a$ is ambient air temperature ($^oC$), and G is 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 absorber area is 67% of gross area. For use with gross area, the optical gain and thermal loss coefficients of equation 2 would be 0.53 and –1.42 $W/m^2C$ respectively.

Each tube contains a sealed cooper pipe (heat pipe). The pipe is then continuously bounded 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 condensate returns to the collector heat zone by gravity (without any capillary wick structure).

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

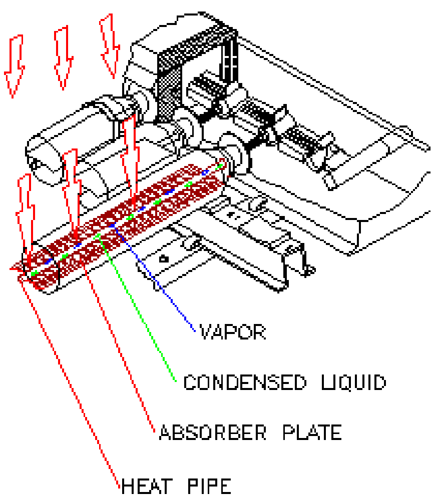


**Figure 3. Components of evacuated tube heat pipe solar collector.**

The tubes are mounted, 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 re-circulation loop flows through the manifold and picks up the 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/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 the heat loss from the potable water is kept to a minimum since it is 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/mK.

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 pre-set temperature. This allows for the condenser fluid to be retained inside the condenser. When the programmed temperature has been achieved, the memory metal spring expands and pushes a plug against the neck of the heat pipe thus 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. It is then evaporated due to the solar heat from the absorber plate, transferring thermal energy to the condenser. The flexible neck system absorbs both thermal and mechanical shocks.

## INITIAL OBSERVED OPERATION OF SYSTEM

System operation is demonstrated by the temperatures and system status illustrated in Figure 4. This data is collected with the recording capability of the system controller. The controller records data every 10 minutes and stores it for up to two years before overwriting old data with new data. Figure 4 shows measured collector outlet temperature, temperature of water supplied by the recirculation loop (assumed constant at 50C), measured temperature of the water in the return leg of the recirculation loop, and 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 by-passing the solar array through a check valve (not all of the water in the recirculation loop necessarily passes through the solar array, depending on the array flowrate induced by the pump). The ambient temperature reported for Philadelphia, PA by the National Climatic Data Center [4] is also illustrated in Figure 4, and stays near $0^oF$ for the entire day. Finally, Figure 4 also indicates system energy collection status: status is a 1 if the pump is on and the solar collector is hotter than the recirculation loop (to collect energy as opposed to prevent freezing).

Collector temperature is seen to drop during the early morning hours until it reaches 4 C at 6:00 am, at which time the pump turns on and circulates hot water to the solar array. The temperature of the collector outlet is seen 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 re-heating. 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 induced by hot water consumption in the building. This effect is especially noticeable about 6:30 am when the workday activity starts. Sunrise occurred at 7:21 am, and by 9 am the array is hot enough that the pump comes 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 of 56 $^oC$ from 12:30 to 2:50 pm.

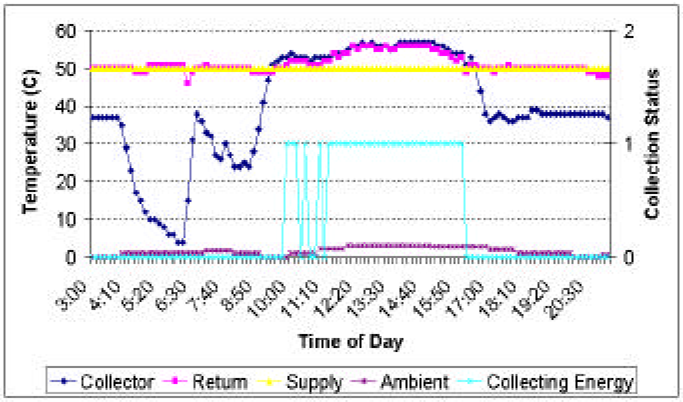


**Figure 4. Collector temperature, recirculation loop supply temperature, return temperature, ambient temperature and energy collection status (1=collecting energy) throughout a selected day (January 10, 2004) illustrating features of system performance.**

## SOLAR WATER HEATING SYSTEM COST

Installed cost of the system is approximately $58,000: 50% of the costs were associated with engineering and installation labor; 43% accounted for solar arrays and their 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 that 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 collector performance; incident angle modifier from [4]; and heat loss from 80m length of 22 cm diameter insulated copper connecting pipe with a heat loss coefficient of 28 W/C. Heat required to maintain the array at 4C (freeze protection) was calculated with both this heat loss from piping and the collector header heat loss coefficient of 0.35 W/mC with a total header length of 30m. Temperature of water delivered to the solar system by the recirculation loop is taken as 50 $^oC$ for all hours of the year. TMY2 weather data for Philadelphia was used in the simulation. Simulation predicts that the pump runs 3,192 hours per year for parasitic pump power of 654 kWh/year. Solar energy incident on the collector, annual heat collected by the solar collector, $Q_{collected}$, annual heat imparted to the recirculation loop after losses from connecting piping, $Q_{delivered}$, energy required to keep the system above 4 $^oC$, $Q_{freeze\ protection}$, and system efficiency are listed in Table 2. Figure 5 presents these energy quantities on a monthly basis.

A simple hand calculation useful for initial sizing and delivery estimates may be devised using this value for efficiency. Flat plate solar collector efficiency is highly depended upon 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

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

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/kgC), $U_{loop}A_{loop}$ 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). Solar system sizing strategy in this case is to meet the load under the sunniest condition.

$$A_c = L/(?_{solar} * I_{max}) \qquad (4)$$

Where $?_{solar}$ 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). Annual heat energy delivery, $Q_{delivered}$, is estimated based on the annual average daily solar radiation, $I_{ave}$ (kWh/$m^2$/day).

$$Q_{delivered} = A_c * I_{ave} * ?_{solar} * (365\ \text{days/yr}) \qquad (5)$$

For this system in Philadelphia, the following values apply: daily hot water load at the center estimated at 3562 kg/day; 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 the system size of 54 m2 gross area annual energy delivery is estimated by Equation 5 at 111 GJ/year, same as the simulation due to the use of the 34% efficiency arrived at by simulation. It should be pointed out that this a system efficiency including all heat loss and parasitic power, 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 Solar Collector; Heat Delivered to 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 |
| $?_{collector}$ | 41% |
| $Q_{freeze\ protection}$ (GJ/year) | 1.37 |
| Pump Energy (GJ/year) | 2.35 |
| $?_{system}$ | 34% |

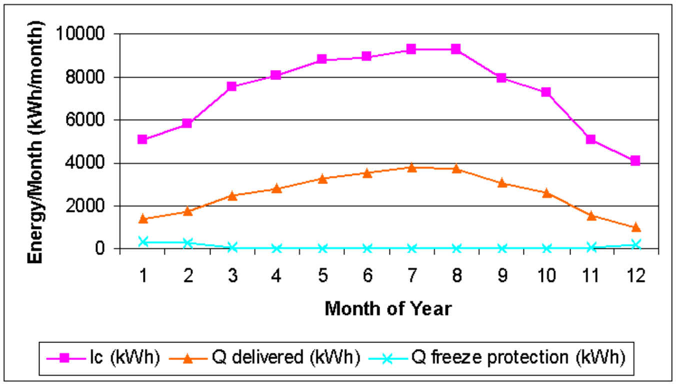


**Figure 5. Simulated incident solar energy, delivered energy, and energy required for freeze protection per month.**

## CONCLUSION

This paper describes a solar water heating system configuration that shows promise to reduce the cost and complexity of solar water heating on commercial buildings with a recirculation loop. The system relies on 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 this 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 supplied to the solar system. Project participants are pleased with the relative ease of implementing this type of system and with initial performance of the system. Long term monitoring will assess the ability of the system to operate and deliver savings under varying conditions.


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## REFERENCES


[1] ASHRAE 90003, 1988, Active Solar Heating Systems Design Manual, American Society of Heating Refrigerating and Air Conditioning Engineers, Inc. 1791 Tullie Circle, NE, Atlanta GA 30329, ISBN 0-910110-54-9.

[2] U.S. Department of Energy, 2002 Buildings Energy Databook, http://www.btscoredatabook.net/, accessed October 2002.

[3] National Climatic Data Center http://climvis.ncdc.noaa.gov/cgi-bin/gsod_stats

[4] Hochschul Rapperswil of Switzerland Test Report No. 264, August 1997

[5] Florida Solar Energy Center (FSEC) Solar Collector Test Report No. 97005, May 1998

[6] www.thermotechs.com/usdata.htm (accessed 3/10/04).