Retrofitting Two Solar Hot Water Systems for Year Round Operation

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RETROFITTING TWO SOLAR HOT WATER SYSTEMS
FOR YEAR ROUND OPERATION

by

Zachary A. Cook

A report submitted in partial fulfillment
Of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

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UTAH STATE UNIVERSITY
Logan, UT

2014
Abstract

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FOR YEAR ROUND OPERATION

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Zachary A. Cook, Master of Science
Utah State University, 2014

Major Professor:  Dr. Byard Wood
Department:  Mechanical and Aerospace Engineering

Solar energy in a variety of applications is again becoming more widely used. Solar collectors have been installed during the construction of two Utah State University buildings: Wetlands Discovery located in Kaysville, Utah and Swaner Nature Preserve located in Park City, Utah. While these systems are capable of capturing a significant amount of solar energy, problems have been encountered when the demand is less than the system’s capacity. This project report documents the problems encountered while operating the two solar water heating systems and how the systems were modified to be operational year round under typical operating conditions. The peak solar gain for the collectors was calculated and modeled to determine the amount of heat that would need to be rejected when the system stalled. Based on these findings, modifications were made to the two solar collector systems and the performance was monitored and analyzed. The systems can now operate throughout the year with minimal maintenance.
Public Abstract

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Zachary A. Cook, Master of Science
Utah State University, 2014

Major Professor: Dr. Byard Wood
Department: Mechanical and Aerospace Engineering

With an increased push for the use of renewable energy sources and rising utility costs, building owners are seeking more energy efficient buildings. Solar energy in a variety of applications is again becoming more widely used. Solar collectors have been installed during the construction of two Utah State University buildings: Wetlands Discovery located in Kaysville, Utah and Swaner Nature Preserve located in Park City, Utah. While these systems are capable of capturing a significant amount of solar energy, problems have been encountered when the demand is less than the system’s capacity. This project report documents the problems encountered while operating the two solar water heating systems and how the systems were modified to be operational year round under typical operating conditions. The peak solar gain for the collectors was calculated and modeled using Transient System Simulation 17.1 (TRNSYS) to determine the amount of heat that would need to be rejected when the system stalled. Based on these findings, modifications were made to the two solar collector systems and the performance was monitored and analyzed. The systems can now operate throughout the year with minimal maintenance.
Acknowledgements

I’d like to express my gratitude to Dr. Byard Wood for taking the time to share his knowledge and experience in the solar industry to help with this project. Also, to my wife for her patience in allowing me to continue my education for nearly 10 years without earning a medical degree. Thank you also to those at Utah State University Facilities who gave their time and resources to take a more in-depth look at this problem and make the modifications I deemed necessary based on the findings in this report.

Zachary A. Cook
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Acronyms

ASHRAE – American Society of Heating, Refrigerating, & Air-Conditioning Engineers

BAS – Building Automation System

LEED - Leadership in Energy and Environmental Design

TRNSYS – Transient Systems Simulation Program

SRCC – Solar Rating & Certification Corporation

NSRDB – National Solar Radiation Data Base

NREL – National Renewable Energy Lab

TMY2 - Typical Meteorological Year (new) data (TMY2)
Nomenclature

\( \alpha \) - absorptance, thermal Diffusivity, effectiveness

\( A_c \) - collector Area

\( A_a \) - aperture Area

\( \beta \) - slope of solar collector

\( \theta \) - angle of incidence (angle between beam radiation and normal of the surface)

\( \omega \) - hourly sun angle

\( \phi \) – latitude

\( I \) – solar intensity

\( n \) – day number of the year

\( \tau \) – transmittance

\( k \) – thermal conductivity

\( \mu \) – absolute viscosity

\( \varepsilon \) – emittance

\( \eta \) – efficiency

\( E \) – energy

\( G \) – irradiance

\( S \) – absorbed solar energy per unit area

\( \theta_z \) – zenith angle

\( h_f \) – heat transfer coefficient from fluid to pipe wall

\( Gr \) – Grashof number
Ra – Raleigh number

$T_a$ – ambient temperature

$T_b$ – absorber plate temperature at tube and plate connection

$T_f$ – average fluid temperature

$T_{\text{collector}}$ – average collector absorber temperature

$R_b$ – ratio of beam radiation on tilted plane to that on plane of measurement

$C_b$ – absorber plate and tube bond material conductance

$c_p$ – specific heat

$T_\infty$ – bulk temperature

$T_s$ – surface temperature

$W$ – distance between tubes, width

$D$ – tube diameter

$D_i$ – inner tube diameter

$\delta$ – absorber plate thickness, angle of declination

$k$ – conduction coefficient of the absorber plate

$U_L$ – loss coefficient of the collector

$F$ – fin efficiency

$F'$ – collector efficiency factor

$F_R$ – collector heat removal factor
Introduction

Construction of the Swaner Eco Center, located on the 1,200 acre Swaner Nature Preserve, was completed in early 2009. The construction met the Leadership in Energy and Environmental Design (LEED) Platinum standard, which is the highest standard for design, construction, and operation of high-performance green buildings. In 2010 the Eco Center and Nature Preserve were donated to Utah State University. Several operation and maintenance items lingered from the original construction that USU Facilities immediately began to resolve. Among these issues was the operation of the solar heating system. It was found that the solar hot water collectors were not functional and had not been for some time.

That same year, a new ecofriendly building was being designed and built at the Utah Botanical Center. The Wetlands Discovery Point Building in Kaysville Utah also received LEED Platinum from the U.S. Green Building Council (USGBC). The intent during design and construction was for this building to be one of the most environmentally friendly buildings in the state and to approach carbon neutrality. After discovering the condition of the Swaner solar heating system the system at the Wetlands building was investigated only to find it was in a similar condition.
There are three basic solar heating systems: active closed loop, thermo-siphon, and drain back. The active closed loop consists of a pump circulating fluid (typically propylene glycol) between the collector and a heat exchange device. This type of system is the most common in a climate like Utah because it makes it possible for the system to operate year round and take advantage of days with high solar radiation during cold ambient temperatures. In milder climates the thermo-siphon design is more common. It is an open loop system that requires no pumps and takes advantage of the density gradient of the cold and hot water to circulate the water. A storage tank is placed above the collectors and as the water is heated in the collectors it rises and is piped to the top of the storage tank. Cold water enters at the bottom of the tank and is piped to the bottom of the solar collector. Lastly, the drain back system consists of a series of valves that go to a specified position to drain the collectors when there is no demand or low solar radiation. When favorable conditions are again available the automated valves refill the collector.
Both systems being studied are variations of an active glycol closed loop systems with tube bundle heat exchangers inserted into the domestic water storage tank. During the initial investigation, it was found that the glycol had been emptied from both systems. The sequence of operation for both solar collector systems included a safety control that turned off the collector circulating pump to prevent overheating and scalding of users. This control sequence caused the fluid in the collector to heat up to the point that steam was generated. The increase in pressure caused the safety relief valve to open and dump the glycol. With very little use of the building and limited domestic hot water demand at times of peak solar gain there was no use for the large amount of energy collected.

Three different methods were considered in solving this problem. Converting the two systems from a glycol system to a drain back system was the first solution investigated. Rather than filling the systems with glycol for freeze protection, the system would be designed to drain under following conditions: low temperatures with limited solar gain and low load causing the system to overheat. The fluid would be drained and under appropriate conditions the system would be filled up again and the air would be purged.

After a conversation with a manufacturer representative it was determined that the Viessmann Vitisol 100-F flat plate collector, which is the collector used in both systems, would not be a good candidate for a drain back system. The serpentine copper coil in the collector would make it difficult to ensure that the collector completely drained. The other two methods considered, passive versus non-passive solutions to reject the excess heat produced by the solar collectors will be discussed in detail in this report.
Peak Solar Collector Performance

Solar Collector Energy Balance

To calculate the available energy from the solar collectors an energy balance of the solar collector was performed. Flat plate collectors have four main components that together determine the effectiveness of the collector. The glazing or cover sheet allows transmittance of electromagnetic energy to the absorber plate while reducing heat losses from convection to the surroundings. The underside of the collector must be well insulated to reduce unwanted conduction losses from the absorber plate. The fluid tubes are bonded to the absorber plate with a highly conductive material to allow heat to be removed from the plate to the coolant fluid.

The figure below illustrates the typical construction of a collector and the factors that need to be considered when setting up an energy balance equation for the collector. This shows all of the heat gains and losses, but based on assumptions some terms can be neglected to simplify the calculations while still providing accurate results.

\[
E_{total} = E_{solar} + Q_{losses}
\]

Where,

\[
Q_{losses} = \dot{Q}_{rad} + \dot{Q}_{refl} + \dot{Q}_{cond} + \dot{Q}_{conv}
\]
Absorbed solar radiation

In order to calculate the performance of the solar panels it is necessary to find the amount of solar energy available at the panel sites. Solar intensity, I (W/m²) at a specific location is a function the latitude and season of the year or more simply put the distance from the sun. Several resources such as the Solar Rating & Certification Corporation (SRCC) and National Solar Radiation Data Base (NSRDB) provide these data at given locations across the country for all seasons and times of the day. The current goal is to determine the peak or maximum solar gain, so the peak solar intensity for the given year for Salt Lake City Utah will be used. Not all of this total energy is absorbed by the collector.

\[ Q = IA \]
Where $A$ is the total surface area of the collector, $Q$ is incident energy from the sun on the given area per time. Figure 2 shows that percentages of the solar energy are reflected, absorbed by the glazing, and transmitted to the absorber plate. Based on the construction of the solar collector there are performance tested parameters for the collector based on the SRCC that determine the transmission coefficient of the glazing ($\tau$) and the effectiveness of the absorber plate ($\alpha$), which results in the following equation:

$$Q_{in} = I(\tau \alpha)A$$

In addition to the glazing transmission coefficient and absorber plate effectiveness, the collector manufacturer provides the overall collector heat loss coefficient $U_L$ (W/m$^2$ K) based on actual performance testing using the SRCC testing procedures. This allows the losses from the collector to be calculated based on the ambient temperature and the calculated temperature of the collector. [1]

$$Q_{out} = U_LA(T_{collector} - T_{ambient})$$

Performing the energy balance with these terms provides the following equation, which gives the solar collectors usable solar energy at the solar absorber plate:

$$Q_{usable} = Q_{in} - Q_{out} = I(\tau \alpha)A - U_LA(T_{collector} - T_{ambient})$$
\[ Q_{usable} = Q_{in} - Q_{out} = I(\tau \alpha)A - U_1A(T_{collector} - T_{ambient}) + U_2A^2(T_{collector} - T_{ambient})^2 \]

**Radiation on Inclined Surface**

Panel incline also determines how much solar radiation is incident on the panel. Two angles define the position of a flat plate solar collector, the tilt or slope (north or south rotation) of the collector in relation to the horizontal and the azimuth (east or west rotation) angle. This angle would be 0 degrees if it was directed due south.

All data gathered for the incident solar radiation for given locations are given for a flat surface. It is necessary to calculate a correction for the ratio of the incident radiation on a tilted surface.

Angle of declination is the angular position of the sun at solar noon with respect to the perpendicular from the equator. This is a function of the day of the year.

\[ \delta = 23.45^\circ \sin \left[ 360^\circ \left( \frac{284 + n}{365} \right) \right] \]

Where \(n\) is the day number of the year (where December 31\(^{st}\) would be \(n=365\))
The angle of incidence is calculated as:

\[
\cos(\theta) = \sin(\delta) \sin(\phi) \cos(\beta) - \sin(\delta) \cos(\phi) \sin(\beta) \cos(\gamma) \\
+ \cos(\delta) \cos(\phi) \cos(\beta) \cos(\omega) + \cos(\delta) \sin(\phi) \sin(\beta) \cos(\gamma) \cos(\omega) \\
+ \cos(\delta) \sin(\beta) \sin(\gamma) \sin(\omega)
\]

In typical solar water heating applications (\(\gamma\)) is typically 0 in the northern hemisphere, which simplifies the equation to the following:

\[
\cos(\theta) = \sin(\delta) \sin(\phi) \cos(\beta) - \sin(\delta) \cos(\phi) \sin(\beta) + \cos(\delta) \cos(\phi) \cos(\beta) \cos(\omega) \\
+ \cos(\delta) \sin(\phi) \sin(\beta) \cos(\omega)
\]

The angle of incidence for a flat surface is the zenith angle \(\theta_z\), simplifying the equation from above by assuming \(\beta=0\) and \(\gamma=0\).

\[
\cos(\theta_z) = \sin(\delta) \sin(\phi) + \cos(\delta) \cos(\phi) \cos(\omega)
\]

The following equation is used to calculate the geometric factor for the ratio of beam radiation on a tilted surface:

\[
R_b = \frac{G_{BT}}{G_b} = \frac{G_{BT} \cos(\theta)}{G_{BT} \cos(\theta_z)}
\]
Substituting the equations above and through simplification and trigonometric identities the ratio of beam radiation is.

\[ R_b = \frac{\cos(\phi - \beta) \cos(\delta) \cos(\omega) + \sin(\phi - \beta) \sin(\delta)}{\cos(\phi) \cos(\delta) \cos(\omega) + \sin(\phi) \sin(\delta)} \]

Peak solar incident typically occurs between the end of May and beginning of July and according to the NSRDB the peak on a horizontal surface in Salt Lake City is 925 W/m². After working through the above calculations, one consideration is to adjust the azimuth angle of the panels to result in the peak gain occurring in the evening when more use of the building and demand for hot water. [1]

**Absorber Plate Energy Balance**

An energy balance must be performed on the absorber plate to calculate how much heat is removed from the plate by the circulating fluid. The temperature of the fluid and the incident solar radiation affect the temperature gradient of the absorber plate between tubes. To determine the heat conducted through the absorber to the tube a one-dimensional energy balance on an element of the absorber plate as shown in the illustration is used. The most convenient coordinate system to use is \( x=0 \) at the symmetric centerline between two fluid tubes.
The energy balance can be given by the following equation.

\[ S\Delta x + U_L\Delta x(T_a - T) + \left(-k\delta \frac{dT}{dx}\right)_x - \left(-k\delta \frac{dT}{dx}\right)_{x+\Delta x} = 0 \]

Taking the limit as \( x \) approaches zero provides a second order differential equation. Using the boundary conditions, zero heat flux at the axis of symmetry (\( x=0 \) and a fixed temperature at the base of the connection between the absorber plate, the differential equation can be solved.

\[ \frac{d^2T}{dx^2} = \frac{U_L}{k\delta} \left( T - T_a - \frac{S}{U_L} \right) \]
Boundary Conditions

\[ \frac{dT}{dx} \bigg|_{x=0} = 0 \]

\[ T \bigg|_{x=0} = T_b \]

\[ T(x) = (T_b - T_a - \frac{S}{U_L}) \left( \frac{\cosh(mx)}{\cos(m(W - D)/2)} \right) + T_a + \frac{S}{U_L} \]

Where \( m \) from substitution in the solution of the differential equation is:

\[ m = \left( \frac{U_L}{k\delta} \right)^{1/2} \]

The solution of the above differential equation is the temperature profile across the absorber. Fourier’s law can be used to find the heat flux from the absorber plate to the base of the fluid tube. The derivative is taken and evaluated at the connection between the absorber and the tube. [1]

\[ q'_{fin} = k\delta \frac{dT}{dx} \]

\[ q'_{fin} = F(W - D)(S - U_L(T_b - T_a)) \]
F is the efficiency of a straight fin.

\[ F = \frac{\tanh \left[ \frac{m(W - D)}{2} \right]}{\frac{m(W - D)}{2}} \]

In typical applications the tube base temperature will not be known so it is desirable to relate the base temperature to the fluid temperature. The total usable energy is the sum of energy conducted through the plate to the base and the amount of energy absorbed directly through the base.

\[ q_{usable}' = [F(W - D) + D](S - U_L(T_b - T_a)) \]

Balancing the energy gain and loss at the fluid and plate interface provides the following equation.

\[ q_{usable}' = \frac{T_b - T_f}{\frac{1}{h_f \pi D_t} + \frac{1}{C_b}} \]

\( T_b \) can be solved for by equating the useable energy flux equations. By substituting \( T_b \) substituted back into the useable heat flux equation and gives the following equation:

\[ q_{usable}' = WF'(S - U_L(T_f - T_a)) \]
where

\[ F' = \frac{1}{\frac{1}{U_L}} \frac{1}{W} \left( \frac{1}{U_L(D + (W - D)F)} + \frac{1}{h_f \pi D_i} \right) \]

Physically, \( F' \) is the collector efficiency. It is the ratio of the actual energy gain to the energy gain if the collectors’ absorber were at the fluid temperature at that location. In this case, the collector efficiency is a property of the collectors’ performance and is given by the collector manufacturer. By analyzing the parameters in the equation above, the efficiency for a collector is constant for a given flow. As the flow rate changes, the convection heat transfer from the collector tubes to the fluid will change. Both \( F \) and \( F' \) relate the absorber plate temperature distribution between the tubes.

**Energy Balance in Flow Direction**

The previous discussion was of the heat transfer in the \( x \) direction. An energy balance in the \( y \) direction (direction of fluid flow) gives the following:

\[ \dot{m} c_p T_{f_y} - \dot{m} c_p T_{f_{y+\Delta y}} + q'_{usable} \Delta y = 0 \]
Taking the limit as \( \Delta y \) goes to zero and substituting in for \( q' \) usable gives the following:

\[
\dot{m}c_p \frac{dT_f}{dy} = nWF'(S - U_L(T_f - T_a))
\]

Assumptions in this equation include that \( U_L \) and \( F' \) are independent of \( y \).

However, the temperature of the collector can be controlled to some extent by the temperature and the amount of the fluid used to remove heat from the absorber plate. So the energy balance of the fluid heat exchange must be solved as well. [1]
\[ Q_{usable} = \dot{m}c_p(T_{out} - T_{in}) \]

Another term, \( F_R \), is defined to help solve for the solar gain of the panel. It is called the “heat removal factor,” which relates the heat transferred on the fluid side and the energy gain of the collector if the entire collection were at the inlet fluid temperature. As the flow rate increases the heat removal factor will increase and the collector temperature will decrease. As the flow rate is reduced, the collector temperature will begin to approach the stagnation or maximum temperature the collector will reach when no heat is removed from the collector, which results in a smaller value for \( F_R \). [4]

\[ F_R = \frac{\dot{m}c_p(T_{out} - T_{in})}{I(\tau \alpha)A - U_LA(T_{in} - T_{ambient})} \]

Another Form of the “Collector Heat Removal Factor (\( F_R \))”

\[ F_R = \frac{\dot{m}c_p}{AUF'} \left( 1 - e^{-\frac{(AUF')}{\dot{m}c_p}} \right) \]

Another efficiency factor, \( F'' \), relates to the temperature distribution in the direction of flow.

\[ F'' = \frac{\dot{m}c_p}{AU_LF'} \left( 1 - e^{-\frac{(AU_LF')}{\dot{m}c_p}} \right) \]
The following expression relates the two factors:

\[ F_R = F'F'' \]

Substituting the heat removal factor, \( F_R \), into calculate the usable energy gain results in what is known as the “Hottel-Whillier-Bliss Equation” [5].

\[ Q_{usable} = F_R A(I(\tau \alpha) - U_L(T_{collector} - T_{ambient})) \]

**Vitisol 100-F Technical Data [2]**

Heat loss coefficients:

\[ U_1 = 4.15 \text{ W}/(\text{m}^2 \text{ K}) \]

\[ U_2 = 0.0114 \text{ W}/(\text{m}^2 \text{ K}^2) \]

Maximum stagnation temperature:

\[ T_{max} = 196^\circ C \]

Collector efficiency:

\[ \eta = 0.76 \]

**System Parameters (Stalled or No-load state)**

Mass Flow Rate

\[ \dot{m} = 0.32 \text{ gpm} \]

Collector inlet water temperature:

\[ T_{in} = 160 ^\circ F \]

Glycol concentration:

40%

Day of the year (peak gain):

\[ n = 240 \]
Site latitude \( \Phi = 41.7^\circ \)

Collector slope \( \beta = 10^\circ \)

The usable heat gain in this case is calculated to be:

\[
Q_{usable} = 5260.737 \frac{BTU}{hr}
\]

**Analytical Serpentine Solution**

Up to this point in the discussion, only single pass parallel tubes have been evaluated. The collectors to be evaluated in this case are a serpentine arrangement. This will result in a smaller heat removal factor as every pass of the fluid the absorber and fluid temperature will increase. The serpentine case is based on an Abdel-Khalik study in 1976 where an analytical solution to calculate the heat removal factor was developed [1]. The critical assumption used in their study was that \( U \) is held constant regardless of the temperature and that the collector temperature is uniform.

By calculating the Reynolds number, it is determined that the flow regime is laminar.

\[
Re_D = \frac{4\dot{m}}{\pi D \mu}
\]

\[ Re_D = 1209.7 \]
The Nusselt number can be calculated knowing that the flow is laminar, fully developed, and that the tube wall temperature is constant. According to the derivation in Incropera and DeWitt, the Nusselt number is constant and equal to 3.66 [3]. Based on this definition of the Nusselt number the convection heat transfer coefficient can be calculated.

\[ h = \frac{Nu_D}{D} \]

\[ h = 83.83 \frac{W}{m^2K} \]

The following equations from Abdel-Khalik were used to calculate the heat removal factor [1].

\[ F_1 = \frac{\kappa}{U_t W} \frac{\kappa R (1 + \gamma)^2 - 1 - \gamma - \kappa R}{\left[ \kappa R (1 + \gamma) - 1 \right]^2 - (\kappa R)^2} \]

\[ F_1 = 1.0251 \]

\[ F_2 = \frac{1}{\kappa R (1 + \gamma)^2 - 1 - \gamma - \kappa R} \]

\[ F_2 = 0.338 \]
Where

\[ \kappa = \frac{(k \delta U_L)^2}{\sinh \left[ (W - D) \left( UL \over k \delta \right)^{1/2} \right]} \]

\[ \kappa = 0.9284 \frac{W}{mK} \]

\[ \gamma = -2 \cosh \left[ (W - D) \left( UL \over k \delta \right)^{1/2} \right] - DU_L \over \kappa \]

\[ \gamma = -2.727 \]

\[ R = \frac{1}{C_b} + \frac{1}{\pi D_i h_f} \]

\[ R = 0.4469 \frac{mK}{W} \]

From the analytical data from Abdel-Khalik found in Figure 6.12.2 of Solar Engineering of Thermal Processes, \( F_R/F_1 \) can be interpolated as 0.55, so \( F_R \) was calculated to be 0.663. In the previous case the heat removal factor was calculated as 0.756, which intuitively makes sense. Case 1 was considering a collector with flow through parallel tubes, whereas case 2 is a continuous flow in series across the absorber
plate. Less heat will be removed because the fluid temperature will increase each pass and because of the smaller temperature difference between the absorber plate and the heat transfer fluid. The calculated heat gain for a serpentine collector was calculated as 4,784 BTU’s per hour compared to 5,261 for the parallel flow collector.

**Transient Systems Simulation Program Model**

To confirm the calculated useful heat gain Transient System Simulation Program (TRNSYS) models of both systems were generated. The model also is useful to evaluate the overall yearly performance and peak solar gain of the solar collector systems. The general model generated is illustrated in Figure 5.

Hourly new typical meteorological year data (TMY2) data from the NREL site was used for the nearest site, the Salt Lake City International Airport (site-725720) to calculate the hourly solar gain of the systems. This also allowed for the yearly solar gain and total predicted useful yearly energy collected.
Fig. 5 TRNSYS model applicable to both systems.
Thermosiphon

Based on the past performance and the calculated gain of the solar collectors both systems need to be able to reject more heat. The Swaner Eco Center was designed with the capability to not only heat domestic water, but also to use the solar energy to heat the building. It will be necessary to determine if there is a problem with rejecting the heat to the boiler loop or if the solar gain still exceeds the building load. Kaysville Wetland’s system, however, was not setup in this manner and required a heat sink. It was desired that the system be as efficient as possible and preferably passive. If differences in density between the cold and hot water in the closed loop could generate a large enough flow rate a circulating pump could be eliminated. A CFD model was used to calculate the generated flow rate.

To determine the flow regime, the Grashof and Raleigh numbers were calculated treating the horizontal pipe at a flat plate using the collector width as the characteristic length.

\[ Gr = \frac{g \beta (T_s - T_{\infty}) L^3}{v^2} \]

\[ Gr = 6.2194 \times 10^{10} \]

\[ Ra = \frac{g \beta (T_s - T_{\infty}) L^3 \rho}{\mu \alpha} \]
\[
\alpha = \frac{k}{\rho c_p}
\]

\[Ra = 4.9162 \times 10^{12}\]

According to the Fluent User’s Guide transition to turbulence occurs in the range of \(10^8 < Gr < 10^9\) and a \(10^8 < Ra < 10^{10}\) so the boundary layer flow will be turbulent in this case and buoyancy will be a significant factor in the flow characterization [10].

**CFD model**

Fig. 6 Graphical temperature distribution from the CFD model.
The calculated peak collector heat gain was used for a constant heat flux in the CFD model. A single panel was modeled in STAR-CCM+ [6]. Convergence of the model was difficult because with the temperatures and associated pressures there was a phase change, which caused the results to diverge. The CFD model was re-evaluated to see if it accurately modeled the physical problem. After reconsideration it was determined that a fixed wall temperature would better model the problem. As the fluid temperature rises while circulating through the collector the heat flux would decrease. This assumes that the effects of the changing wall temperature as a function of the distance from the collector entrance are insignificant. Wall surface temperatures of the collector and sink were modified iteratively until the total heat flux approached the calculated values. The CFD model was run for various collector slopes. The figure below contains the outputs of the CFD model with the flow rates induced by the buoyance gradient. The calculation assumes a 170 degree F collector inlet temperature and 250 degree F outlet temperature. Higher system pressures prevent the phase change to steam.

The following parameters were used for the CFD model:

Surface Remesher

Enabled Model

Boussinesq approximation

Segregated Fluid Temperature

Two-Layer All y+ wall treatment
Coupled/segregated flow

Gravity

IAPWS-IF97 (Water)

Steady

Gradients

Two Dimensional

Buoyancy

The model had two fixed temperatures regions (heat sinks): cooling (350K) and heating (394K). Below are the results from the model at the various collector angles.

<table>
<thead>
<tr>
<th>Collector Slope</th>
<th>Total Radiation on Incline Surface (BTU/hr)</th>
<th>Average Velocity of Flow Profile (ft/s)</th>
<th>Volumetric Flow Rate (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4935.3</td>
<td>0.074</td>
<td>0.025</td>
</tr>
<tr>
<td>20</td>
<td>5215.6</td>
<td>0.121</td>
<td>0.042</td>
</tr>
<tr>
<td>30</td>
<td>5304.1</td>
<td>0.151</td>
<td>0.052</td>
</tr>
<tr>
<td>40</td>
<td>5197.3</td>
<td>0.187</td>
<td>0.064</td>
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<tr>
<td>50</td>
<td>4898.8</td>
<td>0.202</td>
<td>0.069</td>
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<tr>
<td>60</td>
<td>4417.5</td>
<td>0.216</td>
<td>0.074</td>
</tr>
<tr>
<td>70</td>
<td>3768.2</td>
<td>0.227</td>
<td>0.078</td>
</tr>
<tr>
<td>80</td>
<td>2970.7</td>
<td>0.237</td>
<td>0.082</td>
</tr>
</tbody>
</table>
Kaysville System Modifications

Heat Gain

Based on the calculations and the TRNSYS model the peak solar energy collected for the Wetlands building is 11,279 BTU/hr for both panels. It is clear from past performance and the building occupancy that there is not demand for that quantity of heat. It should be noted that these peak gains in the two systems occur at different times of the year. The slope of the Kaysville collectors provides a peak solar gain in the summer. The standard guideline is to angle the collector at approximately the latitude of the install site. For summer optimal performance it is recommended that the collector be tilted 15 degrees less than the site latitude. In this case, to prevent the system from overheating it is necessary that a method of rejecting the heat be developed.

A tube bundle inserted in the bottom of an 80 gallon storage tank circulates glycol through from the set of solar collectors to the tank. If the solar thermal system isn’t able to meet the current demands, a supplemental electric heating element turns on.

Unfortunately a passive system would not meet the demands for the needed heat rejection. It was decided that a coil could be installed in an existing exhaust duct and as the system temperature rose above the threshold the fan would be turned on and the storage tank would be bypassed as a safety precaution.
Sequence of Operation

The controller programming was modified using Struxureware Building Operation [9] as follows: The solar collector circulating pump shall be enabled and run continuously once the collector temperature rises above 120 F with a 10 minute off-delay to prevent the pump from cycling. As the water heater tank temperature drops below 100 F the electrical heat element shall be enabled. A rise in the tank temperature above 130 F will modulate the 3-way valve to bypass flow around the domestic hot water tank. As the tank temperature rises above 140 F, exhaust fan (EF-1) is to be commanded on until the temperature drops to 130 F.
Fig. 8  Kaysville building automation graphic page.

Fig. 9  Installed coil in exhaust ductwork.
System Performance

After observing the operation of the system with the modifications made, it was seen that the heat rejection (bypass valve with coil in exhaust air stream) operated frequently during the summer operation. This was due to limited usage of the building during the afternoons. It did however maintain the storage tank set point and the system did not dump due to high temperatures or pressures.

![Graph showing system performance](image)

Fig. 10 Kaysville system performance from 6:00 am to 6:00 pm February 23rd thru February 26th 2014.

The figure above shows trend data for four days in February 2014. It should be noted that the collector supply and return temperatures do not provide any useful information while the collector circulating pump is off. The sensor reading approaches the ambient air temperature of the sensor location or the readings are impacted by residual heat from the tank due to the proximity of the sensor to the tank. It also can be
seen that on 2/24/14 the collector temperature did not reach 120 degrees F and the pump remained off.

Trend data show that as the collector temperature increases the pump is enabled. A sudden drop in collector temperature is experienced as the colder water in the glycol loop begins circulating through the collector. A temperature difference between the collector supply and return water temperature can be seen in the trend data. This represents the amount of heat transferred to the tank. As expected the tank temperature begins to approach the water temperature of the fluid leaving the collector. As the pump is shutoff the tank temperature gradually begins to decrease due to heat losses from the storage tank to the surrounding mechanical room.
Swaner Eco-Center System Modifications

Heat Gain

For the 10 panels at the Swaner building the peak solar gain is 51,673 BTU/hr. In the case of the Eco Center the peak occurs during the winter as the collectors are tilted at the latitude of the site plus 15 degrees. The TRNSYS model confirmed the manual calculations.

The intent for the solar collectors was to be used to heat domestic water and as supplementary building heat. As the hot water storage tank temperature rose above 120 F the system would be able to reject the heat to the hydronic heating system and preheat the return water to the boilers. One issue encountered was that building maintenance personal had increased the boiler water temperature above the intended temperature and the system began to use the boilers to heat the collectors.

Two 120 gallon storage tanks connected in parallel are connected in series to a standard 40 gallon gas water heater. Each tank has two tube bundles, the lowest heat exchanger is for the solar collector loop and the second that is inserted at the mid-elevation of the tank is for heat rejection to the boiler loop. The solar collector layout consists of two series of five panels.

The building’s heating system consists of a direct return primary loop without primary loop pumps. Constant speed secondary pumps draw flow through the primary loop and circulate flow through the load (radiant slab loops and various coils). Three-way valves keep near constant flow through the load (secondary loop), while the control
valve varies flow from the primary loop to account for changes in load demand. Two take-offs on the return line are less than twelve inches apart and connect the solar heat rejection to the boiler loop. Pump 19, in this case, draws water from the return line and pumps it through the two tube bundles and back to the downstream return connection towards the boiler in the direction of flow.

After the initial investigation of the system it was found the solar collector loop had very little pressure and was subsequently found empty. Without much forethought an attempt was made to fill the system on a hot sunny afternoon only to find that steam was being produced. The system was filled on a later day that was overcast. With the system filled and air bled from the loop, trends were setup to evaluate the operation and performance of the system. After several weeks of operation the trend data showed that the storage tank temperature would continually rise regardless of the operation of the heat rejection pump (pump 19).

The piping was traced out and a one line layout of the piping system was made. To calculate various pressure drops and node pressures the system was modeled in a piping network modeling software called PIPE-FLO. This allowed for simulating various operating conditions of the system and calculates flow rates through each branch line and the pressure at each node of the system. It was found that under certain conditions, conditions typical of periods when there was a high solar gain, flow would reverse. The heat rejection loop would circulate through the solar storage tank heat exchanger. With no circulating pumps on the primary loop, it was not possible to ensure the proper flow
direction. with certain pumps off the differential pressure in the system was such that it
wouldn’t flow to the boiler. The one line drawing and output from PIPE-FLO can be
seen below [8].

After doing heat and cooling loads on the building it was found that the zones
further out in the system past the heat rejection tie in had a significant amount of glass
with a southern exposure and required cooling at times of peak solar gain during the
winter months. With no need for heat, the pumps would shut off and prevent circulation
of the heat rejection out to the remaining system.

![One-line schematic of the Eco-Center hydronic piping.](image)

Fig. 11 One-line schematic of the Eco-Center hydronic piping.
Fig. 12 Eco-Center piping schematic and flow calculations for as-built conditions.

Fig. 13 Eco-Center piping schematic and flow calculations after piping modifications.
Modified Sequence of Operation

The controller programming was modified using StruxureWare Building Operation [9] as follows: As either the solar panel temperature or the solar tank inlet temperature rise above the solar storage tank temperature, the solar collector pump (P-20) will be enabled and run for a minimum of 10 minutes (adjustable). If the solar panel temperature becomes unreliable the pump will turn on and an alarm will be generated. If the tank temperature rises above 125 degrees (adjustable) and the tank temperature is...
greater than the boiler hot water return temperature the heat rejection pump (P-19) will be commanded on. The hot water circulating pump (Circ Pump-1) will be commanded on if the DHW inlet temperature is less than 100 degrees (adjustable). At that point the circulating pump will be commanded off. If the tank temperature is above 150 degrees (adjustable) and the following pumps are off (Pumps for VAV2-01, VAV2-02, VAV2-03, VAV2-04, VAV2-05, VAV2-06, VAV2-07, VAV2-08, VAV2-09, and AHU-2 hot water coil) snowmelt pumps will be commanded on (P-16 & P-18).

**Performance**

![Swaner solar hot water system performance data.](image)
The figure above shows trends of important data points to evaluate the performance and operation of the Swaner solar hot water system. The blue line represents when the collector circulating pump (P-20) runs. It shows that after running for a period of time (heating up the storage tank) the heat-rejection pump (P-19), (red line) turns on and runs for an extended period of time well beyond the collector pump run time. For a short time period in the afternoon the heat rejection pump (ice melt loop), green line, is enabled. The performance data shows the temperatures of the system over roughly a four day period. The benefit of the two 120 gallon storage tanks can be seen as its temperature gradually decreases after the sun goes down and the circulator for the collectors is shut off and the heat-rejection pump continues to run. This allows the useful energy from the peak solar incidence to be stored and used in the evening as the sun goes down. Temperature differences between the glycol to and from the collector show the heat gained by the system. The rise of the storage tank to nearly 150 degrees follows the rise of the collector water temperature. It is important to note the effect on the boiler water return temperature. Trend data shows that heat is affectively being rejected to the boiler loop as the temperature follows the same common trend through the day as the collector return and supply and storage tank water temperatures increase with the solar gain throughout the late morning through evening.
Conclusions

After discovering the inoperable systems and making the described modifications to the two systems, they now function year round with minimal maintenance.

Solar energy is widely available, but requires thorough design consideration to be a worthwhile investment. Solar hot water heating systems can work well if they are designed and sized correctly. For them to operate correctly oversight of the contractor’s installation and ongoing maintenance are required. Often because the systems have supplemental heat, owners aren’t aware that collectors are not performing.

Difficulty arises when using solar energy when the peak solar gains do not line up with peak demand. More extensive means have to be taken to store the energy, level out the peaks to meet the current demand, or to dissipate the heat.

In the case at the Swaner Eco-Center it appears that at the system was oversized due to the south facing exposure. When the collectors are at the peak useful gain much of the building load is already being accounted for by the passive solar gain through the windows. In this scenario the system should have either been sized solely for heating domestic water or had additional storage to allow for the ability to store the energy until the sun has gone down.

An additional consideration that could be beneficial for future collector design would be to consider some type of shading device. Newer technology is becoming available that allows an electric signal to tint a transparent film. As the system stalled the shading could be adjusted to lower the absorber temperature and match the current load.
With the systems operating properly the TRNSYS model indicates a yearly gain of 16,400,000 BTU’s or 4756 kWh for the Wetlands building. Of this energy collected, 6,100,000 BTU’s will be rejected. Overall it is calculated that the collectors will reduce the electrical consumption by 2978 kWh per year. Based on these calculations and the actual building usage one collector would better match the building demand. In the case of the Swaner Center the yearly gain would be 97,200,000 BTU’s with an estimated 11,580,000 BTU’s being rejected this should reduce the buildings gas consumption by a maximum of 85 decatherms. The payback on these projects is quite lengthy, but sizing the equipment for the appropriate load conditions would shorten the payback period.
References


[9] StruxureWare Building Operation (version 1.4) [Software], (2013).

Wetlands Discovery Point Equipment List

Collector – VIESSMAN VITOSOL 100-F (Quantity 2)

Solar Electric Tank – RHEEM SOLARAIDE 82V120HE-1 (120 gallon storage tank with 4500W electric heater)

3-way diverting valve – Belimo B317 with LRB24-SR (Spring Return) actuator

Rejection Coil – HEATCRAFT 12” x 12” 10,750 BTU/hr 3 gpm

Exhaust Fan – COOK 80 SQN-B (600 cfm @ 4,500ft 0.5 External Static Pressure)

Pump – GRUNDFOS UP15-42F (3 gpm @ 15’ Head with 30% glycol)

Pipe Sensors Honeywell T775-SENS-STRAP 1097 ohm (Quantity 2)

Tank Sensor & Collector Sensor -1/2” NPT insert with Honeywell T775-SENS-WT (quantity 2)
Swaner Eco-Center Equipment List

Collector – VIESSMAN VITOSOL 100-F (Quantity 10)

Tanks – VIESSMAN VITOCELL 450-B Dual coil domestic hot water storage tank (quantity 2)

Collector Pump – Bell & Gosset PL-30 5 gpm @ 15’ Head

Heat Rejection Pump – Bell & Gosset PL-30 5 gpm @ 15’ Head

Snow Melt Pump – Bell & Gosset PL-30 5 gpm @ 15’ Head (quantity 2)

Pipe Sensors Honeywell T775-SENS-STRAP 1097 ohm (Quantity 5)

Tank Sensor & Collector Sensor -1/2” NPT insert with Honeywell T775-SENS-WT (quantity 2)