Solar Heating

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Storage mediums and temperature-control strategies for predictable and consistent performance

SYSTEMS

Residential solar installations are on the rise nationwide, but deployment of solar space-heating systems lags well behind photovoltaic, solar pool heating and domestic water heating technologies. A variety of factors contribute to this trend. Foremost among them is the complexity of space-heating system design and installation, especially heat storage and system controls. Space heating represents more than 40% of home energy use. As more proven designs and modular components are brought to market, many heating contractors will routinely offer solar heating.

For solar heating to become mainstream, systems need to have consistent, predictable performance and offer a user interface that is comparable to conventional heating systems. The customer should have to adjust only the thermostat, and the rest of the system should take care of itself. If the control approach sheds excess solar heat into a concrete floor, the floor's temperature must not fluctuate dramatically. Customers do not want rooms overheating due to excessive system output. If a hot tub or swimming pool is used to shed excess heat, a safe high-limit temperature must be maintained.

To ensure quality solar heating installations, you must carefully balance customer satisfaction with the proper operating parameters of the solar collectors. A key recurring challenge in closed-loop hydronic solar heating design and implementation is the need to manage excess solar heat, especially in the shoulder seasons—spring and fall. One method to manage excess solar heat is by the use of water storage tanks as heat sinks. However, this involves added system costs, space requirements and complexity as well as the need for control strategies when the water in the storage tanks gets too hot.

At Cedar Mountain Solar, we developed control strategies for closed-loop glycol systems that facilitate automatic solar heat storage in the thermal mass of buildings while mitigating potential overheating issues. The methods we use are appropriate for the high desert climate in New Mexico and locations with similar characteristics, which include wide diurnal temperature swings, cold winters and ample sunlight.

WATER AND CONCRETE AS HEAT-STORAGE MEDIUMS

Compared to concrete, water has a higher heat-storage capacity but a lower density. In solar heating systems, concrete is often available in a much greater volume than water. These variables complicate the comparison between the two heat-storage approaches. To illustrate the difference in performance of direct solar-heated concrete to the more common solar-heated water tanks,

Physical Properties of Water and Concrete Storage Mediums

Property	Water	Concrete	Units	Comments
Specific heat capacity	1	0.2	Btu/lb. – °F	Heat stored in 1 lb. when temperature rises 1°F
Density	62	120	lb./ft.^{3}	Weight per unit volume (water is 8.3 lb./gallon)
Earth temperature	50	50	°F	Earth temperature 6' below house (similar to the average annual temperature)
Heat load	7	7	Btu/ft.^{2} floor area	Average hourly heat load on cold day in energy-efficient house
R-value	15	15	ft.^{2} – °F – hr./Btu	Value for insulation surrounding water storage tank and under cement slab
Room temperature	70	70	°F	Average daily ambient room temperature
Slab temperature	73	73	°F	Average daily slab surface temperature

Table 1 We assume these conditions in order to compare water and concrete storage mediums in the example. Note that we use a conservative pound per cubic foot weight of concrete.

we can employ a simplified analysis of two hypothetical heating systems modeled for the climate in New Mexico. We round off the numbers and make assumptions based on our experience to get into the ballpark for a reasonable comparison.

A good snapshot of these two heat-storage systems must include storage capacity as well as heat loss from the different configurations. The specific heat capacity and the density of the heat-storage material define the storage capacity. The heat loss is driven by the temperature difference between the warm mass material and the environment, the insulating value and the surface area. Table 1 summarizes the key conditions needed to make a comparison. We calculate heat loss by multiplying the surface area by the temperature difference and dividing by the insulation's R-value. We then calculate heat storage by multiplying the specific heat by the density and then by the temperature rise (or drop) in the material.

A HYPOTHETICAL SOLAR-HEATED HOUSE

Consider an energy-efficient residence with 3,200 square feet of heated living space with the energy use and performance temperatures shown in Table 2. The owners decide to integrate eight 4-by-10-foot flat plate collectors to supplement a hot water heating system that uses a hydronic boiler. One option is to store the heat produced by the collector array in water tanks. The second option is direct heat storage using insulated, slab-on-grade hydronic radiant concrete floors. The size of the collector array is typical of systems installed in the area and represents about 10% of the floor surface area. Water-tank storage for this system is typically sized to provide two gallons for each square foot of collector area, or 640 gallons. Setting aside the other obvious design issues such as integrated DHW, room temperature-control strategies and protection from overheating, we can focus on how much heat generation is involved and how the thermal storage systems react to it.

Even though the concrete floor weighs 24 times as much as the water in storage, the concrete's total heat-storage capacity is about only 5 times that of the water. In addition, it is interesting to note that in this example system, the backup boiler burns the equivalent of about one gallon of propane *per hour* at full output. In comparison, the solar CONTINUED ON PAGE 82

Example 3,200-Square-Foot Solar-Heated Dwelling

Item	Tanks	Slab	Comments
Size	640 gal.	3,200 ft.^{2}	Cylindrical tanks containing boiler fluid (low-pressure water)
Weight	5,312 lb.	128,000 lb.	4-inch slab
Heat capacity	5,312 Btu/°F	25,600 Btu/°F	Heat stored when average temperature rises 1°F
Heat loss	1,693 Btu/hr.	4,907 Btu/hr.	Tank loss to mechanical room; floor loss to ground
Solar collectors	320 ft.^{2}	320 ft.^{2}	Eight 4-by-10-foot flat plate collectors
Solar heat	320,000 Btu/day	320,000 Btu/day	1,000 Btu per ft.^{2} per clear day
Boiler	80,000 Btu/hr.	80,000 Btu/hr.	Typical minimum hydronic boiler output

Table 2 Assuming identical values of solar heat delivered on a clear day, water and concrete storage mediums perform differently based on the heat capacity and heat loss characteristics of each storage approach.

collectors deliver about four times this amount of heat *per day*.

THERMAL RESPONSE OF WATER VERSUS CONCRETE

We use the data shown in Table 2 to calculate the temperature rise in the thermal mass driven by the available solar heat. We then calculate the heat loss from the tanks, the heat loss from the floor and the heat needed by the building. This lets us determine the net solar heat delivered and compare the solar savings, as shown in Table 3. The water tanks must operate at a much higher temperature range than the concrete floors to store the daily ration of solar heat. The tanks can gain more than 50°F of net temperature rise, while the floors gain less than 8°F. If the tanks begin the day at 100°F, they will be 150°F at the end of a sunny day. The concrete floor surfaces will typically stay below 80°F. Lower temperatures are generally associated with higher solar thermal system efficiencies. Based on the daily heating summary, in this example, the direct floor system is capable of providing a savings of greater than 25% above the storage tank system with the same size collector array.

Even though the concrete has a lower specific heat-storage capacity, because there is so much of it, the temperatures can easily be maintained within a comfortable range. The room temperature can be allowed to drift as much as 8°F from day to night without exceeding the limits of human comfort. Programmable two-stage thermostats allow the owners to control temperatures on a room-by-room basis. A wider temperature fluctuation can be tolerated in some rooms, resulting in higher savings in those particular rooms.

Keep in mind that a house must be energy efficient to obtain a high percentage of heat from solar collectors, which provide a finite amount of heat each sunny day. The solar heating percentage does not exceed 40% on the coldest day in our example. During milder cold weather, the solar contribution is higher. Engineering buildings that provide a high solar contribution to the heating energy balance is certainly possible.

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You can see that concrete is a useful storage medium for solar heat. It can replace storage tanks and reduce system cost and complexity. However, the challenge of controlling the excess solar heat so that the concrete floors act as storage but do not overheat remains.

GLYCOL-BASED SYSTEMS

To minimize seasonal overheating, you should first apply passive measures. Mounting the collectors at a steep tilt optimizes winter heat gain and minimizes heat production in the summer when space heating is not needed. For an installation that includes both heating and domestic hot water in Santa Fe at latitude 36°N, the tilt is typically 75°–85° from horizontal, or nearly vertical for larger banks of solar heat collectors.

In addition to controlling heat within the building, another primary reason for effective solar-heat dissipation is to maintain a safe high-limit temperature for the solar collectors during normal operation. Low-temperature propylene glycol (PG) mixtures are formulated for maximum temperatures of approximately 225°F. High-temperature PG mixtures are formulated for a high limit of about 325°F. When you specify a particular glycol CONTINUED ON PAGE 84

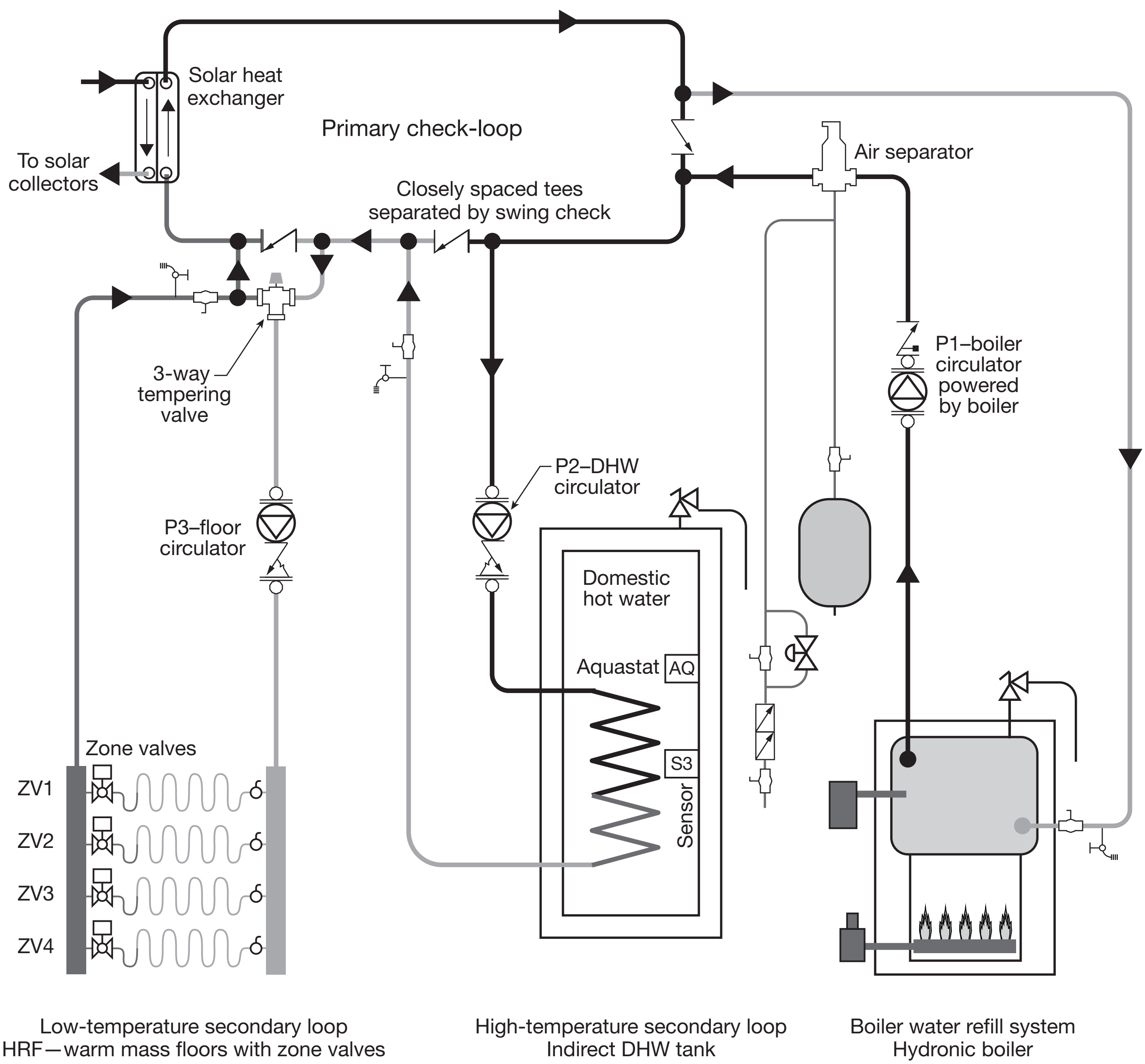
Daily Solar Heat Response

Item	Tanks	Slab	Comments
Temperature gain	60.2°F	12.5°F	Average storage temperature rise possible in one sunny day
Temperature loss	7.7°F	4.6°F	Typical temperature drop in storage mass per day due to heat loss
Net temperature gain	52.5°F	7.9°F	Useful temperature rise available per sunny day for space heating
Net solar heat delivered	161,120 Btu/day	202,240 Btu/day	Less tank loss to mechanical room; less slab loss to ground
Boiler run-time saved	2.01 hrs./day	2.53 hrs./day	Boiler running at full output (80,000 Btu/hr.)
Boiler run-time with no solar input	6.72 hrs./day	6.72 hrs./day	Boiler running at full output on cold day
Solar percent of heating load	29.9%	37.6%	Expressed as percentage of normal boiler run-time

Table 3 In the example, the values for net temperature gain, solar heat delivered and boiler run-time saved determine the solar heating system's contribution to the total heating load as a percentage.

product based on the system design and control set points, you should verify its temperature limit in the manufacturer's specifications or user's manuals prior to system charging.

Normal glycol mixtures are virtually transparent with a Ph slightly higher than distilled water (slightly alkaline). When glycol gets too hot, it can "cook," which changes its chemical structure. Low-temperature glycol begins to turn brown and thickens when it is repeatedly operated above its rated temperature. High-temperature PG holds up better. Nonetheless, temperatures over the limit lower the Ph of any glycol, which becomes more acidic over time. High stagnation temperatures can negatively impact the chemical structure of glycol when the fluid remains in the solar collectors for more than about half an hour without the circulator operating. This includes left-over glycol residue inside of collectors that have been drained. CONTINUED ON PAGE 86



Heat control This diagram shows a typical combi system piping approach. The system controls limit excessive slab and interior temperatures while maintaining safe high-limit temperatures for the collector array.

HEAT DISSIPATION CONTROLS

A typical solar home heating system that we install in the Santa Fe area consists of a large bank of solar heat panels used to heat a single DHW tank along with warm mass floors. We call this the *Combi 101* solar heating system, because it is the most common and simplest solar combi system we install. The controls for this system typically consist of a differential thermostat for the DHW tank and some set point thermostats to control the space heating. Two-stage room thermostats allow controlled solar-heat banking in the floor mass of each room. The objective for this control system is to make the best use of the solar heat from day to day without exceeding comfortable conditions inside the house, while maintaining safe high-limit temperatures for the collectors.

The control system used in the Combi 101 heating system is designed to dissipate extra heat into a floor zone as a last resort to keep the solar collectors from exceeding the normal operational high-limit temperature. The following rules are implemented sequentially before the control system allows solar heat dumping:

The control system used in the Combi 101 heating system is designed to dissipate extra heat into a floor zone as a last resort to keep the solar collectors from exceeding the normal operational high-limit temperature.

1. If the collector fluid output is hotter than the DHW tank, heat is directed to the tank. A tempering valve is provided to eliminate the danger of scalding at the faucets.
2. If the DHW tank has reached a safe high limit (165°F–180°F), controls stop delivering solar heat to the tank.
3. If there is a Stage 1 call for solar-heat banking from any room and collectors are hot (120°F–130°F), solar heat is directed into that floor.
4. If the Stage 1 high-limit comfort temperature (72°–76°F) has been reached in the room, the solar heat is no longer directed to that floor.
5. If all four of the conditions above have been met and the collectors are still hot, coolant is circulated around the solar collector loop until the glycol reaches its safe high-limit temperature (180°F–200°F).
6. When the safe high-limit temperature of the glycol is reached, controls direct heat to one or more mass floor zones to dissipate heat from the glycol until its temperature drops approximately 10°F–15°F below the safe high-limit temperature.
7. Steps 5 and 6 are continued until sunset.

All the temperature ranges listed provide a reasonable starting point, but they may need to be adjusted once the responses of the system and the home's occupants have been taken into account.

REAL-LIFE TEMPERATURE DATA

We can verify the performance possible with a well-designed and well-controlled direct solar heating system by reviewing data on a solar-heated radiant slab system that we designed and installed. The project was fully instrumented with the beta version of the Solar Logic Integrated Control (SLIC) system. The SLIC controller allows secure monitoring of this installation in real-time from any computer on the Internet, capturing data from more than 200 points in the heating system and remotely changing the settings and updating the software if needed.

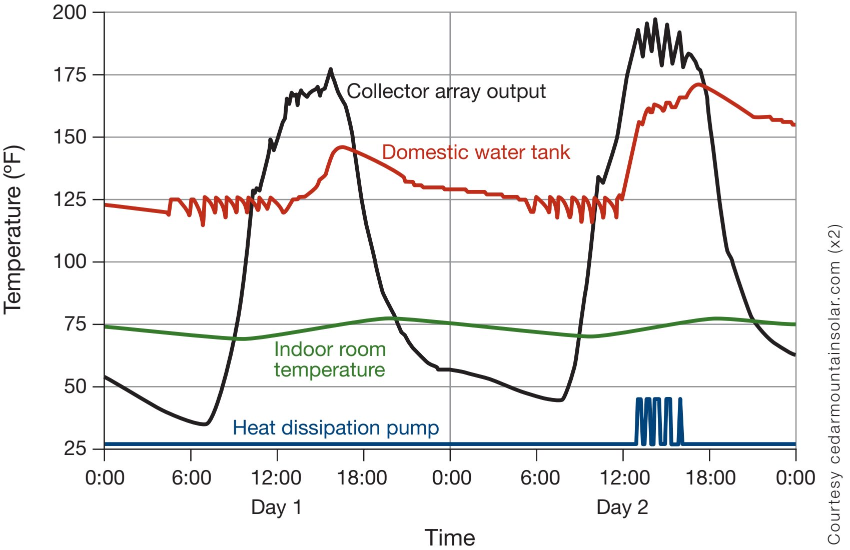
The installation is a solar heating retrofit to a home in Placitas, New Mexico (36°N latitude), near Albuquerque. The house is in a cold winter climate at a 6,000-foot elevation in the mountain foothills. It had an existing hydronic boiler heating system, and all of the dwelling's rooms have radiant-heated mass floors. There are nine radiant floor-heating zones and an 80-gallon solar DHW storage tank. The solar heating system is installed just like a Combi 101 system. Instead of a single bank of collectors, this system has two banks of six panels, each with its own PV-powered glycol pump. The collectors are mounted in landscape orientation and hidden behind parapet walls on the roof. The collectors are mounted at a 75° tilt to provide maximum heat in winter, minimize overheating in the summer, and supply ample solar DHW year-round.

Graph 1 (p. 88) provides performance data captured over 2 days in October 2009. During data collection, the house was in solar-only mode, which prevents the boiler from firing whenever the solar heat supply pipe is hot. Heat was needed on Day 1 but not on Day 2 because of fluctuating outdoor air temperatures. Outdoor temperatures are shown on Graph 2 (p. 88) for reference. The dew point temperature is included in Graph 2 to show how much cooling is available from these collectors at night if needed. Night sky radiant cooling, if desired, can be achieved at a temperature about half way between the air temperature and the dew point. CONTINUED ON PAGE 88

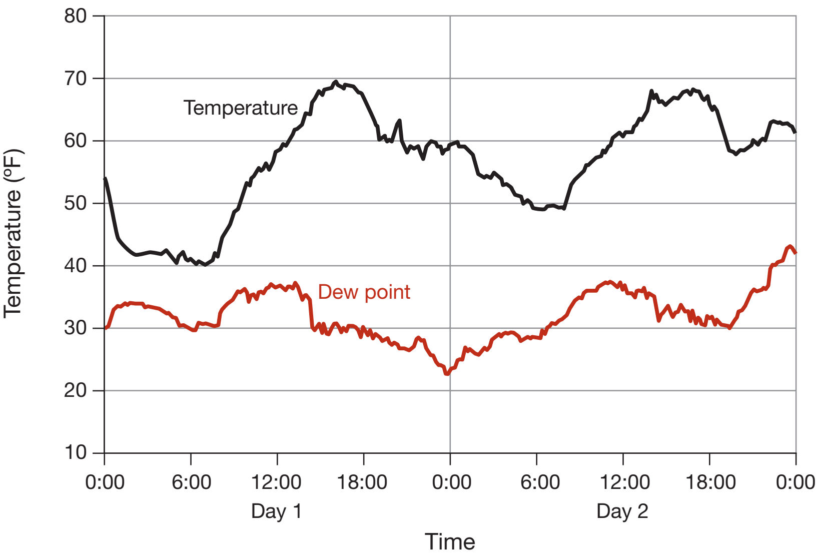
Graph 1 shows that on Day 1, the night temperatures are cold enough to allow heat banking in the mass floors as soon as the sun comes up. Heat banking continues until around 5pm, when the collector output temperature spikes as that heating load turns off. The spike is not big enough to activate the heat dissipation control at the end of Day 1. Because of the thermal-flywheel effect of the solar-heated mass floors, the room continues to warm up into the early evening and stays warm throughout the night. On Day 2, the water tank absorbs heat until its high-temperature set point is reached, but there is no call for heat banking in the slab because the house is a few degrees warmer than the previous morning. Just after noon, the heat dissipation control takes over and cycles on and off approximately every 20 minutes to prevent the glycol temperature from reaching 200°F. The DHW tank appears to reach its operating high limit near 170°F just before sunset.

During the sunny part of the day, the solar DHW tank absorbs heat simultaneously with the floors being warmed by heat banking on Day 1 and while heat dissipation is active on Day 2. A thermal mixing valve on the outlet of the DHW tank prevents scalding at the faucets. This house has an instant hot water circulator pump that is timer controlled to cycle every 15 minutes. This provides the comfort and convenience of instant hot water throughout the house. Much of the continuous heat losses from the domestic water tank and the temperature cycling in the early morning are due to this circulator constantly removing tempered hot water from the DHW tank.

Whenever we introduce the idea of heat dissipation to the mass floors, we are asked: “Won’t this overheat the rooms inside the house?” The data in Graph 1 illustrate that the answer is “No,” when thermal storage is sized and controlled properly. The glycol in the solar collectors can be kept at a safe temperature without adversely affecting human comfort. The data show that the maximum room temperature remains the same during heat banking on Day 1 as it does on Day 2 during heat dissipation. The reason is partly because we are following the seven rules listed earlier to control overheating, but also because of the nature of solar collector thermal efficiency. A hot collector is less efficient and loses more heat to its surroundings than a cool collector. Thanks to the laws of physics, a collector naturally tends to cool itself when it heats up.



Graph 1 Data collected over 2 days illustrate that in solar-only mode, the solar space heating system maintains consistent interior temperatures through good system design, storage integration and solar input control.



Graph 2 Comparing outdoor temperature and dew point values illustrates the potential for nighttime storage-medium cooling if system controls are designed to enable night sky radiant cooling.

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