Related Commercial Resources

CHAPTER 36

SOLAR ENERGY EQUIPMENT

SOLAR energy use is becoming more economical as the cost of energy continues to climb, especially with increasing government and utility incentives as well as growing interest in green and/or sustainable construction. In addition, many countries consider solar and renewable energy as a security measure to ensure the availability of power under adverse conditions. While the United States continues to grow its solar industry, China, Europe, Asia, and the Mediterranean basin are leading development of advanced manufacturing techniques and applications. However, equipment and systems are still very similar in all markets; therefore, this chapter primarily discusses the basic equipment used, with particular attention to collectors. More detailed descriptions of systems and designs can be found in Chapter 33 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Commercial and industrial solar energy systems are generally classified according to the heat transfer medium used in the collector loop (i.e., air or liquid). Although both systems share basic fundamentals of conversion of solar radiant energy, the equipment used in each is entirely different. Air systems are primarily limited to forced-air space heating and industrial and agricultural drying processes. Liquid systems are suitable for a broader range of applications, such as hydronic space heating, service water heating, industrial process water heating, energizing heat-driven air conditioning, and pool heating, and as a heat source for series-coupled heat pumps. Because of this wide range in capability, liquid systems are more common than air systems in commercial and industrial applications.

Photovoltaic systems, an entirely different class of solar energy equipment, convert light from the sun directly into electricity for a wide variety of applications.

SOLAR HEATING SYSTEMS

Solar energy system design requires careful attention to detail because solar radiation is a low-intensity form of energy, and the equipment to collect and use it can be expensive. A brief overview of air and liquid systems is presented here to show how the equipment fits into each type of system. Chapter 33 of the 2007 *ASHRAE Handbook—HVAC Applications* covers solar energy use, and books on design, installation, operation, and maintenance are also available (ASHRAE 1988, 1990, 1991).

Solar energy and HVAC systems often use the same components and equipment. This chapter covers only the following elements, which are either exclusive to or have specific uses in solar energy applications:

- Collectors and collector arrays
- Thermal energy storage
- Heat exchangers
- Controls

Thermal energy storage is also covered in Chapter 34 of the 2007 *ASHRAE Handbook—HVAC Applications*. Heat exchangers are also covered in Chapter 47 of this volume, as well as pumps in Chapter 43, and fans in Chapter 20.

AIR-HEATING SYSTEMS

Air-heating systems circulate air through ducts to and from an air heating collector (Figure 1). Air systems are effective for space heating because a heat exchanger is not required and the collector inlet temperature is low throughout the day (approximately room temperature). Air systems do not need protection from freezing, overheat, or corrosion. Furthermore, air costs nothing and does not cause disposal problems or structural damage. However, air ducts and air-handling equipment require more space than pipes and pumps, ductwork is hard to seal, and leaks are difficult to detect. Fans consume more power than the pumps of a liquid system, but if the unit is installed in a facility that uses air distribution, only a slight power cost is chargeable against the solar space-heating system. Thermal storage for hot-air systems has been problematic as well because of the difficulty in controlling humidity and mold growth in pebble beds and other such devices, particularly in humid climates.

Most air space-heating systems also preheat domestic hot water through an air-to-liquid heat exchanger. In this case, tightly fitting dampers are required to prevent reverse thermosiphoning at night, which could freeze water in the heat exchanger coil. If this system heats only water in the summer, the parasitic power consumption must be charged against the solar energy system because no space heating is involved and there are no comparable energy costs associated with conventional water heating. In some situations, solar water-heating systems could be more expensive than conventional water heaters, particularly if electrical energy costs are high. To reduce parasitic power consumption, some systems use the low speed of a two-speed fan.

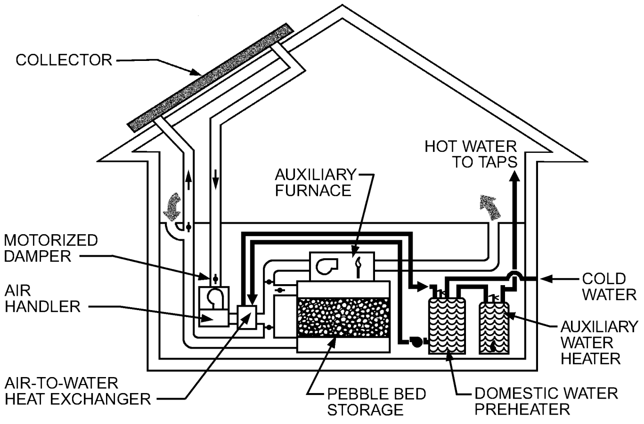


Fig. 1 Air-Heating Space and Domestic Water Heater System

The preparation of this chapter is assigned to TC 6.7, Solar Energy Utilization.

LIQUID-HEATING SYSTEMS

Liquid-heating systems circulate a liquid, often a water-based fluid, through a solar collector (Figures 2 and 3). The liquid in solar collectors must be protected against freezing, which could damage the system.

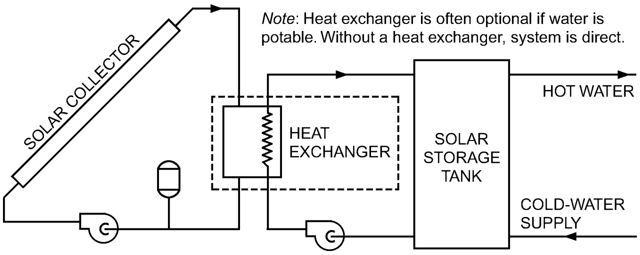
Freezing is the principal cause of liquid system failure. For this reason, freeze tolerance is an important factor in selecting the heat transfer fluid and equipment in the collector loop. A solar collector radiates heat to the cold sky and freezes at air temperatures well above 32°F. Where freezing conditions are rare, small solar heating systems are often equipped with low-cost protection devices that depend on simple manual, electrical, and/or mechanical components (e.g., electronic controllers and automatic valves) for freeze protection. Because of the large investment associated with most commercial and industrial installations, solar designers and installers must consider designs providing reliable freeze protection, even in the warmest climates.

Direct and Indirect Systems

In a direct liquid system, city water circulates through the collector. In an indirect system, the collector loop is separated from the high-pressure city water supply by a heat exchanger. In areas of poor water quality, isolation protects the collectors from fouling by minerals in the water. Indirect systems also offer greater freeze protection, so they are used almost exclusively in commercial and industrial applications.

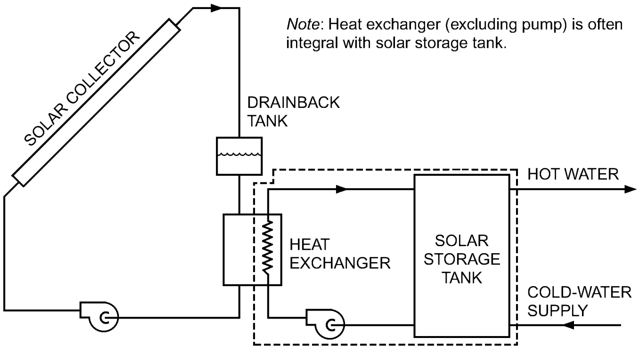
Freeze Protection

Direct systems, used where freezing is infrequent and not severe, can avoid freeze damage by (1) recirculating warm storage water through the collectors, (2) continually flushing the collectors with cold water, or (3) isolating collectors from the water and draining them. Systems that can be drained to avoid freeze damage are called **draindown** systems. Although all of these methods can be effective, none of them are generally approved by sanctioning bodies or recommended by manufacturers. Use caution when designing direct systems in freezing climates with any of these freeze protection schemes.



Note: Heat exchanger is often optional if water is potable. Without a heat exchanger, system is direct.

Fig. 2 Simplified Schematic of Indirect Nonfreezing System



Note: Heat exchanger (excluding pump) is often integral with solar storage tank.

Fig. 3 Simplified Schematic of Indirect Drainback Freeze Protection System

Indirect systems use two methods of freeze protection: (1) nonfreezing fluids and (2) drainback.

Nonfreezing Fluid Freeze Protection. The most popular solar energy system for commercial use is the indirect system with a nonfreezing heat transfer fluid to transmit heat from the solar collectors to storage (Figure 2). The most common heat transfer fluid is water/propylene glycol, although other heat transfer fluids such as silicone oils, hydrocarbon oils, or refrigerants can be used. Because the collector loop is closed and sealed, the only contribution to pump pressure is friction loss; therefore, the location of solar collectors relative to the heat exchanger and storage tank is not critical. Traditional hydronic sizing methods can be used for selecting pumps, expansion tanks, heat exchangers, and air removal devices, as long as the heat transfer liquid's thermal properties are considered.

When the control system senses an increase in solar panel temperature, the pump circulates the heat transfer liquid, and energy is collected. The same control also activates a pump on the domestic water side that circulates water through the heat exchanger, where it is heated by the heat transfer fluid. This mode continues until the temperature differential between the collector and the tank is too slight for meaningful energy to be collected. At this point, the control system shuts the pumps off. At low temperatures, the nonfreezing fluid protects the solar collectors and related piping from bursting. Because the heat transfer fluid can affect system performance, reliability, and maintenance requirements, fluid selection should be carefully considered.

Because the collector loop of the nonfreezing system remains filled with fluid, it allows flexibility in routing pipes and locating components. However, a double-separation (double-wall) heat exchanger is generally required (by local building codes) to prevent contamination of domestic water in the event of a leak. The double-wall heat exchanger also protects the collectors from freeze damage if water leaks into the collector loop. However, the double-wall heat exchanger reduces efficiency by forcing the collector to operate at a higher temperature. The heat exchanger can be placed inside the tank, or an external heat exchanger can be used, as shown in Figure 2. The collector loop is closed and, therefore, requires an expansion tank and pressure-relief valve. Air purge is also necessary to expel air during filling and to remove air that has been absorbed into the heat transfer fluid.

Overtemperature protection is necessary to ensure that the system operates within safe limits and to prevent collector fluid from corroding the absorber or heat exchanger. For maximum reliability, glycol should be replaced every few years.

In some cases, systems have failed because the collector fluid in the loop thermosiphoned and froze the water in the heat exchanger. This disastrous situation must be avoided by design if the water side is exposed to the city water system because the collector loop eventually fills with water, and all freeze protection is lost.

Drainback Freeze Protection. A drainback solar water-heating system (Figure 3) uses ordinary water as the heat transport medium between the collectors and thermal energy storage. Reverse-draining (or back-siphoning) the water into a drainback tank located in a nonfreezing environment protects the system from freezing whenever the controls turn off the circulator pump or a power outage occurs.

For drainback systems with a large amount of working fluid in the collector loop, heat loss can be significantly decreased and overall efficiency increased by including a tank for storing the heat transfer fluid at night. Using a night storage tank in large systems is an appropriate strategy even for regions with favorable meteorological conditions.

The drainback tank can be a sump with a volume slightly greater than the collector loop, or it can be the thermal energy storage tank. The collector loop may or may not be vented to the atmosphere. Many designers prefer the nonvented drainback loop because makeup water is not required and the corrosive effects of air that would otherwise be ingested into the collector loop are eliminated.

The drainback system is virtually fail-safe because it automatically reverts to a safe condition whenever the circulator pump stops. Furthermore, a 20 to 30% glycol solution can be added to drainback loops for added freeze protection in case of controller or sensor failure. Because the glycol is not exposed to stagnation temperatures, it does not decompose.

A drainback system requires space for the necessary pitching of collectors and pipes for proper drainage. Also, a nearby heated area must have a room for the pumps and the drainback tank. Plumbing exposed to freezing conditions drains to the drainback tank, making the drainback design unsuitable for sites where the collector cannot be elevated above the storage tank.

Both dynamic and static pressure losses must be considered in drainback system design. Dynamic pressure loss is due to friction in the pipes, and static pressure loss is associated with the distance the water must be lifted above the level of the drainback tank to the top of the collector. There are two distinct designs of drainback systems: the oversized downcomer (or open-drop) and the siphon return. The static head requirement remains constant in the open-drop system and decreases in the siphon return.

Drainback performs better than other systems in areas with low temperatures or high irradiance. Drainback has the advantage that time and energy are not lost in reheating a fluid mass left in the collector and associated piping (as in the case of antifreeze systems). Also, water has a higher heat transfer capacity and is less viscous than other heat transfer fluids, resulting in smaller parasitic energy use and higher overall system efficiency. In closed-return (indirect) designs, there is also less parasitic energy consumption for pumping because water is the heat transfer fluid. Drainback systems can be worked on safely under stagnation conditions, but should not be restarted during peak solar conditions to avoid unnecessary thermal stress on the collector.

SOLAR THERMAL ENERGY COLLECTORS

Collector Types

Solar collectors depend on air heating, liquid heating, or liquid-vapor phase change to transfer heat. The most common type for commercial, residential, and low-temperature (<200°F) industrial applications is the flat-plate collector.

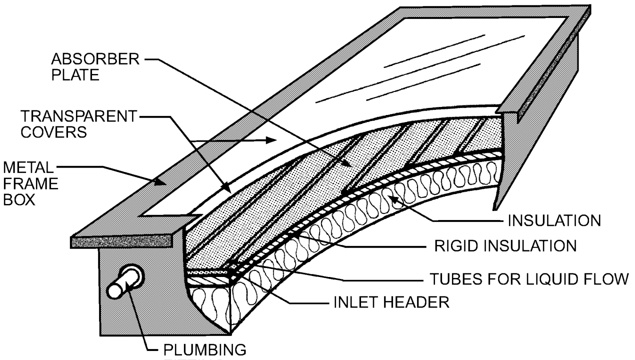
Liquid-Heating Collectors. Figure 4A shows a cross section of a flat-plate liquid collector. A flat-plate collector contains an absorber plate covered with a black coating and one or more transparent covers. The covers are transparent to incoming solar radiation and relatively opaque to outgoing (long-wave) radiation, but their principal purpose is to reduce convection heat loss. The collector box is insulated to prevent conduction heat loss from the back and edge of the absorber plate. This type of collector can supply hot water or air at temperatures up to 200°F, although efficiency diminishes rapidly above 160°F. The advantages of flat-plate collectors are simple construction, low relative cost, no moving parts, relative ease of repair, and durability. They also absorb diffuse radiation, which is a distinct advantage in cloudy climates.

Another type of collector is the integral collector storage (ICS) system. These collectors incorporate thermal storage within the collector itself. The storage tank surface serves as the absorber surface. Most ICS systems use only one tank, but some use several tanks in series. As with flat-plate collectors, insulated boxes enclose the tanks with transparent coverings on the side facing the sun. Although the simplicity of ICS systems is attractive, they are generally suitable only for applications in mild climates with small thermal storage requirements. Freeze protection by manually draining the unit is necessary in colder climates.

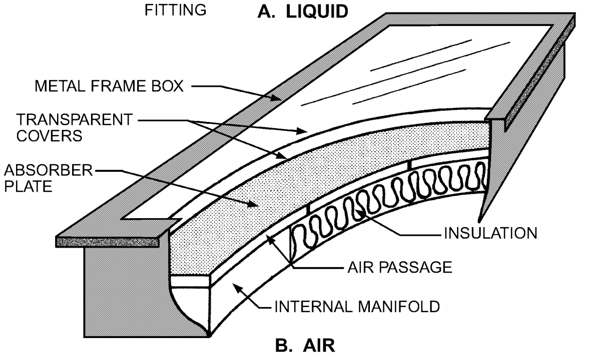
Still another type of collector is the evacuated tube, where the absorber mechanism is encased in a glass vacuum tube (Figure 5). Absorbers may be a simple copper fin tube on a copper sheet, a large copper cylinder in ICS applications, or a heat pipe. The latter uses a phase-change fluid to transfer heat to a common manifold where the working fluid circulates. The vacuum envelope reduces convection and conduction losses, so the tubes can operate at higher temperatures than flat-plate collectors. Like flat-plate collectors, they collect both direct and diffuse radiation. Because of its high-temperature capability, the evacuated-tube collector is favored for energizing heat-driven air-conditioning equipment, particularly when combined with concentrating reflectors behind the tubes.

Flat-plate and evacuated-tube collectors are usually mounted in a fixed position. Concentrating collectors are available that must be arranged to track the movement of the sun. These are mainly used for high-temperature industrial applications above 240°F. For more information on concentrating collectors, see Chapter 33 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Finally, unglazed flat-plate absorbers are often used for low-temperature applications such as pool heating. The most popular configurations are made of plastic structured to create an almost fully wetted surface or uses very small fins on extruded tubes. Metal

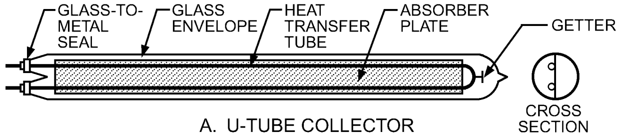


A. LIQUID

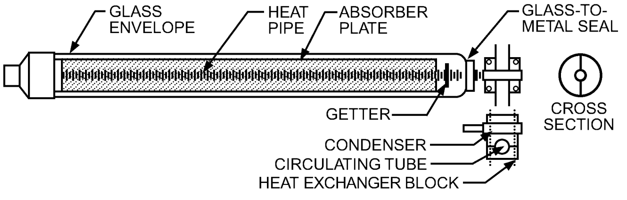


B. AIR

Fig. 4 Solar Flat-Plate Collectors



A. U-TUBE COLLECTOR



B. HEAT PIPE COLLECTOR

Fig. 5 Evacuated-Tube Collector

absorber plates from glazed collectors are also used, but generally with a heat exchanger to avoid contact with the pool water chemicals.

Air-Heating Collectors. Air-heating collectors are also contained in a box, covered with one or more glazings, and insulated on the sides and back. Figure 4B shows a cross section of a flat-plate air collector. The primary differences from liquid-heating collectors are in the design of the absorber plate and flow passages. Because the working fluid (air) has poor heat transfer characteristics, it flows over the entire absorber plate, and sometimes on both the front and back of the plate, to make use of a larger heat transfer surface. In spite of the larger surface area, air collectors generally have poorer overall heat transfer than liquid collectors. However, they are usually operated at a lower temperature for space heating applications because they require no intervening heat exchangers.

Transpired air collectors can be attached to the roof or side of a building to create a plenum for the preheated air. The collector is simply the siding material with many small holes through which the air is drawn, thus warming the air for space-heating or drying applications.

Liquid-Vapor Collectors. A third class of collectors uses liquid-vapor phase change to transfer heat at high efficiency. These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum sealed tube (Figure 5B). The heat pipe contains a small amount of fluid (e.g., methanol) that undergoes an evaporating/condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapor travels to a heat sink region, where it condenses and releases its latent heat. This process is repeated by a return feed of the condensed fluid back to the solar absorber.

Most phase-change fluids have low freezing temperatures, so the heat pipe offers inherent protection to the tubes from freezing and overheating, but not to the fluid being heated. This self-limiting temperature control is a unique feature of the evacuated heat pipe collector.

Collector Construction

Absorber Plates. The key component of a flat-plate collector is the absorber plate. It contains the heat transfer fluid and serves as a heat exchanger by converting radiant energy into thermal energy. It must maintain structural integrity at temperatures ranging from below freezing to well above 300°F. Chapter 33 of the 2007 *ASHRAE Handbook—HVAC Applications* illustrates typical liquid collectors and shows the wide variety of absorber plate designs in use.

Materials for absorber plates and tubes are usually highly conductive metals such as copper, aluminum, and steel, although low-temperature collectors for swimming pools are usually made from extruded elastomeric material such as ethylene-propylene terpolymer (EPDM) and polypropylene. Flow passages and fins are usually copper, but aluminum fins are sometimes inductively welded to copper tubing. Occasionally, fins are mechanically attached, but there is potential for corrosion with this design. A few manufacturers produce all-aluminum collectors, but they must be checked carefully to determine whether they incorporate corrosion protection in the collector loop.

Figure 6 shows a plan view of typical absorber plates. The serpentine design (Figure 6A) is used less frequently because it is difficult to drain and imposes a high pressure drop, but it can produce higher temperatures at lower flow rates. Most manufacturers use absorber plates similar to those shown in Figures 6D and 6E.

In liquid collectors, manifold selection is important because the design can restrict the array piping configuration. The manifold must be drainable and free-floating, with generous allowance for thermal expansion. Some manufacturers provide a choice of manifold connections to give designers flexibility in designing arrays.

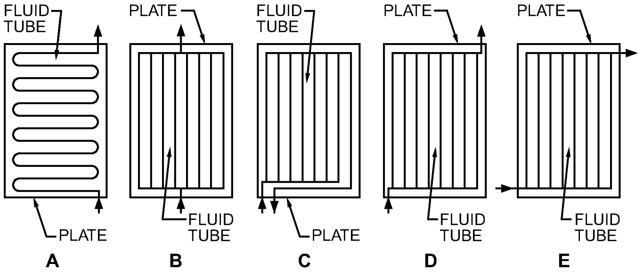


Fig. 6 Plan View of Liquid Collector Absorber Plates

In air collectors, most manufacturers increase the heat transfer area by using fins, matrices, or corrugated surfaces (Figure 7). Many of these designs increase air turbulence, which improves collector efficiency (at the expense of increased fan power).

Figure 7 also shows cross sections of typical solar water collectors. Water passages can be integrated with the absorber plate to ensure good thermal contact (Figure 7E), or they can be soldered, brazed, or otherwise fastened to the absorber plate (Figure 7F). Manufactured collectors are made in modular sizes, typically 4 by 8 ft, and these are connected to form a bank or row. Because most commercial-scale systems involve more than 1000 ft^2 of collector, there can be numerous piping connections, depending on design.

Absorber plates may be coated with spectrally selective or nonselective materials. Selective coatings are more efficient, but cost more than nonselective, or flat black, coatings. However, their higher efficiencies may reduce the overall size of the array, resulting in lower total cost. The Argonne National Laboratory has published detailed guidelines on various coating materials used in solar applications (ANL 1979a).

Housing. The collector housing is the container that provides structural integrity for the collector assembly. The housing must be structurally sound, weathertight, fire-resistant, and mechanically connectable to a substructure to form an array. Collector housing materials include the following:

- Galvanized or painted steel
- Aluminum folded sheet stock or extruded wall materials
- Various plastics, either molded or extruded
- Composite wood products
- Standard elements of the building

Extruded anodized aluminum, including extruded channels, offers durability and ease of fabrication. Grooves are sometimes included in the extruded channels to accommodate proprietary mounting fixtures. The high temperatures of a solar collector deteriorate wood housings; consequently, wood is often forbidden by fire codes.

Glazing. Solar collectors for domestic hot water are usually single-glazed to reduce absorber plate convective and radiative losses. Some collectors have double glazing to further reduce these losses; however, double glazing should be restricted to applications where the value of $(t_i - t_a)/I_t$ exceeds that of domestic hot-water applications (e.g., space heating or activating absorption refrigeration). Glazing materials are plastic, plastic film, or glass. Glass can absorb the longwave thermal radiation emitted by the absorber coating, but it is not affected by ultraviolet (UV) radiation. Because of their impact tolerance, only tempered, low-iron glass covers should be considered. These covers have a solar transmission rating of 84 to 91%.

If the probability of vandalism is high, polycarbonate, which has high impact resistance, should be considered. Unfortunately, its transmittance is not as high as that of low-iron glass, and it is susceptible to long-term UV degradation.

Insulation. Collector enclosures must be well insulated to minimize heat losses. The insulation adjacent to the absorber plate must

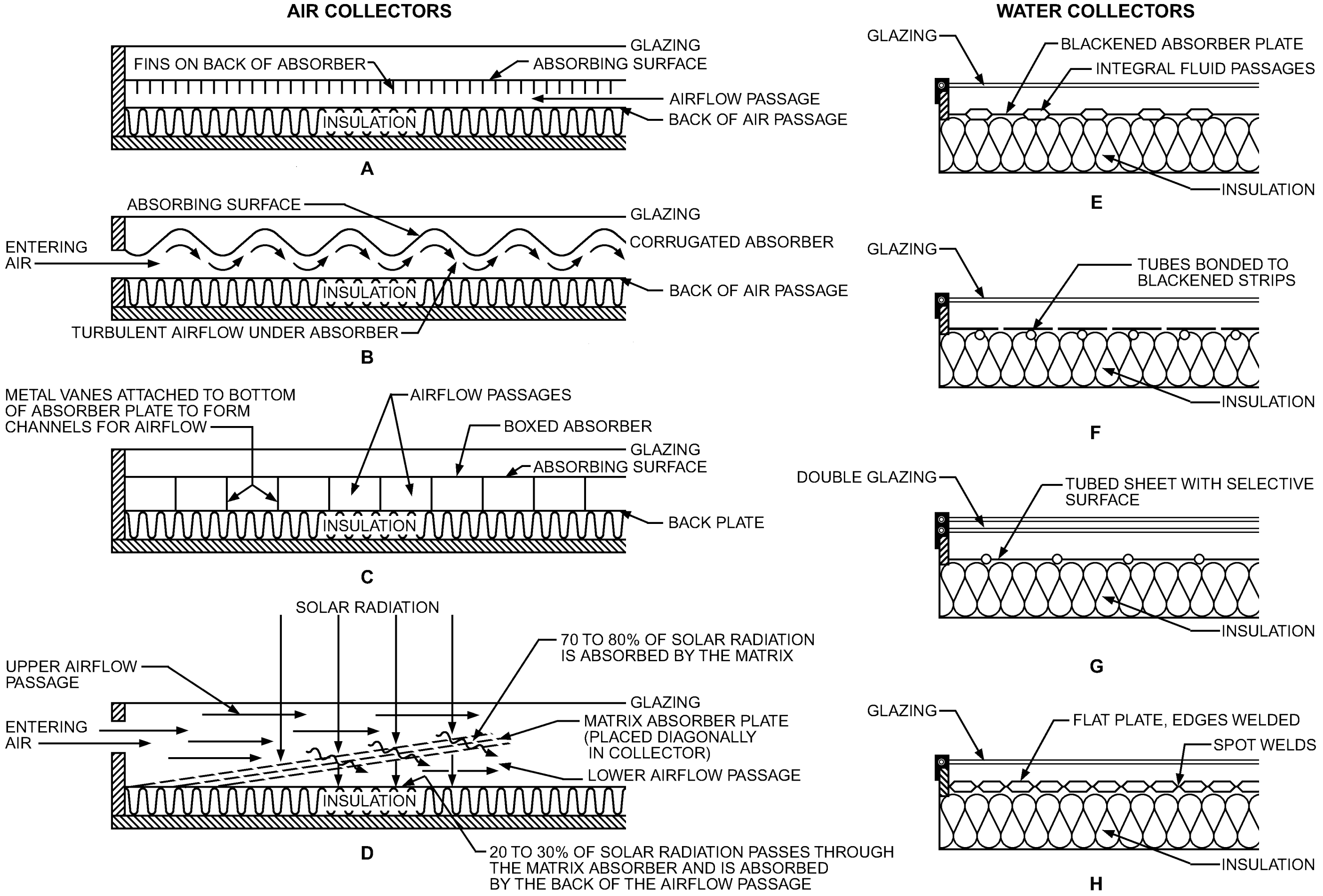


Fig. 7 Cross Sections of Various Solar Air and Water Heater

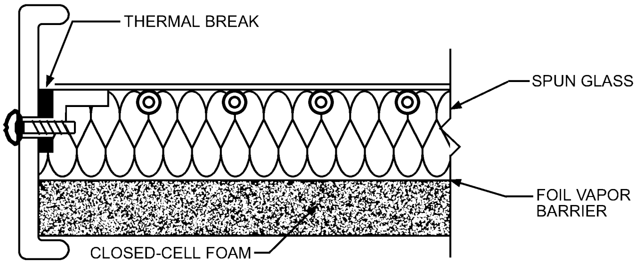


Fig. 8 Cross Section of Suggested Insulation to Reduce Heat Loss from Back Surface of Absorber

withstand temperatures up to 400°F and, most importantly, must not outgas volatile products within this range. Many insulation materials designed for construction applications are not suitable for solar collectors because the binders outgas volatiles at normal collector operating temperatures.

Solar collector insulation is typically made of mineral fiber, ceramic fiber, glass foam, plastic foam, or fiberglass. Fiberglass is the least expensive insulation and is widely used in solar collectors. For high-temperature applications, rigid fiberglass board with a minimum of binder is recommended. Also, a layer of polyisocyanurate foam in collectors is often used because of its superior R-value. Because it can outgas at high temperatures, the foam must not be allowed to contact the collector plate.

Figure 8 illustrates the preferred method of combining fiberglass and foam insulations to obtain both high efficiency and durability. Note that the absorber plate should be free-floating to avoid thermal stresses. Despite attempts to make collectors watertight, moisture is always present in the interior. This moisture can physically degrade mineral wool and reduce the R-value of fiberglass, so drainage and venting are crucial.

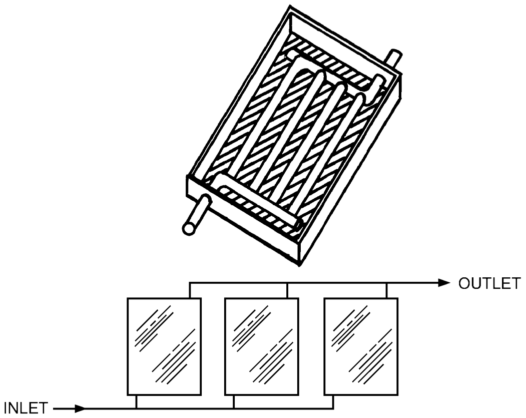
ROW DESIGN

Piping Configuration

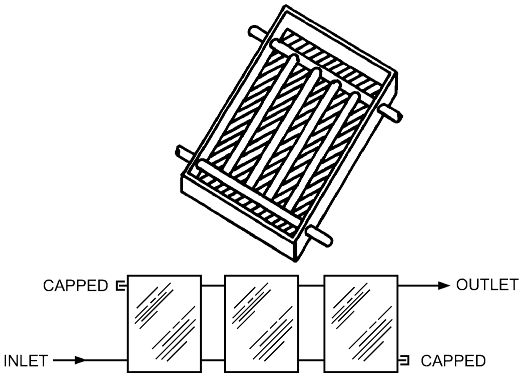
Most commercial and industrial systems require a large number of collectors. Connecting the collectors with one set of manifolds makes it difficult to ensure drainability, balanced flow, and low pressure drop. An array usually includes many individual groups of collectors, called rows, to provide the necessary flow characteristics. Rows can be grouped into (1) parallel flow or (2) combined series-parallel flow. Parallel flow is the most frequently used because it is inherently balanced, has low pressure drop, and is drainable. Figure 9 illustrates various collector header designs for forming a parallel-flow row (the flow is parallel but the collectors are connected in series).

Generally, flat-plate collectors connect to the main piping in one of the methods shown in Figure 9. The **external manifold** collector has a small-diameter connection meant to carry only the flow for one collector. It must be connected individually to the manifold piping, which is not part of the collector panel, as depicted in Figure 9A.

Internal manifold collectors incorporate the manifold piping integral with each collector (Figure 9B). Headers at either end of the collector distribute flow to the risers. Several collectors with large headers can be placed side by side to form a continuous supply and return manifold. With 1 in. headers, four to six 40 ft^2 collectors can be placed side by side. Collectors with 1 in. headers can be mounted in a row without producing unbalanced flow. Most collec-



A. EXTERNAL MANIFOLDING



B. INTERNAL MANIFOLDING END CONNECTIONS

Fig. 9 Collector Manifolding Arrangements for Parallel-Flow Row

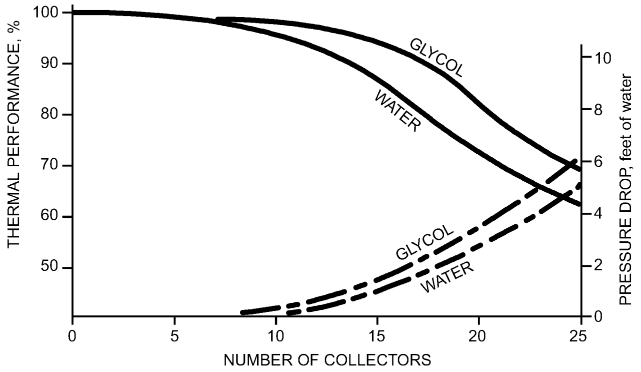
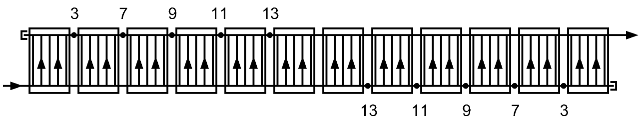


Fig. 10 Pressure Drop and Thermal Performance of Collectors with Internal Manifolds Numbers



Note: Numbers indicate restrictor hole diameter in sixteenths of an inch.

Fig. 11 Flow Pattern in Long Collector Row with Restrictions

tors have four plumbing connections, some of which may be capped if the collector is located on the end of the array. Internally manifolded collectors have the following advantages:

- Piping costs are lower because fewer fittings and less insulation are required.
- Heat loss is less because less piping is exposed.
- Installation is more attractive.

Some of their disadvantages are as follows:

- For drainback systems, the entire row must be pitched, thus complicating mounting.
- Flow may be imbalanced if too many collectors are connected in parallel.
- Removing the collector for servicing may be difficult.
- Stringent thermal expansion requirements must be met if too many collectors are combined in a row.

Velocity Limitations

Fluid velocity limits the number of internally manifolded collectors that can be contained in a row. For 1 in. headers, up to eight 40 ft^2 collectors can usually be connected for satisfactory performance. If too many are connected in parallel, the middle collectors will not receive enough flow, and performance will decrease. Connecting too many collectors also increases pressure drop. Figure 10 shows the effect of collector number on performance and pressure drop for one particular design. Newton and Gilman (1983) describe a general method to determine the number of internally manifolded collectors that can be connected.

Flow restrictors can be used to accommodate a large number of collectors in a row. The flow distribution in the 12 collectors of Figure 11 would not be satisfactory without the flow restrictors shown at the interconnections. The flow restrictors are barriers with a drilled hole of the diameter indicated. Some manufacturers calculate the required hole diameters and provide predrilled restrictors.

Chapter 35 of the 2001 *ASHRAE Handbook—Fundamentals* gives information on sizing piping. Knowles (1980) provides the following expression for the minimum acceptable header diameter:

$$D = 0.24(Q/\Delta p)^{0.45}N^{0.64} \tag{1}$$

where

D = header diameter, in.
N = number of collectors in module
Q = recommended flow rate for collector, gpm
Δp = pressure drop across collector at recommended flow rate, psi

Because pipe is available in a limited number of diameters, selection of the next larger size ensures balanced flow. Usually, the sizes of supply and return piping are graduated to maintain the same pressure drop while minimizing piping cost. Complicated configurations may require a hydraulic static regain calculation.

Thermal Expansion

Thermal expansion will affect the row shown in Figure 11. Thermal expansion (or contraction) of a module of collectors in parallel may be estimated by the following equation:

$$\Delta = 0.000335n(t_c - t_i) \tag{2}$$

where

Δ = expansion or contraction of collector array, in.
n = number of collectors in array
t_c = collector temperature, °F (generally the maximum stagnation temperature)
t_i = installation temperature of collector array, °F (generally the lowest possible air temperature)

Because absorbers are rigidly connected, the absorber must have sufficient clearance from the side frame to allow the expansion indicated in Equation (2). Information on dealing with expansion in piping may also be found in Chapter 45.

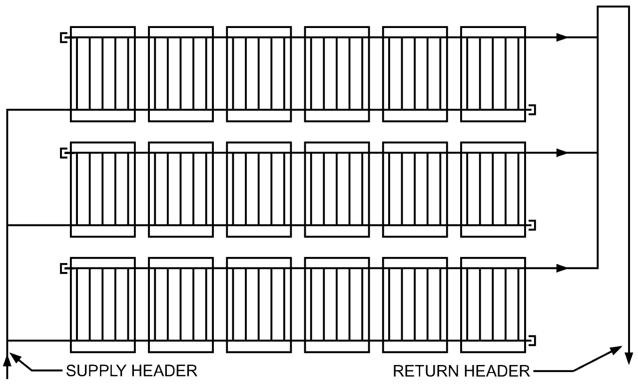


Fig. 12 Reverse-Return Array Piping

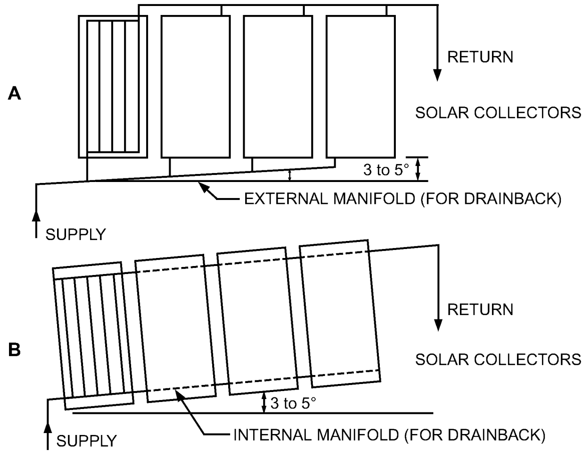


Fig. 13 Mounting for Drainback Collector Modules

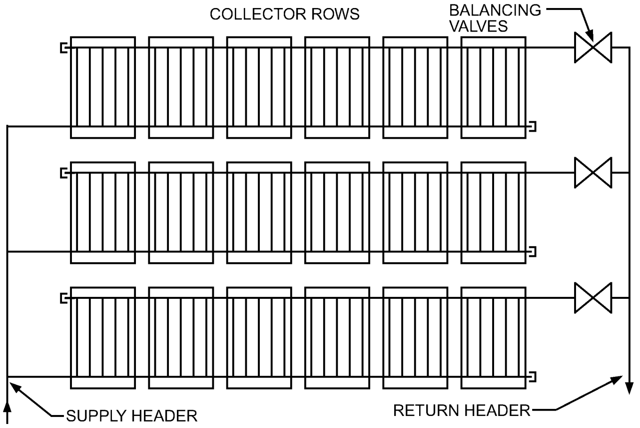


Fig. 14 Direct-Return Array Piping

ARRAY DESIGN

Piping Configuration

Liquid Systems. To maintain balanced flow, an array or field of collectors should be built from identical rows configured as described in previous sections. Whenever possible, rows must be connected in reverse-return fashion (Figure 12), which ensures that the array is self-balanced. With proper care, an array can drain, which is an essential requirement for drainback freeze protection.

Piping to and from the collectors must be sloped properly in a drainback system. Typically, piping and collectors must slope to drain at 1/4 in. per linear foot. Elevations throughout the array, especially the highest and lowest point of the piping, should be noted on the drawings.

The external manifold collector has different mounting and plumbing considerations from the internal manifold collector (Figure 13). A row of externally manifolded collectors can be mounted horizontally, as shown in Figure 13A. The lower header must be pitched as shown. The pitch of the upper header can be either horizontal or pitched toward the collectors so it can drain back through the collectors.

Arrays with internal manifolds pose a greater challenge in designing and installing the collector mounting system. For these collectors to drain, the entire bank must be tilted, as shown in Figure 13B.

Reverse return always implies an extra pipe run. Sometimes, it is more convenient to use direct return (Figure 14). In this case, balancing valves are needed to ensure uniform flow through the rows. The balancing valves *must* be connected at the row outlet to provide the flow resistance necessary to ensure filling of all rows on pump start-up.

It is often impossible to configure parallel arrays because of the presence of rooftop equipment, roof penetrations, or other building-imposed constraints. Although the list is not complete, the following requirements should be considered when developing the array configuration:

- Strive for a self-balancing configuration.
- For drainback, design rows, subarrays, and arrays to be individually and collectively drainable.
- Always locate collectors or rows with high flow resistance at the outlet to improve flow balance and ensure the drainback system fills.
- Minimize flow and heat transfer losses.

In general, it is easier to configure complex array designs for nonfreezing fluid systems. Newton and Gilman (1983) provide some typical examples. However, with careful attention to these criteria, it is also possible to design successful large drainback arrays.

Air Systems. Air distribution within the collector array is the most critical feature of an air system for effective operation. Proper airflow must take into account the overall pressure drop to allow efficient fan motor sizing. Balancing, automatic, backdraft, and fire dampers are usually needed. Air leaks (both into and out of the ducts and from component to component) must be minimized.

For example, some air collector systems contain a water coil for preheating water. Despite the inclusion of automatic and backdraft dampers, leakage within the system can freeze coils. One possible solution is to position the coil near the warm end of the storage bin. Another is to circulate an antifreeze solution in the coil. Whatever the solution, the designer must remember that even the lowest-leakage dampers will leak if improperly installed or adjusted.

As with liquid systems, the main supply and return ducts should be connected in a reverse-return configuration, with balancing dampers on each supply branch to the collector modules. If reverse return is not feasible, the main ducts should include balancing dampers at strategic locations. Here too, having fewer branch ducts reduces balancing needs and costs.

Unlike liquid systems, air collectors can be built on site. Although material and cost savings can be substantial with site-built collectors, extreme care must be taken to ensure long life, low leakage, and proper air distribution. Quality control in the field can be a problem, so well-trained designers and installers are critical to the success of these systems.

Performance. The effect of array and air distribution system designs on the overall system performance must be considered. Beckman et al. (1977) give standard procedures for estimating the impact of series connection and duct thermal losses. The effect on fan operation and fan power is more difficult to determine. For unique system designs and more detailed performance estimates, including fan power, an hourly simulation such as TRNSYS (Klein et al. 2004) can be used.

Shading

When large collector arrays are mounted on flat roofs or level ground, multiple rows of collectors are usually installed in a sawtooth fashion. These multiple rows should be spaced so that they do not shade each other at low sun angles. However, it is usually not desirable to avoid mutual shading altogether. It is sometimes possible to add additional rows to a roof or other constrained area; this increases the solar fraction but sacrifices efficiency. Kutscher (1982) presents a method of estimating the energy delivered annually when there is some row-to-row shading in the array. The most common practice is to base the row spacing on the lowest sun angle during the most important time of the year. For example, water and pool heating systems that operate mostly in the summer can use the higher sun angles of summer or spring and fall. Space-heating systems may want to maximize exposure in the winter, so they should use the lowest sun angle at the winter solstice. A system that operates year round may use the spring equinox sun angle as a reasonable compromise to allow more rows.

Thermal Collector Performance

Under steady-state flow conditions, the useful heat delivered by a solar collector is equal to the energy absorbed in the heat transfer fluid minus the direct and indirect heat losses from the surface to the surroundings. This principle can be stated in the following relationship:

$$q_u = A_c[I_t\tau\alpha - U_L(\bar{t}_p - t_a)] \tag{3}$$

where

q_u = useful energy delivered by collector, Btu/h
A_c = total aperture collector area, ft^2
I_t = irradiance, total (direct plus diffuse) solar energy incident on upper surface of sloping collector structure, $\text{Btu/h}\cdot\text{ft}^2$
τ = transmittance (fraction of incoming solar radiation that reaches absorbing surface), dimensionless
α = absorptance (fraction of solar energy reaching surface that is absorbed), dimensionless
U_L = overall heat loss coefficient, $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$
$\bar{t}_p$ = average temperature of absorbing surface of absorber plate, °F
t_a = atmospheric temperature, °F

Except for average plate temperature $\bar{t}_p$, these terms can be readily determined. For convenience, Equation (3) can be modified by substituting inlet fluid temperature for the average plate temperature, if a suitable correction factor is included. The resulting equation is

$$q_u = F_R A_c[I_t\tau\alpha - U_L(t_i - t_a)] \tag{4}$$

where

F_R = correction factor, or collector heat removal efficiency factor, having a value less than 1.0
t_i = temperature of fluid entering collector, °F

The heat removal factor F_R can be considered the ratio of the heat actually delivered to that delivered if the collector plate were at a uniform temperature equal to that of the entering fluid. An F_R of 1.0 is theoretically possible if (1) the fluid is circulated at such a high rate that its temperature rises a negligible amount, and (2) the heat transfer coefficient and fin efficiency are so high that the temperature difference between the absorber surface and the fluid is negligible.

In Equation (4), the temperature t_i of the inlet fluid depends on the characteristics of the complete solar heating system and the building's heat demand. However, F_R is affected only by the solar collector characteristics, fluid type, and fluid flow rate through the collector.

Solar air heaters remove substantially less heat than liquid collectors. However, their lower collector inlet temperature makes their system efficiency comparable to that of liquid systems for space-heating applications.

Equation (4) may be rewritten in terms of the instantaneous efficiency of total solar radiation collection by dividing both sides of the equation by $I_t A_c$. The result is

$$\eta = F_R\tau\alpha - F_R U_L \frac{(t_i - t_a)}{I_t} \tag{5}$$

where η = collector efficiency, dimensionless.

Equation (5) plots as a straight line on a graph of efficiency versus the heat loss parameter $(t_i - t_a)/I_t$. Plots of Equation (5) for various liquid collectors are shown in Figure 15. The intercept (intersection of the line with the vertical efficiency axis) equals $F_R\tau\alpha$. The slope of the line (i.e., any efficiency difference divided by the corresponding horizontal scale difference) equals $-F_R U_L$. If experimental data on collector heat delivery at various temperatures and solar conditions are plotted, with efficiency as the vertical axis and $(t_i - t_a)/I_t$ as the horizontal axis, the best straight line through the data points correlates collector performance with solar and temperature conditions. The intersection of the line with the vertical axis is where the temperature of the fluid entering the collector equals the ambient temperature, and collector efficiency is at its maximum. At the intersection of the line with the horizontal axis, collection efficiency is zero. This condition corresponds to such a low radiation level, or to such a high temperature of the fluid into the collector, that heat losses equal solar absorption, and the collector delivers no useful heat. This condition, normally called **stagnation**, usually occurs when no coolant flows to a collector. Solving Equation (5) for t_i under the hottest conditions yields the stagnation temperature for the collectors at that site.

Equation (5) includes all important design and operational factors affecting steady-state performance except collector flow rate and solar incidence angle. Flow rate indirectly affects performance through the average plate temperature. If the heat removal rate is

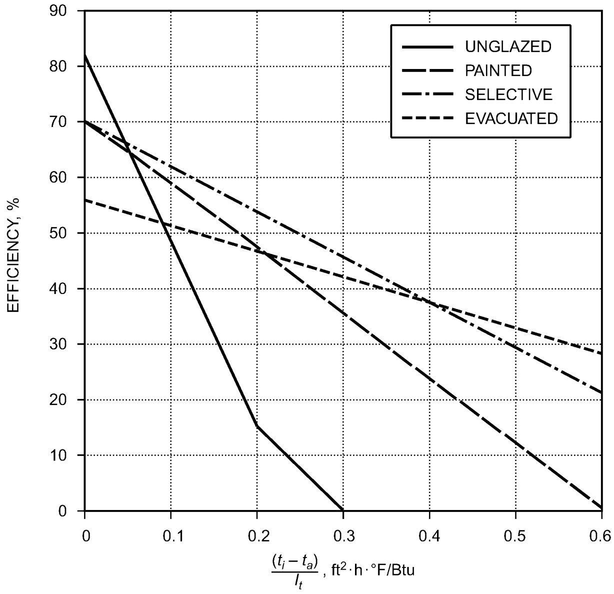


Fig. 15 Solar Collector Type Efficiencies

reduced, the average plate temperature increases, and more heat is lost. If the flow is increased, collector plate temperature and heat loss decrease.

Solar Incidence Angle. These relationships assume that the sun is perpendicular to the plane of the collector, which rarely occurs. For glass cover plates, specular reflection of radiation occurs, thereby reducing the $\tau\alpha$ product. The incident angle modifier $K_{\tau\alpha}$, defined as the ratio of $\tau\alpha$ at some incidence angle θ to $\tau\alpha$ at normal radiation $(\tau\alpha)_n$, is described by the following simple expression for specular reflection:

$$K_{\tau\alpha} = \frac{\tau\alpha}{(\tau\alpha)_n} = 1 + b_o\left[\frac{1}{\cos\theta} - 1\right] \tag{6}$$

For a single glass cover, b_o is approximately –0.10. Many flat-plate collectors, particularly evacuated tubes, have some limited focusing capability. The incident angle modifiers for these collectors are not modeled well by Equation (6), which is a linear function of $(1/\cos\theta) - 1$.

Cellular Flow Rate. Equation (5) is not convenient for air collectors when it is desirable to present data based on collector outlet temperature t_{out} rather than inlet temperature, which is the commonly measured variable for liquid systems. The relationship between the heat removal factors for these two cases is

$$F_R\tau\alpha = \frac{(F_R\tau\alpha)'}{1 + (F_R U_L)'/\dot{m}c_p} \tag{7a}$$

$$F_R U_L = \frac{(F_R U_L)'}{1 + (F_R U_L)'/\dot{m}c_p} \tag{7b}$$

where $\dot{m}c_p$ is mass flow times specific heat of air, $F_R U_L$ and $F_R\tau\alpha$ apply to $t_i - t_a$ in Equation (5), and $(F_R U_L)'$ and $(F_R\tau\alpha)'$ apply to $t_{out} - t_a$.

Testing Methods

ASHRAE *Standard* 93 gives information on testing solar energy collectors using single-phase fluids and no significant internal storage. The data can be used to predict performance in any location and under any conditions where load, weather, and insolation are known.

The standard presents efficiency in a modified form of Equation (5). It specifies that the efficiency be reported in terms of gross collector area A_g rather than aperture collector area A_c. The reported efficiency is lower than the efficiency based on net area, but the total energy collected does not change by this simplification. Therefore, gross collector area must be used when analyzing performance of collectors based on experiments that determine $F_R\tau\alpha$ and $F_R U_L$ according to ASHRAE *Standard* 93.

Standard 93 suggests that testing be done at 0.03 gpm per square foot of gross collector area for liquid systems, and that the test fluid be water. Although it is acceptable to use lower flow rates or a heat transfer fluid other than water, the designer must adjust the F_R for a different heat removal rate based on the product $\dot{m}c_p$ of mass flow and specific heat. The following approximate approach may be used to estimate small changes in $\dot{m}c_p$:

$$\frac{(F_R U_L)_2}{(F_R U_L)_1} = \frac{1 - \exp[-A_c(F_R U_L)'/(\dot{m}c_p)_2]}{1 - \exp[-A_c(F_R U_L)'/(\dot{m}c_p)_1]} \tag{8}$$

Air collectors are tested at a flow rate of 2 scfm per square foot, and the same relationship applies for adjusting to other flow rates. Annual compilations of collector test data that meet the criteria of ASHRAE *Standards* 93 and 96 may be obtained from Solar Rating and Certification Corporation (www.solar-rating.org).

Another source for this information is the collector manufacturer. However, a manufacturer sometimes publishes efficiency data at a much higher flow rate than the recommended design value, so collector data should be obtained from an independent laboratory qualified to conduct testing prescribed by ASHRAE *Standard* 93.

Collector Test Results and Initial Screening Methods

Final collector selection should be made only after energy analyses of the complete system, including realistic weather conditions and loads, have been determined. Also, a preliminary screening of collectors with various performance parameters should be conducted to identify those that best match the load. One way to accomplish this is to identify the expected range of heat loss parameter $(t_i - t_a)/I_t$ for the load and climate on a plot of efficiency η as a function of heat loss parameter, as indicated in Figure 15.

Ambient temperature during the swimming season may vary by 18°F above or below pool temperature. The corresponding parameter values range from 0.15 $\text{Btu/h}\cdot\text{ft}^2\cdot°\text{F}$ on cool overcast days (low I_t) to as low as –0.15 $\text{Btu/h}\cdot\text{ft}^2\cdot°\text{F}$ on hot overcast days. For most swimming pool heating, unglazed collectors offer the highest performance and are the least expensive.

The heat loss parameter for service water heating can range from 0.05 to 0.35 $\text{Btu/h}\cdot\text{ft}^2\cdot°\text{F}$, depending on the climate at the site and the desired hot-water delivery temperature. Convective space heating requires an even greater collector inlet temperature than water heating, and the primary load coincides with lower ambient temperature. In many areas of the United States, space heating coincides with low radiation values, which further increases the heat loss parameter. However, many space-heating systems are accompanied by water heating, and some space-heating systems (e.g., radiant panels) are available at a lower $(t_i - t_a)/I_t$ value.

Air conditioning with solar-activated absorption equipment is economical only when the cooling season is long and solar radiation levels are high. These devices require at least 180°F water. Thus, on an 80°F day with radiation at 300 $\text{Btu/h}\cdot\text{ft}^2$, the heat loss parameter is 0.3. Higher operating temperatures are desirable to prevent excessive derating of the air conditioner. Only the most efficient (low $F_R U_L$) collector is suitable. Derating may also be minimized by using convective-radiant hybrid air-conditioning systems.

Collector efficiency curves may be used as an initial screening device. However, efficiency curves illustrate only instantaneous performance of a collector. They do not include incidence angle effects (which vary throughout the year); heat exchanger effects; probabilities of occurrence of t_i, t_a, and I_t; system heat loss; or control strategies. Final selection requires determining a collector's long-term energy output as well as performing cost-effectiveness studies. Estimating a particular collector's and system's annual performance requires appropriate analysis tools such as *f*-Chart (Beckman et al. 1977) or TRNSYS (Klein et al. 2004). The Solar Rating and Certification Corporation (SRCC), International Organization for Standardization (ISO), European Committee for Standardization (CEN), and other rating agencies provide day-long collector outputs under various solar and operating conditions. These ratings can greatly simplify selection of the proper collector type, including cost considerations. Table 1 shows a comparison of generic types of liquid flat-plate collectors.

Generic Test Results

The generic types of liquid flat-plate collectors are **unglazed**, **single-glazed painted-** and **selective-surface absorbers**, and **evacuated tubes**. Table 1 shows the average output, intercept, and slope for these. The normalized day-long energy output for a clear day in category C points out the difficulties in using only the instantaneous efficiency data. Category C holds the temperature difference constant at 36°F all day, and a clear day is defined as 2000 $\text{Btu/ft}^2\cdot\text{day}$, which is high for most of the United States. Note that evacuated-tube collectors do not perform very well under these

Table 1 Average Performance Parameters* for Generic Types of Liquid Flat-Plate Collectors

Collector Type	Vertical Intercept	Slope, Btu/h·ft²·°F	Clear-Day Category C Output, Btu/h·ft²·°F
Unglazed	0.807	–3.289	420
Glazed			
Painted absorber	0.701	–1.15	927
Selective-surface absorber	0.699	–0.814	1007
Evacuated tube	0.554	–0.443	840

*Derived from data of Solar Rating and Certification Corporation (SRCC), www.solar-rating.org (Oct. 2006).

Table 2 Thermal Performance Ratings* for Generic Types of Liquid Flat-Plate Collectors, Btu/ft²·day

	Solar Day, Btu/ft²·day		
Category*	Clear Day 2000	Mildly Cloudy 1500	Cloudy Day 1000
Unglazed			
A	1600	1200	900
B	1000	700	400
C	400	200	—
D	—	—	—
E	—	—	—
Painted			
A	1285	971	658
B	1128	815	533
C	908	595	282
D	407	157	—
E	—	—	—
Selective surface			
A	1316	971	658
B	1191	877	564
C	1003	689	376
D	595	313	63
E	219	31	—
Evacuated tube			
A	872	655	436
B	841	623	405
C	810	592	374
D	685	467	280
E	592	374	156

*Categories	$T_i - T_a$, °F	Application
A	–9	Pool heating, warm climate
B	9	Pool heating, cool climate
C	36	Water heating, warm climate
D	90	Water heating, cool climate
E	144	Air conditioning

*Derived from data of Solar Rating and Certification Corporation (SRCC), www.solar-rating.org (Oct. 2006).

circumstances. SRCC and other rating agencies publish a matrix of collector outputs for various temperature differences and solar days. Table 2 shows the SRCC matrix for each generic collector type. Further explanation of the categories is available on the SRCC Web site, www.solar-rating.org, or in their standards.

The daily outputs in Table 2 show a clear advantage for each type of collector starting from the upper left corner and proceeding diagonally down and across. At low temperature differences, for categories A and B under clear and mildly cloudy conditions, unglazed collectors provide a clear advantage. The middle of the matrix is a bit less definitive, but painted and selective-surface collectors tend to perform best in the range. At the lower right corner, evacuated tubes perform best under high temperature differences and low solar inputs. Determining where a project falls in this rating matrix is very important in selecting the proper collector; the designer should be familiar with the location's average daily solar input and the desired operating temperature. For example, selective-surface collectors might work well for a high-temperature application in Phoenix in the summer because the daytime temperature difference is low and the solar input is high, whereas evacuated tubes are a better choice in Atlanta.

THERMAL ENERGY STORAGE

Design and selection of thermal storage equipment is one of the most neglected elements of solar energy systems. In fact, the energy storage system has an enormous influence on overall system cost, performance, and reliability. Furthermore, the storage system design is highly interactive with other system elements such as the collector loop and thermal distribution system. Thus, it should be considered within the context of the total system.

Energy can be stored in liquids, solids, or phase-change materials (PCMs). Water is the most frequently used liquid storage medium, although the collector loop may contain water, oils, or aqueous glycol as a collection fluid. For service water heating and most building space heating, water is normally contained in some type of tank. Air systems typically store heat in rocks or pebbles, but sometimes use the building's structural mass. Chapter 33 of the 2007 *ASHRAE Handbook—HVAC Applications* and ASHRAE (1991) cover this topic in more detail.

Air System Thermal Storage

The most common storage media for air collectors have been rocks or a regenerator matrix made from concrete masonry units (CMUs). Gravel was widely used as a storage medium because it is plentiful and relatively inexpensive; however, the inherent cost and likelihood of mold growth in humid climates put an end to its use. Other possible media include PCMs, water, and the inherent building mass.

In places where large interior temperature swings are tolerable, the inherent mass of the building may be sufficient for thermal storage. Designated storage may also be eliminated where the array output seldom exceeds the concurrent demand. Loads requiring no storage are usually the most cost-effective applications of air collectors, and heated air from the collectors can be distributed directly to the space.

Water can be used as a storage medium for air collectors by using a conventional heating coil to transfer heat from the air to the water in the storage tank. Advantages of water storage include compatibility with hydronic heating systems and relative compactness (roughly one-third the volume of pebble beds).

Liquid System Thermal Storage

For units large enough for commercial liquid systems, the following factors should be considered:

- Pressurized versus unpressurized storage
- External versus internal heat exchanger
- Single versus multiple tanks
- Steel versus nonmetallic tank(s)
- Type of service [i.e., service hot water (SHW), building space heating (BSH), or a combination of the two]
- Location, space, and accessibility constraints imposed by architectural limitations
- Interconnect constraints imposed by existing mechanical systems
- Limitations imposed by equipment availability

The following sections present examples of the more common configurations.

Pressurized Storage. Defined here as storage that is open to the city water supply, pressurized storage is preferred for small service water heating systems because it is convenient and provides an economical way of meeting ASME *Boiler and Pressure Vessel Code* requirements with off-the-shelf equipment. Typical storage size is about 1 to 2 gal per square foot of collector area. The largest off-the-shelf water heater is 120 gal; however, no more than three or four of these should be connected in parallel. Hence, the largest storage that can be considered with off-the-shelf water heater tanks is about 360 to 480 gal, and must be compared to a single tank with the additional labor and material to connect them, plus the amount of floor space required. For larger solar hot-water and combined systems, the following concerns are important when selecting storage:

- Higher cost per unit volume of ASME rated tanks in sizes greater than 120 gal
- Handling difficulties because of large weight
- Accessibility to locations suitable for storage
- Interfacing with existing SHW and BSH systems
- Corrosion protection for steel tanks

The choice of pressurized storage for medium-sized systems is based on the availability of suitable low-cost tanks near the site. Identifying a suitable supplier of low-cost tanks can extend the advantages of pressurized storage to larger SHW installations.

Storage pressurized at city water supply pressure is not practical for building space heating, except for small applications such as residences, apartments, and small commercial buildings.

With pressurized storage, the heat exchanger is always located on the collector side of the tank. Either the internal or external heat exchanger configuration can be used. Figure 16 illustrates the three principal types of internal heat exchanger concepts: an immersed coil, a wraparound jacket, and a tube bundle. Small tanks (less than 120 gal) are available with either of the first two heat exchangers already installed. For larger tanks, a large assortment of tube bundle heat exchangers are available that can be incorporated into the tank design by the manufacturer.

Sometimes, more than one tank is needed to meet design requirements. Additional tanks offer the following benefits:

- Added storage volume
- Increased heat exchanger surface
- Reduced pressure drop in the collection loop
- Increased stratification for larger volumes

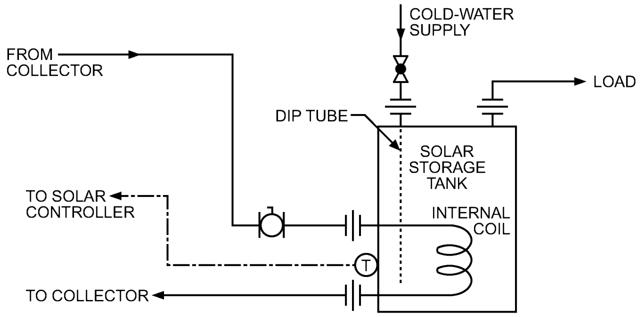
Figure 17 illustrates the multiple-tank configuration for pressurized storage. The exchangers are connected in reverse-return fashion to minimize flow imbalance. A third tank may be added. Additional tanks have the following disadvantages compared to a single tank of the same volume:

- Higher installation costs
- Greater space requirements
- Higher heat losses (reduced performance)

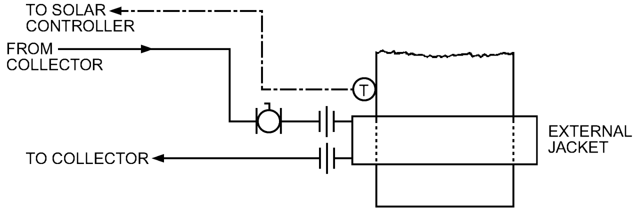
An external heat exchanger provides greater flexibility because the tank and heat exchanger can be selected independently of each other (Figure 18). Flexibility is not achieved without cost, however, because an additional pump, with its parasitic energy consumption, is required.

When selecting an external heat exchanger for a system protected by a nonfreezing liquid, the following factors related to startup after at least one night in extremely cold conditions should be considered:

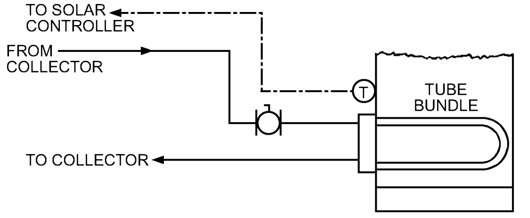
- Freeze-up of the water side of the heat exchanger
- Performance loss due to extraction of heat from storage



A. IMMERSED-COIL HEAT EXCHANGER



B. WRAPAROUND HEAT EXCHANGER



C. TUBE BUNDLE HEAT EXCHANGER

Fig. 16 Pressurized Storage with Internal Heat Exchanger

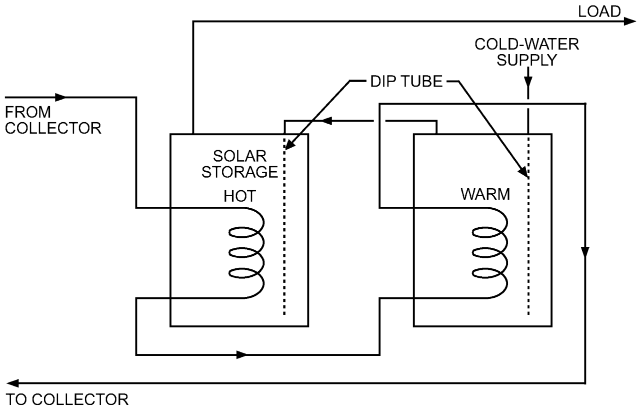


Fig. 17 Multiple Storage Tank Arrangement with Internal Heat Exchangers

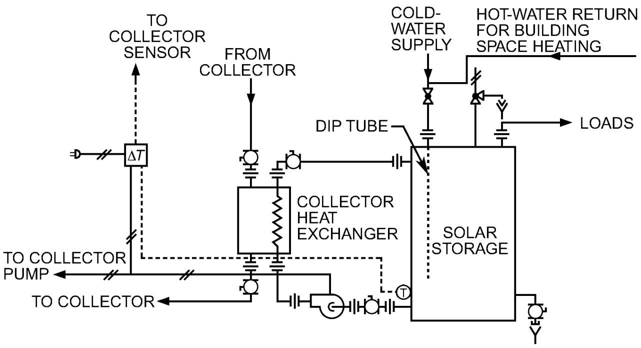


Fig. 18 Pressurized Storage System with External Heat Exchanger

For small systems, an internal heat exchanger/tank arrangement prevents the water side of the heat exchanger from freezing. However, the energy required to maintain the water above freezing must be extracted from storage, thereby decreasing overall performance. With the external heat exchanger/tank combination, a bypass can be arranged to divert cold fluid around the heat exchanger until it has been heated to an acceptable level, such as 80°F. When the heat transfer fluid has warmed to this level, it can enter the heat exchanger without causing freezing or extraction of heat from storage. If necessary, this arrangement can also be used with internal heat exchangers to improve performance.

Unpressurized Storage. For systems greater than about 1000 ft^3 (1500 gal storage volume minimum), unpressurized storage is usually more cost-effective than pressurized. As used in this chapter, the term *unpressurized* means tanks at or below the pressure expected in an unvented drainback loop.

Unpressurized storage for water and space heating implies a heat exchanger on the load side of the tank to isolate the high-pressure (potable water) loop from the low-pressure collector loop. Figure 19 illustrates unpressurized storage with an external heat exchanger. In this configuration, heat is extracted from the top of the solar storage tank, and cooled water is returned to the bottom. On the load side of the heat exchanger, water to be heated flows from the bottom of the backup storage tank, and heated water returns to the top. The heat exchanger may have a double wall to protect a potable water supply. A differential temperature controller controls the two pumps on either side of the heat exchanger. When small pumps are used, both may be controlled by the same controller without overloading it.

The external heat exchanger shown in Figure 19 provides good system flexibility and freedom in component selection. In some cases, system cost and parasitic power consumption may be reduced by an internal heat exchanger. Some field-fabricated heat exchangers use coiled soft copper tube. For larger systems, where custom fabrication is more feasible, a specified heat exchanger can be installed at the top of the tanks.

Storage Tank Construction

Steel. For most liquid solar energy systems, steel is the preferred material for storage tank construction. Steel tanks are relatively easy to fabricate to ASME *Pressure Vessel Code* requirements, readily available, and easily attached by pipes and fittings.

Steel tanks used for pressures of 30 psi and above must be ASME rated. Because water main pressure is usually above this level, open systems must use ASME code tanks. These pressure-rated storage tanks are more expensive than nonpressurized types. Costs can usually be significantly reduced if a nonpressurized tank can be used.

Steel tanks are subject to corrosion, however. Because corrosion rates increase with temperature, the designer must be particularly aware of corrosion protection methods for solar energy applications. A steel tank must be protected against (1) electrochemical corrosion, (2) oxidation (rusting), and (3) galvanic corrosion (ANL 1979b).

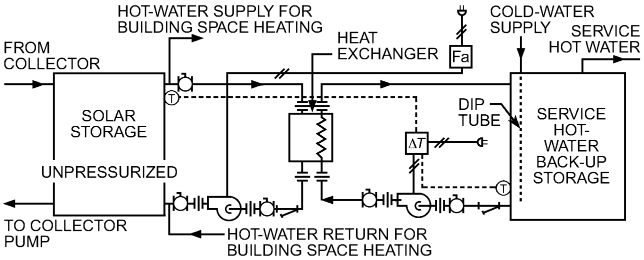


Fig. 19 Unpressurized Storage System with External Heat Exchanger

The pH of the liquid and the electric potential of the metal are the primary governing factors of electrochemical corrosion. A sacrificial anode fabricated from a metal more reactive than steel can provide protection. Magnesium is recommended for solar applications. Because protection ends when the anode has dissolved, the anode must be inspected annually.

Oxygen can enter the tank through air dissolved in the water entering the tank or through an air vent. In pressurized storage, oxygen is continually replenished by the incoming water. Besides causing rust, oxygen catalyzes other types of corrosion. Unpressurized storage systems are less susceptible to corrosion caused by oxygen because they can be designed as unvented systems, so corrosion is limited to the small amount of oxygen contained in the initial fill water.

Coatings on the tank interior protect it from oxidation. The following are some of the most commonly used coatings:

- **Phenolic epoxy** should be applied in four coats.
- **Baked-on epoxy** is preferred over painted-on epoxy.
- **Glass lining** offers more protection than the epoxies and can be used under severe water conditions.
- **Hydraulic stone** provides the best protection against corrosion and increases the tank's heat retention capabilities. Its weight may cause handling problems in some installations.

The coating should either be flexible enough to withstand extreme thermal cycling or have the same coefficient of expansion as the steel tank. In the United States, all linings used for potable water tanks should be approved by the Food and Drug Administration (FDA) for the maximum temperature expected in the tank.

Dissimilar materials in an electrolyte (water) are in electrical contact with each other and corrode by galvanic action. Copper fittings screwed into a steel tank corrode the steel, for example. Galvanic corrosion can be minimized by using dielectric bushings to connect pipes to tanks.

Plastic. Fiberglass-reinforced plastic (FRP) tanks offer the advantages of low weight, high corrosion resistance, and low cost. Premium-quality resins permit operating temperatures as high as 210°F, well above the temperature imposed by flat-plate solar collectors. Before delivery of an FRP tank is accepted, the tank should be inspected for damage that may have occurred during shipment. The gel coat on the inside must be intact, and no glass fibers should be exposed.

Concrete. Concrete vessels lined with a waterproofing membrane may also be used (in vented systems only) to contain a liquid thermal storage medium. Concrete storage tanks are inexpensive, and can be shaped to fit almost any retrofit application. Also, they have excellent resistance to the loading that occurs when they are placed in a below-grade location. Concrete tanks must have smooth corners and edges.

Concrete storage vessels have some disadvantages. Seepage often occurs unless a proper waterproofing surface is applied. Waterproofing paints are generally unsatisfactory because the concrete often cracks after settling. Other problems may occur because of poor workmanship, poor location, or poor design. Usually, tanks should stand alone and not be integrated with a building or other structure. Careful attention should be given to expansion joints and seams because they are particularly difficult to seal. Sealing at pipe taps can be a problem. Penetrations should be above liquid level, if possible.

Finally, concrete tanks are heavy and may be more difficult to support in a proper location. Their weight may make insulating the tank bottom more expensive and difficult.

Storage Tank Insulation

Heat loss from storage tanks and appurtenances is one of the major causes of poor system performance. The average R-value of storage tanks in solar applications is about half the insulation design value because of poorly insulated supports. Different standards recommend various design criteria for tank insulation. The Sheet Metal and Air Conditioning Contractors National Association (SMACNA) recommendation of a 2% loss in 12 h is generally accepted because it is more stringent than other standards. The following equation can be used to calculate the insulation R-value for this requirement:

$$\frac{1}{R} = \frac{fQ}{A\theta}\,\frac{1}{(t_{avg} - t_a)} \qquad (9)$$

where

R = thermal resistivity of insulation, ft²·h·°F/Btu
f = specified fraction of stored energy that can be lost in time θ
Q = stored energy, Btu
A = exposed surface area of storage unit, ft²
θ = given time period, h
t_{avg} = average temperature in storage unit, °F
t_a = ambient temperature surrounding storage unit during heating season, °F

The insulation factor $fQ/A\theta$ is found from Table 3 for various tank shapes (ANL 1980).

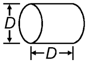
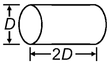
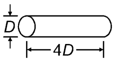
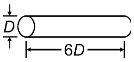
Most solar water-heating systems use large steel pressure vessels, which are usually shipped uninsulated. Materials suitable for field insulation include fiberglass, rigid foam, and flexible foam blankets. Fiberglass is easy to transport and make fire-retardant, but it requires significant labor to apply and seal.

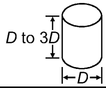
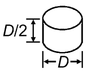
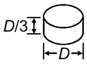
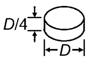
Another widely used insulation consists of rigid sheets of polyisocyanurate foam cut and taped around the tank. Material that is 3 to 4 in. thick can provide R-20 to R-30 insulation value. Rigid foam insulation is sprayed directly onto the tank from a foaming truck or in a shop. It bonds well to the tank surface (no air space between tank and insulation) and insulates better than an equivalent thickness of fiberglass. When most foams are exposed to flames, they ignite and/or produce toxic gases. When located in or adjacent to a living space, they often must be protected by a fire barrier and/or sprinkler system.

Some tank manufacturers and suppliers offer custom tank jackets of flexible foam with zipper-like connections that provide quick installation and neat appearance. Some of the fire considerations for rigid foam apply to these foam blankets.

The tank supports are a major source of heat loss. To provide suitable load-bearing capability, the supports must be in direct contact with the tank wall or attached to it. Thermal breaks must be provided between the supports and the tank (Figure 20). If insulating the tank from the support is impractical, the external surface of the supports must be insulated, and the supports must be placed on insulative material capable of supporting the compressive load. Wood, foam glass, and closed-cell foam can be used, depending on the compressive load.

Table 3 Insulation Factor $fQ/A\theta$ for Cylindrical Water Tanks

Size, gal	Horizontal Tank Insulation Factor, Btu/h·ft²			
	 D, D	 D, 2D	 D, 4D	 D, 6D
250	3.63	3.46	3.05	2.77
500	4.57	4.36	4.84	3.49
750	5.24	4.99	4.40	3.99
1000	5.76	5.49	4.84	4.39
1500	6.60	6.28	5.54	5.03
2000	7.26	6.92	6.10	5.53
3000	8.31	7.92	6.98	6.33
4000	9.15	8.71	7.68	6.97
5000	9.86	9.39	8.28	7.51

Size, gal	Vertical Tank Insulation Factor, Btu/h·ft²			
	 D to 3D, D	 D/2, D	 D/3, D	 D/4, D
80	2.10	1.88	2.15	1.97
120	2.39	2.15	2.46	2.26
250	3.07	2.74	2.46	2.88
500	3.87	3.46	3.96	3.63
750	4.43	3.96	4.53	4.16
1000	4.87	4.36	4.99	4.57
1500	5.58	4.99	5.71	5.24
2000	6.13	5.49	6.28	5.76
3000	7.03	6.28	7.19	6.60
4000	7.73	6.92	7.92	7.26
5000	8.33	7.45	8.53	7.82

Stratification and Short Circuiting

Because hot water rises and cold water sinks in a vessel, the pipe to the collector inlet should always be connected to the bottom of the tank. The collector then operates at its best efficiency because it is always at the lowest possible temperature. The return from the collector should always run near the bottom of the tank to encourage stratification and avoid introducing cooler fluid to the top of the tank after a draw occurs. Similarly, the load should be extracted from the top of the tank, and cold makeup water should be introduced at the bottom. Because of increased static pressure, vertical storage tanks enhance stratification better than horizontal tanks.

If a system has a rapid tank turnover or if the buffer tank of the system is closely matched to the load, thermal stratification does not offer any advantages. However, in most solar energy systems, thermal stratification increases performance because temperature differences are relatively small. Thus, any enhancement of temperature differentials improves heat transfer efficiency.

Thermal stratification can be enhanced by the following:

- Using a tall vertical tank
- Situating the inlet and outlet piping of a horizontal tank to minimize vertical fluid mixing
- Sizing the inlets and outlets such that exhaust flow velocity is less than 2 fps
- Using flow diffusers (Figure 21)
- Plumbing multiple tanks in series

Multiple tanks generally yield the greatest temperature difference between cold water inlet and hot water outlet. With the piping/tank configuration shown in Figure 17, the difference can approach 30°F. In addition to the cost of the second tank, the cost of extra footings, insulation, and sensors must be considered. However, multiple tanks may save labor at the site because of their small diameter and shorter length. Smaller tanks require less demolition to install in retrofit (e.g., access through doorways, hallways, and windows).

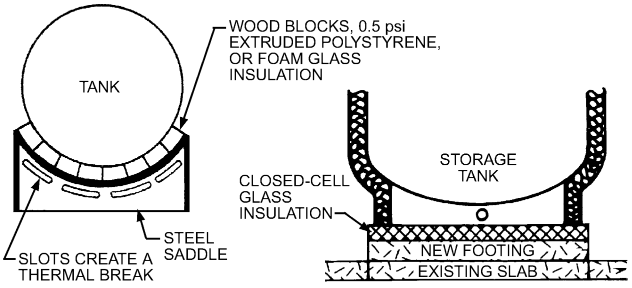


Fig. 20 Typical Tank Support Detail

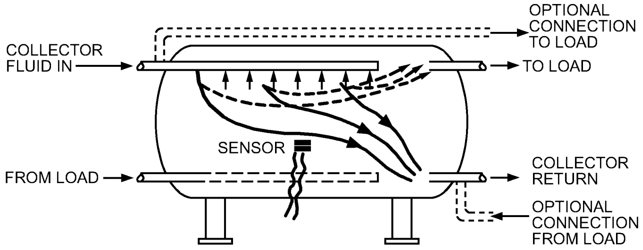


Fig. 21 Tank Plumbing Arrangements to Minimize Short Circuiting and Mixing
(Adapted from Kreider 1982)

Additional information on stratification and thermal storage may be found in Chapter 34 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Storage Sizing

The following specific site factors are related to system performance or cost.

Solar Fraction. Most solar energy systems are designed to produce anywhere from 50 to 90% of the energy required to satisfy the load. If a system is sized to produce less than this, there must be greater coincidence between load and available solar energy. Therefore, smaller, lower-cost storage can be used with low-solar-fraction systems without impairing system performance.

Load Matching. The load profile of a commercial application may be such that less storage can be used without incurring performance penalties. For example, a company cafeteria or a restaurant serving large luncheon crowds has its greatest hot-water usage during, and just after, midday. Because the load coincides with the availability of solar radiation, less storage is required for carryover. For loads that peak during the morning, collectors can be rotated toward the southeast (in the northern hemisphere), sometimes improving output for a given array.

Storage Cost. If a solar storage tank is insulated adequately, performance generally improves with increased storage volume, but the savings must justify the investment. The cost of storage can be minimized by using multiple low-cost water heaters and unpressurized storage tanks made from materials such as fiberglass or concrete.

The performance and cost relationships between solar availability, collector design, storage design, and load are highly interactive. Furthermore, the designer should maximize the benefits from investment for at least one year, rather than for one or two months. For this reason, solar energy system performance models combined with economic analyses should optimize storage size for a specific site. Models that can determine system performance include *f*-Chart, SOLCOST, RETSCREEN and TRNSYS. The *f*-Chart (Beckman et al. 1977) model is readily available either in worksheet form for hand calculations or as a computer program; however, it contains a built-in daily hot-water load profile of three equal draws specifically for residential applications. Studies have shown that the daily hot-water profile may affect system performance by up to 20% more if the load is heavier in the evening and 20% less if the load occurs in the morning.

For daily profiles with extreme deviations from the residential profile, such as the company cafeteria example used previously, *f*-Chart may not provide satisfactory results. SOLCOST (DOE 1978) can accommodate user-selected daily profiles, but it is not widely available. Neither program can accommodate special days (e.g., holidays and weekends) when no service hot-water loads are present. TRNSYS (Klein et al. 2000), which has been modified for operation on personal computers, is readily available and well supported. It is time-consuming to set up and run for the first time, but after it is set up, various design parameters, such as collector area and storage size, can be easily evaluated for a given system configuration.

Many hydronic solar energy systems are used with a series-coupled heat pump or an absorption air-conditioning system. In the case of a heat pump, lower storage temperatures, which create higher collector efficiencies, are desirable. In this case, the collector size may be greater than recommended for conventional SHW or hydronic building space heating (BSH) systems. In contrast, absorption air conditioners require much higher temperatures (>175°F) than BSH or hydronic BSH systems to activate the generator. Therefore, the storage-to-collector ratio can be much less than recommended for BSH. For absorption air conditioning, thermal energy storage may act as a buffer between the collector and generator, which prevents cycling caused by frequent changes in insolation level.

HEAT EXCHANGERS

Requirements

The heat exchanger transfers heat from one fluid to another. In closed solar energy systems, it also isolates circuits operating at different pressures and separates fluids that must not be mixed. Heat exchangers are used in solar applications to separate the heat transfer fluid in the collector loop from the domestic water supply in the storage tank (pressurized storage) or the domestic water supply from the storage (unpressurized storage). Heat exchangers for solar applications may be placed either inside or outside the storage or drainback tank.

Selecting a heat exchanger involves the following considerations:

Performance. Heat exchangers always degrade the performance of a solar system; therefore, selecting an adequate size is important. When in doubt, an oversized heat exchanger should be selected.

Guaranteed separation of fluids. Many code authorities require a vented, double-wall heat exchanger to ensure fluid isolation. System protection requirements may also dictate the need for guaranteed fluid separation.

Thermal expansion. The temperature in a heat exchanger may vary from below freezing to the boiling temperature of water. The design must withstand these thermal cycles without failing.

Materials. Galvanic corrosion is always a concern in liquid solar energy systems. Consequently, the piping, collectors, and other hydronic component materials must be compatible.

Space constraints. Often, limited space is available for mounting and servicing the heat exchanger. Physical size and configuration must be considered when selection is made.

Serviceability. The water side of a heat exchanger is exposed to the scaling effects of dissolved minerals, so design must provide access for cleaning and scale removal.

Pressure loss. Energy consumed in pumping fluids reduces system performance. Pressure drop through the heat exchanger should be limited to 1 to 2 psi to minimize energy consumption.

Pressure capability. Because the heat exchanger is exposed to cold-water supply pressure, it should be rated for pressures above 75 psig.

Internal Heat Exchanger

The internal heat exchanger can be a coil inside the tank or a jacket wrapped around the pressure vessel (see Figure 16). Several manufacturers supply tanks with either type of internal heat exchanger. However, the maximum size of pressurized tanks with internal heat exchangers is usually about 120 gal. Heat exchangers may be installed with relative ease inside nonpressurized tanks that open from the top. Figures 22 and 23 illustrate methods of achieving double-wall protection with either type of internal heat exchanger.

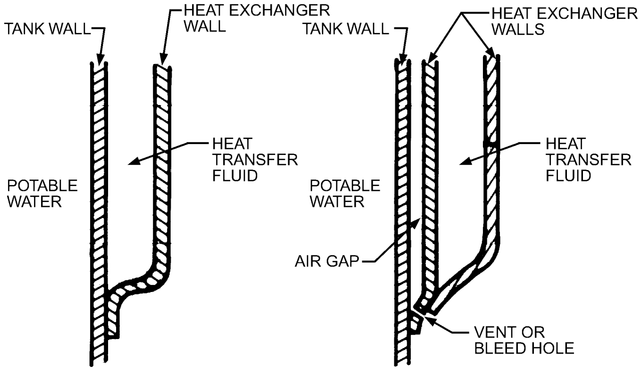


Fig. 22 Cross Section of Wraparound Shell Heat Exchangers

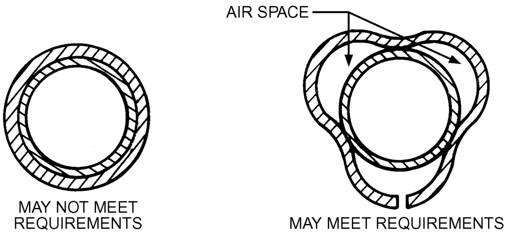


Fig. 23 Double-Wall Tubing

For installations with larger tanks or heat exchangers, a tube bundle is required. However, it is not always possible to find a heat exchanger of the desired area that will fit within the tank. Consequently, a horizontal tank with the tube bundle inserted from the tank end can be used. A second option is to place a shroud around the tube bundle and to pump fluid around it (Figure 24). Such an approach combines the performance of an external heat exchanger with the compactness of an internal heat exchanger. Unfortunately, this approach causes tank mixing and loss of stratification.

External Heat Exchanger

The external heat exchanger offers a greater degree of design flexibility than the internal heat exchanger because it is detached from the tank. For this reason, it is preferred for most commercial applications. Shell-and-tube, tube-and-tube, and plate-and-frame heat exchangers are used in solar applications. Shell-and-tube heat exchangers are found in many solar designs because they are economical, easy to obtain, and constructed with suitable material. One limitation of the shell-and-tube heat exchanger is that it normally does not have double-wall protection, which is often required for potable-water-heating applications. A number of manufacturers produce tube-and-tube heat exchangers that offer high performance and the double-wall safety required by many code authorities, but they are usually limited in size. The plate-and-frame heat exchanger is more cost-effective for large potable-water applications where positive separation of heat transfer fluids is required. These heat exchangers are compact and offer excellent heat transfer performance.

Shell-and-Tube. Shell-and-tube heat exchangers accommodate large heat exchanger areas in a compact volume. The number of shell-side and tube-side passes (i.e., the number of times the fluid changes direction from one end of the heat exchanger to the other) is a major variable in shell-and-tube heat exchanger selection. Because the exchanger must compensate for thermal expansion, flow in and out of the tube side are generally at the same end of the exchanger. Therefore, the number of tube-side passes is even. By appropriate baffling, two, four, or more tube passes may be created. However, as the number of passes increases, the path length grows, resulting in greater pressure drop of the tube-side fluid. Unfortunately, double-wall shell-and-tube heat exchangers are hard to find.

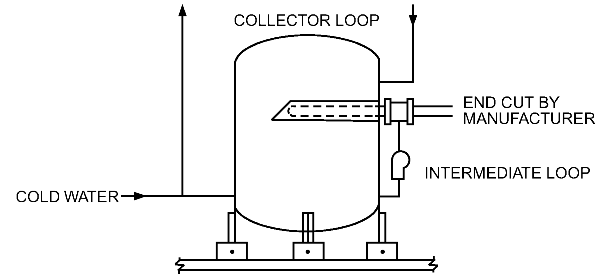


Fig. 24 Tube Bundle Heat Exchanger with Intermediate Loop

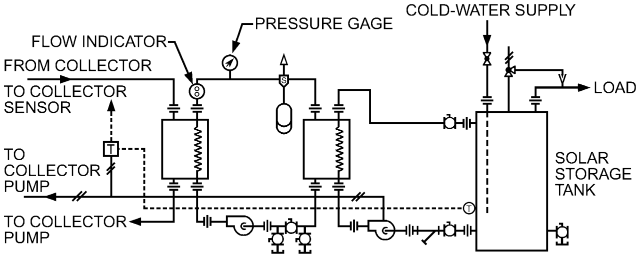


Fig. 25 Double-Wall Protection Using Two Heat Exchangers in Series

Tube-and-Tube. Fluids in the tube-and-tube heat exchanger run counterflow, which gives closer approach temperatures. The exchanger is also compact and only limited by system size. Several may be piped in parallel for higher flow, or in series to provide approach temperatures as close as 15°F. Many manufacturers offer the tube-and-tube with double-wall protection.

The counterflow configuration operates at high efficiency. For two heat exchangers in series, effectiveness may reach 0.80. For single heat exchangers or multiple ones in parallel, effectiveness may reach 0.67. Tube-and-tube heat exchangers are cost-effective for smaller residential systems.

Plate-and-Frame. These heat exchangers are suitable for pressures up to 300 psig and temperatures to 400°F. They are economically attractive when a high-quality, heavy-duty construction material is required or if a double-wall heat exchanger is needed for leak protection. Typical applications include food industries or domestic water heating when any possibility of product contamination must be eliminated. This exchanger also gives added protection to the collector loop.

Contamination is not possible when an intermediate loop is used (Figure 25) and the integrity of the plates is maintained. A colored fluid in the intermediate loop gives a visual means of detecting a leak through changes in color. The sealing mechanism of the plate-and-frame heat exchanger prevents cross-contamination of heat transfer fluids. Plate-and-frame heat exchangers cost the same as or less than equivalent shell-and-tube heat exchangers constructed of stainless steel.

Heat Exchanger Performance

Solar collectors perform less efficiently at high fluid inlet temperatures. Heat exchangers require a temperature difference between the two streams to transfer heat. The smaller the heat transfer surface area, the greater the temperature difference must be to transfer the same amount of heat and the higher the collector inlet temperature must be for a given tank temperature. As the solar collector is forced to operate at the progressively higher temperature associated with a smaller heat exchanger, its efficiency is reduced.

In addition to size and surface area, the heat exchanger's configuration is important for achieving maximum performance. The performance of a heat exchanger is characterized by its effectiveness (a type of efficiency), which is defined as follows:

$$E = \frac{q}{(\dot{m}c_p)_{min}(t_{hi} - t_{ci})} \qquad (10)$$

where

E = effectiveness
q = heat transfer rate, Btu/h
$\dot{m}c_p$ = minimum mass flow rate times fluid specific heat, Btu/h·°F
t_{hi} = hot (collector-loop) stream inlet temperature, °F
t_{ci} = cold (storage) stream inlet temperature, °F

For heat exchangers located in the collector loop, minimum flow usually occurs on the collector side rather than the tank side.

The effectiveness E is the ratio between the heat actually transferred and the maximum heat that could be transferred for given flow and fluid inlet temperature conditions. E is relatively insensitive to temperature, but it is a strong function of heat exchanger design.

A designer must decide what heat exchanger effectiveness is required for the specific application. A method that incorporates heat exchanger performance into a collector efficiency equation [Equation (5)] uses storage tank temperature t_s as the collector inlet temperature with an adjusted heat removal factor F_R. Equation (11) relates F_R and heat exchanger effectiveness:

$$\frac{F_R'}{F_R} = \frac{1}{1 + (F_R U_L/\dot{m}c_p)[A\dot{m}c_p/E(\dot{m}c_p)_{min} - 1]} \qquad (11)$$

The heat exchanger effectiveness must be converted into heat transfer surface area. SERI (1981) provides details of shell-and-tube heat exchangers and heat transfer fluids.

For more information on heat exchangers, see Chapter 47.

CONTROLS

The brain of an active solar energy system is the automatic temperature control. Numerous studies and reports of operational systems show that faulty controls, usually the sensors, are often the cause of poor performance. Reliable controllers are available, and with a full understanding of each system function, proper control systems can be designed. In general, control systems should be simple; additional controls are not a good solution to a problem that can be solved by better mechanical design. The following key considerations pertain to control system design:

- Collector sensor location/selection
- Storage sensor location
- Overtemperature sensor location
- On/off controller characteristics
- Selection of reliable solid-state devices, sensors, controllers, etc.
- Control panel location in heated space
- Connection of controller according to manufacturer's instructions
- Design of control system for all possible system operating modes, including heat collection, heat rejection, power outage, freeze protection, auxiliary heating, etc.
- Selection of alarm indicators for pump failure, low and high temperatures, loss of pressure, controller failure, nighttime operation, etc.

The following control categories should be considered when designing automatic controls for solar energy systems:

- Collection to storage
- Storage to load
- Auxiliary energy to load
- Alarms
- Miscellaneous (e.g., for heat rejection, freeze protection, draining, and overtemperature protection)

Types of controllers include snap switches, timers, photovoltaic (PV) modules, and differential temperature controllers. The latter is the most common, with PV popular for residential systems.

Differential Temperature Controllers

Most controls used in solar energy systems are similar to those for HVAC systems. The major exception is the differential temperature controller (DTC), which is the basis of solar energy system control. The DTC is a comparing controller with at least two temperature sensors that controls one or several devices. Typically, the sensors are located at the solar collectors and storage tank (Figure 26). On unpressurized systems, other DTCs may control the extraction of heat from the storage tank.

The DTC monitors the temperature difference, and when the temperature of the panel exceeds that of the storage by the predetermined amount (generally 8 to 20°F), the DTC switches on the actuating devices. When the temperature of the panel drops to 3 to 10°F above the storage temperature, the DTC, either directly or indirectly, stops the pump. Indirect control through a control relay may operate one or more pumps and possibly perform other control functions, such as the actuation of control valves.

The manufacturer's predetermined set point of the DTC may be adjustable or fixed. If the controller set point is a fixed temperature differential, the controller selected should correspond to the requirements of the system. An adjustable differential set point makes the controller more flexible and allows it to be adjusted to the specific system. The optimum *off* temperature differential should be the minimum possible; the minimum depends on whether there is a heat exchanger between the collectors and storage.

If the system requires a heat exchanger, the energy transferred between two fluids raises the differential temperature set point. The minimum, or *off*, temperature differential is the point at which pumping the energy costs as much as the value of the energy being pumped. For systems with heat exchangers, the *off* set point is generally between 5 and 10°F. If the system does not have a heat exchanger, a range of 3 to 6°F is acceptable for the *off* set point. The heat lost in piping and the power required to operate the pump should also be considered.

The optimum differential *on* set point is difficult to calculate because of the changing variables and conditions. Typically, the *on* set point is 10 to 15°F above the *off* set point. The optimum *on* set point is a balance between optimum energy collection and avoiding short-cycling the pump. ASHRAE's *Active Solar Heating System Design Manual* (1988) describes techniques for minimizing short cycling.

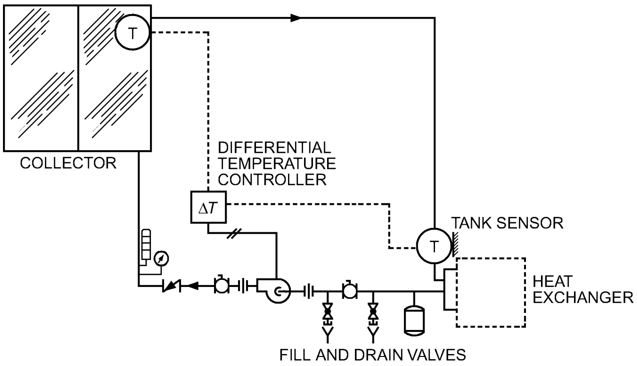


Fig. 26 Basic Nonfreezing Collector Loop for Building Service Hot Water Heating—Nonglycol Heat Transfer Fluid

Photovoltaically Powered Pumps

The ability to drive a pump in direct proportion to the available irradiance without an external electric power makes PV pumps very popular in residential applications. The lack of larger DC motors with low turning amp draws inhibits their adoption in commercial solar systems. Advantages of using PV pumps include an increase in day-long energy production and the security of having power during power outages. Disadvantages include higher first cost and the need for more frequent maintenance.

Overtemperature Protection

Overheating may occur during periods of high insolation and low load; thus, all portions of the solar energy system require protection against overheating. Liquid expansion or excessive pressure may burst piping or storage tanks, and steam or other gases within a system may restrict liquid flow, making the system inoperable. Glycols break down and become corrosive if subjected to temperatures greater than 240°F. The system can be protected from overheating by (1) stopping circulation in the collection loop until storage temperature decreases, (2) discharging overheated water from the system and replacing it with cold makeup water, or (3) using a heat exchanger coil as a means of heat rejection to ambient air.

The following questions should be answered to determine whether overtemperature protection is necessary.

- Is the load ever expected to be off, such that the solar input will be much higher than the load? The designer must determine possibilities based on the owner's needs and a computer analysis of system performance.
- Do individual components, pumps, valves, circulating fluids, piping, tanks, and liners need protection? The designer must examine all components and base the overtemperature protection set point on the component that has the lowest specified maximum operating temperature. This may be a valve or pump with a 180 to 300°F maximum operating temperature. Sometimes, this criterion may be met by selecting components capable of operating at higher temperatures.
- Is steam formation or discharging boiling water at the tap possible? If the system has no mixing valve that mixes cold water with the solar-heated water before it enters the tap, the water must be maintained below boiling temperature. Otherwise, the water will flash to steam as it exits the tap and, most likely, scald the user. Some city codes require a mixing valve to be placed in the system for safety.

Differential temperature controllers are available that sense overtemperature. Depending on the controller used, the sensor may be mounted at the bottom or the top of the storage tank. If it is mounted at the bottom, the collector-to-storage differential temperature sensor can be used to sense overtemperature. Input to a DTC mounted at the top of the tank is independent of the bottom-mounted sensor, and the sensor monitors the true high temperature.

The normal action taken when the DTC senses an overtemperature is to turn off the pump to stop heat collection. After the panels in a drainback system are drained, they attain stagnation temperatures. Although drainback is not desirable, the panels used for these systems should be designed and tested to withstand overtemperature. In addition, drainback panels should withstand the thermal shock of start-up when relatively cool water enters the panels while they are at stagnation temperatures. The temperature difference can range from 75 to 300°F. Such a difference could warp panels made with two or more materials of different thermal expansion coefficients. If the solar panels cannot withstand the thermal shock, an interlock should be incorporated into the control logic to prevent this situation. One method uses a high-temperature sensor mounted on the collector absorber that prevents the pump from operating until the collector temperature drops below the sensor set point.

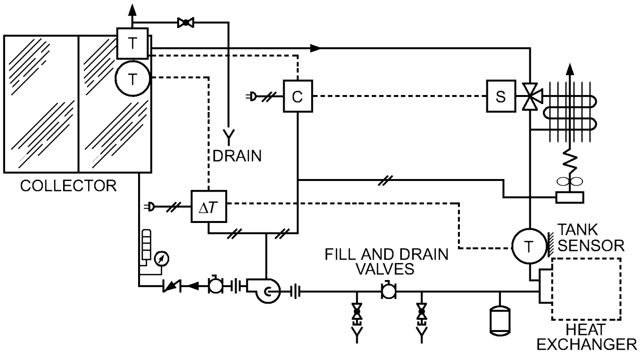


Fig. 27 Heat Rejection from Nonfreezing System Using Liquid-to-Air Heat Exchanger

If circulation stops in a closed-loop antifreeze system that has a heat exchanger, high stagnation temperatures will occur. These temperatures could break down the glycol heat transfer fluid. To prevent damage or injury caused by excessive pressure, a pressure-relief valve must be installed in the loop, and a means of rejecting heat from the collector loop must be provided. The section on Hot Water Dump describes a common way to relieve pressure. Pressure increases because of thermal expansion of any fluid; when water-based absorber fluids are used, pressure builds from boiling.

The pressure-relief valve should be set to relieve at or below the maximum operating pressure of any component in the closed-loop system. Typical settings are around 50 psig, corresponding to a temperature of approximately 300°F. However, these settings should be checked. When the pressure-relief valve does open, it discharges expensive antifreeze solution. Glycol antifreeze solutions damage many types of roof membranes. The discharge can be piped to large containers to save the antifreeze, but this design can create dangerous conditions because of the high pressures and temperatures involved.

If a collector loop containing glycol stagnates, chemical decomposition raises the liquid's fusion point, and freezing becomes possible. An alternative method continues fluid circulation but diverts flow from storage to a heat exchanger that dumps heat to the ambient air or other sink (Figure 27). This wastes energy, but protects the system. A sensor on the solar collector absorber plate that turns on the heat rejection equipment can provide control. The temperature sensor set point is usually 200 to 250°F and depends on the system components. When the sensor reaches the high-temperature set point, it turns on pumps, fans, alarms, or whatever is necessary to reject the heat and warn of the overtemperature. The dump continues to operate until the overtemperature control in the collector loop DTC senses an acceptable drop in tank temperature and is reset to its normal state.

Hot-Water Dump

If water temperatures above 200°F are allowed, the standard temperature-pressure (210°F, 150 psig) safety relief valve may operate occasionally. If these temperatures are reached, the valve opens, and some of the hot water vents out. However, these valves are designed for safety purposes, and after a few openings, they leak hot water. Thus, they should not be relied on as the only control device. An aquastat that controls a solenoid, pneumatic, or electrically actuated valve should be used instead.

Heat Exchanger Freeze Protection

The following factors should be considered when selecting an external heat exchanger for a system protected by a nonfreezing fluid that is started after an overnight, or longer, exposure to extreme cold.

- Freeze-up of the water side of the heat exchanger
- Performance loss due to extraction of heat from storage

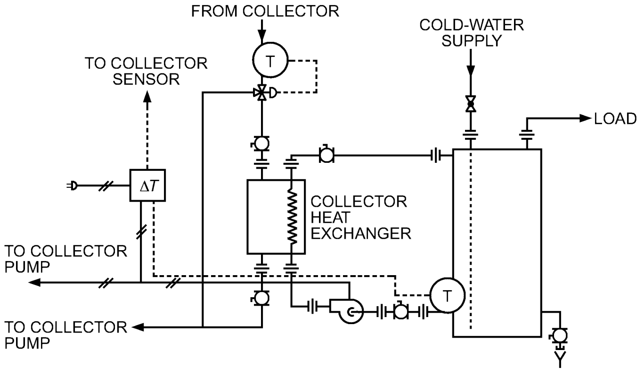


Fig. 28 Nonfreezing System with Heat Exchanger Bypass

An internal heat exchanger/tank has been placed on the water side of the heat exchanger of small systems to prevent freezing. However, the energy required to maintain the water above freezing must be extracted from storage, which decreases overall performance. With the external heat exchanger/tank combination, a bypass can be installed, as illustrated in Figure 28. The controller positions the valve to bypass the heat exchanger until the fluid in the collector loop attains a reasonable level (e.g., 80°F). When the heat transfer fluid has warmed to this level, it can enter the heat exchanger without freezing or extracting heat from storage. The arrangement in Figure 28 can also be used with an internal heat exchanger, if necessary, to improve performance.

PHOTOVOLTAIC SYSTEMS

Photovoltaic (PV) devices, or cells, convert light directly into electricity. These cells are connected in series and parallel strings and packaged into modules to produce a specific voltage and current when illuminated. PV modules can also be connected in series or in parallel into arrays to produce larger voltages or currents. PV systems rely on sunlight, have few or no moving parts, are modular to match power requirements on any scale, are reliable and long-lived, and are easily produced. Photovoltaic systems can be used independently or in conjunction with other electrical power sources.

Most early PV installations were **stand-alone** systems, (i.e., located at sites where utility power was unavailable). Some stand-alone applications powered by PV systems include communications, remote power, remote monitoring, lighting, water pumping, battery charging, and cathodic protection. These systems could include a battery bank to provide power during nighttime hours. Excess power had to be generated during the day to keep the battery bank charged through a charge controller.

More recently, **utility-interconnected** systems predominate. These systems use an inverter to produce the AC waveform to match that of the utility. If excess power is produced during the day, it is fed back to the utility. Typically, power needed at night is drawn from the utility. If utility power is lost, these systems automatically shut down to prevent backfeeding power into the lines, to protect utility personnel.

Some **hybrid** systems are utility interactive but also operate in stand-alone mode. If utility power is lost, they automatically isolate critical circuits from the utility service, and power only those circuits. They have a smaller battery bank, sized to handle just the critical loads. These systems normally keep the battery bank fully charged to use at night as back-up if utility power fails.

Fundamentals of Photovoltaics

Photovoltaic Effect. When a photon enters a PV material, the photon can be reflected, absorbed, or transmitted through. If the photon is absorbed, an electron, with its additional energy, leaves its atom. It may also jump across an established layer of junctions (within the structure of the PV cell) laid down during the manufacturing process. With many electrons jumping the junction layer, an electric charge is established between the front and back of the PV cell. Conductors placed on the front and back of the cell provide a path through which the electrons that have built up can create a current through a load from one side of the cell to the other. Without a connection to provide an electron flow, electrons build up on one side of the junction layer until their like-charge field is large enough to repel further electrons from jumping the junctions, and the number that jump over are equaled by the number that jump back and recombine with the originating atoms. This charge field represents the open-circuit voltage of the cell.

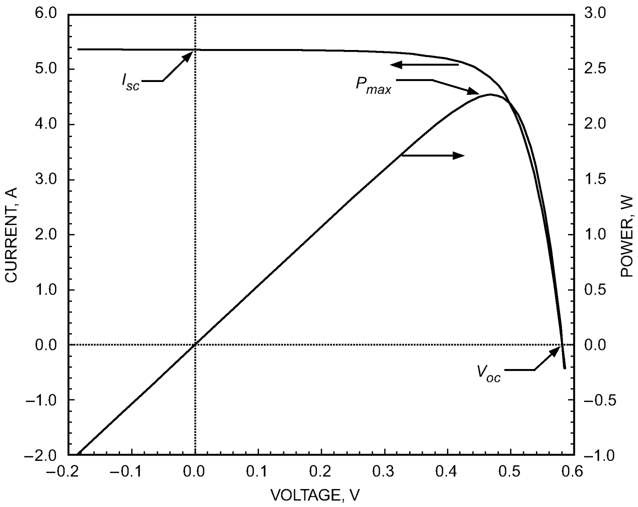


Fig. 29 Representative Current-Voltage and Power-Voltage Curves for Photovoltaic Device

Cell Design. A PV cell consists of the active PV material, metal grids, antireflection coatings, and supporting material. The complete cell is optimized to maximize both the amount of light entering the cell and the power out of the cell. The photovoltaic material can be one of a number of compounds. Metal grids enhance current collection from the front and back of the solar cell. Grid design varies among manufacturers. The antireflective coating is applied to the top of the cell to maximize the light going into the cell; typically, this coating is a single layer optimized for sunlight. As a result, PV cells range in color from black to blue. In some, the top of the cell is covered with a semitransparent conductor that functions as both the current collector and the antireflection coating. A completed PV cell is a two-terminal device with positive and negative leads, and its output is direct current.

Current-Voltage Curves. The current from a PV module depends on the external voltage applied and the amount of light on the module. When the module is short-circuited, the current is at maximum (short-circuit current I_{sc}), and the voltage across the module is zero. When the PV module circuit is open, with the leads not making a circuit, the voltage is at a maximum (open-circuit voltage V_{oc}), and the current is zero. In either case, at open or short circuit, the power (current times voltage) is zero. Between open and short circuit, the power output is greater than zero. A current-voltage curve (Figure 29) represents the range of combinations of current and voltage.

Power versus voltage can be plotted on the same graph. There exists an operating point P_{max}, I_{max}, V_{max} at which the output power is maximized. Given P_{max}, an additional parameter, fill factor FF, can be calculated such that

$$P_{max} = I_{sc} V_{oc} \mathrm{FF} \qquad (12)$$

By illuminating and loading a PV module so that the voltage equals the PV cell's V_{max}, the output power is maximized. The module can be loaded using resistive loads, electronic loads, or batteries. The typical parameters of a single-crystal solar cell are current density J_{sc} = 206 mA/in^2; V_{oc} = 0.58 V; V_{max} = 0.47 V; FF = 0.72; and P_{max} = 2273 mW.

Efficiency and Power. Efficiency is another measure of PV cells. Efficiency is the maximum electrical power output divided by the incident light power. It is commonly reported for a PV cell temperature of 77 °F and incident light at an irradiance of 92.94 W/ft^2 with a spectrum of 1.5 atmospheres equivalent spectral absorption (close to that of sunlight at solar noon).

Photovoltaic Cells and Modules

Photovoltaic Cells. In general, all PV cells perform similarly. However, the choice of the PV material can have important effects on system design and performance. Both the composition of the material and its atomic structure are influential. PV materials include silicon, gallium arsenide, copper indium diselenide, cadmium telluride, indium phosphide, and many others. The atomic structure of a PV cell can be single-crystal, polycrystalline, or amorphous (i.e., having no crystalline structure). The most commonly produced PV modules are made of crystalline silicon, either single-crystal or polycrystalline. A distinction is made in the industry between cells made with junctions embedded in the crystals, and "thin film," made by laminating layers to produce the junctions.

Because of quantum effects, electrons designated to leave their atoms in a PV cell only absorb photon energy of a certain band of wavelengths; the other light energy is not absorbed. Multijunction cells (thin-film cells with two or more layers of junctions laid on top of one another) can have higher efficiency because each junction layer can be designed to respond to different wavelengths of incoming radiation.

Module Construction. A module is a collection of PV cells that protects the cells and provides a usable operating voltage. PV cells can be fragile and susceptible to corrosion by humidity or fingerprints and can have delicate wire leads. Also, the operating voltage of a single PV cell is less than 1 V, making it unusable by itself for many applications. Depending on the manufacturer and type of PV material, modules have different appearances and performance characteristics. Also, modules may be designed for specific conditions, such as hot or marine environments.

Single-crystal and polycrystalline silicon cells are produced individually. Some amorphous silicon cells, although manufactured in large rolls, are later processed as individual cells. These cells are connected in series and parallel to produce the desired operating voltage and wattage. These strings of cells are then encapsulated with a polymer, a front glass piece, and a back material.

Cells made of amorphous silicon, cadmium telluride, or copper indium diselenide are manufactured on large rolls of material that become either the front or the back of the module. A large area of PV material is divided into smaller cells by scribing or cutting the material into electrically isolated cells. Later processing steps automatically interconnect the cells in series and parallel. Depending on the manufacturer, a front glass or a back material is glued on using polymers. Modules include a robust junction box attached to the back of the module for wiring to other modules or other electrical equipment.

Module Reliability and Durability. PV modules are reliable and durable when properly made. As with any electrical equipment, the designer must verify that the product is tested or rated for the intended application. A PV module is a large-area semiconductor with no internal moving parts. Even a concentrator module has no internal moving parts, although there are external parts that keep the module aimed at the sun.

PV modules are designed for outdoor use in harsh surroundings such as marine, tropic, arctic, and desert environments. There are many international standards that test the suitability of PV modules for outdoor use in different climates. A buyer or user should check the suitability of the module for a given climate.

Modules are also tested for electrical safety. All modules have a maximum voltage rating supplied by the manufacturer or labeled on the module. This becomes important when interconnecting several modules into an array and connecting arrays to other electrical equipment. Most modules are tested for ground isolation to prevent personal injury or property damage. To meet the *National Electrical Code*®, modules must be listed by Underwriters Laboratories (UL).

Module Performance. The performance output of a module is provided by the manufacturer and shown on a label on each module. The value provided is in watts per square meter, and represents the expected peak power point output of the module in watts at standard test conditions (STC). These conditions, established by international standard, are defined as 92.94 W/ft^2 incident irradiation at a spectrum of 1.5 atmospheres equivalent spectral absorption, with a cell surface temperature of 68°F. Modules are typically marketed and sold by this peak watt value. Designers are cautioned that the actual performance of a module may be as much as 10% below the manufacturer's listed value. Performance values independently tested at STC are available for some modules from the Florida Solar Energy Center.

The performance output is provided for new modules with only brief exposure. Modules with crystalline cells are quite stable over exposure time, but thin-film cells degrade in performance over time of exposure. Some thin-film manufacturers derate their module ratings to account for this exposure degradation; others do not. Improving the stability of thin-film modules over exposure time is an active area of research in the PV industry.

Related Equipment

Batteries. Batteries are used in some PV systems to supply power at night or when the PV system cannot meet the demand. The selection of battery type and size depends primarily on load and availability requirements. In all cases, batteries must be located in an area without extreme temperatures and with some ventilation.

Battery types include lead-acid, nickel cadmium, nickel hydride, lithium, and many others. For a PV system, the main requirement is that the batteries be capable of repeated deep discharges without damage. Starting-lighting-ignition batteries (car batteries) are not designed for this and should not be used.

Deep-cycle lead-acid batteries are commonly used. These batteries can be flooded or valve-regulated (sealed) batteries and are commercially available in a variety of sizes. Flooded, or wet, batteries require greater maintenance but can last longer with proper care. Valve-regulated batteries require less maintenance. For more capacity, batteries can be arranged in parallel.

Battery Charge Controllers. Charge controllers regulate power from the PV modules to prevent the batteries from overcharging. The controller can be a shunt or series type and can also function as a low-battery-voltage disconnect to prevent battery overdischarge. The controller is chosen for the correct capacity and desired features.

Normally, controllers allow battery voltage to determine the PV system's operating voltage. However, battery voltage may not be the optimum PV operating voltage. Some stand-alone charge controllers can optimize the operating voltage of the PV modules independently of battery voltage so that the PV operates at its maximum power point. (See the Peak Power Tracking section following.)

Inverters. An inverter is used to convert direct current (dc) into alternating current (ac) electricity. The inverter's output can be single-phase or multiphase, with a voltage of 120 V, 220 V, 440 V, etc., and a frequency of 50 or 60 Hz. Inverters are rated by total power capacity, which ranges from hundreds of watts to megawatts. Some inverters have good surge capacity for starting motors; others have limited surge capacity. The designer should specify both the type and the size of the load the inverter is intended to service.

The output waveform of the inverter, though still ac, can be square, modified square (also called modified sine wave), or sine. For some small applications, modified sine wave inverters are available. Inverters should be selected with care, because equipment that contains silicon-controlled rectifiers (SCRs) or variable-speed motors, such as some vacuum cleaners and laser printers, can be damaged by square- and modified-square-wave inverter outputs. Electric utilities supply sine wave output, and most manufacturers produce inverters with sine wave outputs that avoid unexpected equipment damage. Stand-alone inverters can supply the ac waveform independently. Utility interactive inverters synchronize the waveform frequency to another ac power supply such as the electric utility or perhaps can be matched to a portable electrical generator.

Peak Power Tracking. Peak power tracking varies the operating voltage of the PV array to optimize the current for maximum power production. Typically, the PV array output wattage is sampled and the voltage is adjusted automatically many times a second. Peak power trackers can be purchased separately or specified as an option with battery-charge controllers. Off-the-shelf inverters typically have peak power tracking circuitry built in.

Balance-of-System (BOS) Components. These components include the mounting structures and wiring, and are just as important as the other major PV system components. PV systems should be designed and installed with the intent of only minimal maintenance.

Photovoltaic modules can be mounted on the ground or on a building or can be included as part of a building. A structural engineer can design the support structures in accordance with local building codes. Wind and snow loading are a major design consideration. PV modules can last 20 or more years; the support structure and building should be designed for at least as long a lifetime.

In the United States, wire sizing, insulation, and use of fuses, circuit breakers, and other protective devices are covered by the *National Electrical Code*® (NFPA *Standard* 70).

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Related Commercial Resources