2.1 Solar collectors

2.1.1 Collector types

There are two basic types of solar collectors and these are usually classified as concentrating and non-concentrating. The latter will be discussed first because their use is far more widespread.

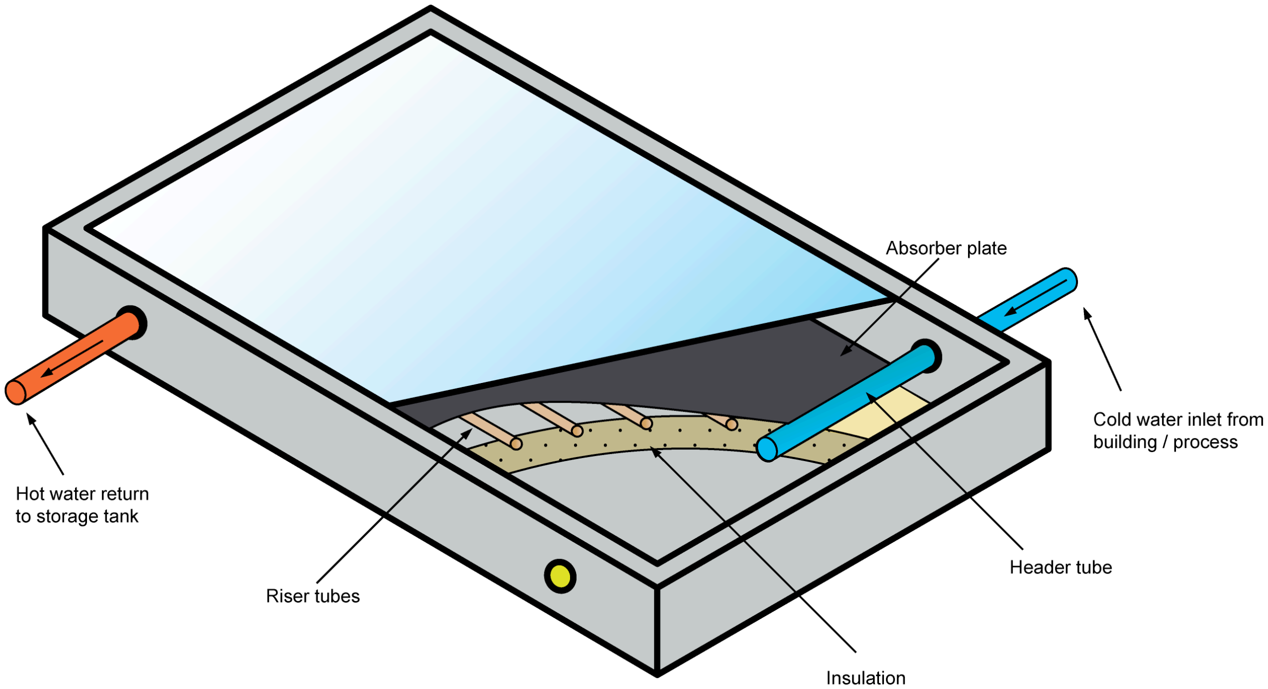
2.1.1.1 Non-concentrating collectors

There are two main types of non-concentrating collectors: flat plate and evacuated tube. In 2007, it was estimated that there were nearly 210 million square metres of solar thermal collectors in operation around the world with a capacity of nearly 147 GW_{th}. Flat plate and evacuated tube collectors provided 80% of this capacity (Weiss et al., 2009).

2.1.1.1.1 Flat plate collector

The flat plate collector is the most commonly used solar collector around the world. Although there are a number of variations possible in the design of the flat plate collector, the basic cross section is shown in Figure 2.1.

Figure 2.1: Typical cross-section through a conventional flat plate solar collector



An absorber plate, usually metal, is connected to a series of riser tubes (or pipes), which are in turn connected at the top and bottom to larger diameter pipes, called headers. The solar energy incident on the absorber plate is transferred to the fluid flowing through the riser tubes. Cool water enters at the bottom header and warmed water exits from the top header. The absorber is usually contained in an insulated box with a transparent cover. The temperature range of flat plate collectors is approximately 30–80°C.

Flat plate collectors can be constructed from a variety of materials and different construction methods are possible. As a result, they may have different performance and costs and be designed for different applications. For example, two layers of glazing are sometimes used to improve thermal performance. Some of the other variations are discussed below.

Unglazed collectors have no glazing or insulation, and usually consist of extruded polymer tubes. Their use in LSTS is rare, although they have been used in the horticultural sector for greenhouse heating and swimming pool heating where lower water temperatures are required. These collectors have the largest share of the flat plate solar collector market, particularly in Australia.

2.1.1.1.2 Evacuated tube collector

There are two common types of evacuated tube collectors: heat pipe and U-tube. Both collector types are formed from an array of evacuated tubes joined to a manifold through which the heat transfer liquid (water or water/glycol) flows.

The solar absorber is located inside a double glass tube with a vacuum between the two tubes, similar to an elongated thermos flask. The tubes are connected to a manifold through which the heat transfer fluid is passed (Figures 2.2 and 2.3). The inner glass tube has a selective surface facing outward to absorb the sun’s energy. The heat is transferred into the inner glass tube and removed by a heat pipe or a copper tube through which the heat transfer fluid flows. The loss of heat from the absorber by natural convection is eliminated by the vacuum and, as a result, high operating fluid temperatures of up to 120ºC can be achieved. The possibility of higher temperatures is of particular importance for solar industrial process heating application because it increases the number of applications where solar energy can be used.

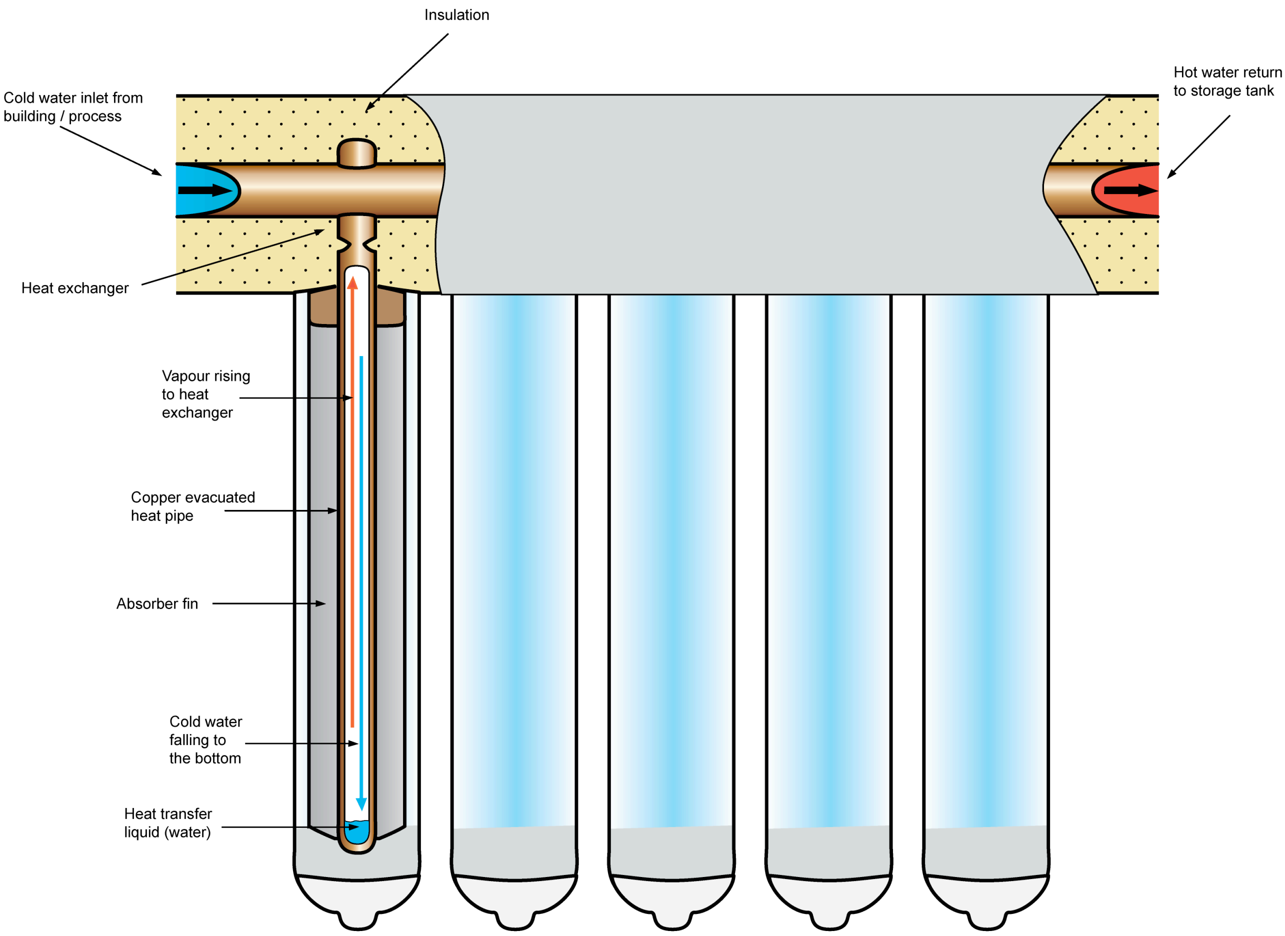
Heat pipe evacuated tube collector

A heat pipe evacuated tube collector uses heat pipes to transfer the collected solar heat from the tube into the fluid in the manifold. Heat pipes are made up of copper tubes which contain a very small amount of water in a partial vacuum. The heat pipe is encased in the inner glass tube.

As the heat pipe is heated, the small amount of water inside vaporises and rises to the top of the heat pipe into the heat exchanger in the manifold. The cold water is heated as it flows through the manifold and at the same time cools the vapour inside the heat pipe where it condenses and falls to the bottom of the heat pipe. The process is repeated, thus creating a highly effective method of transferring the sun's energy, which strikes the tubes into the fluid.

Heat pipe evacuated tube collectors are not suitable for horizontal installation, as inclination should be at least 25° to function.

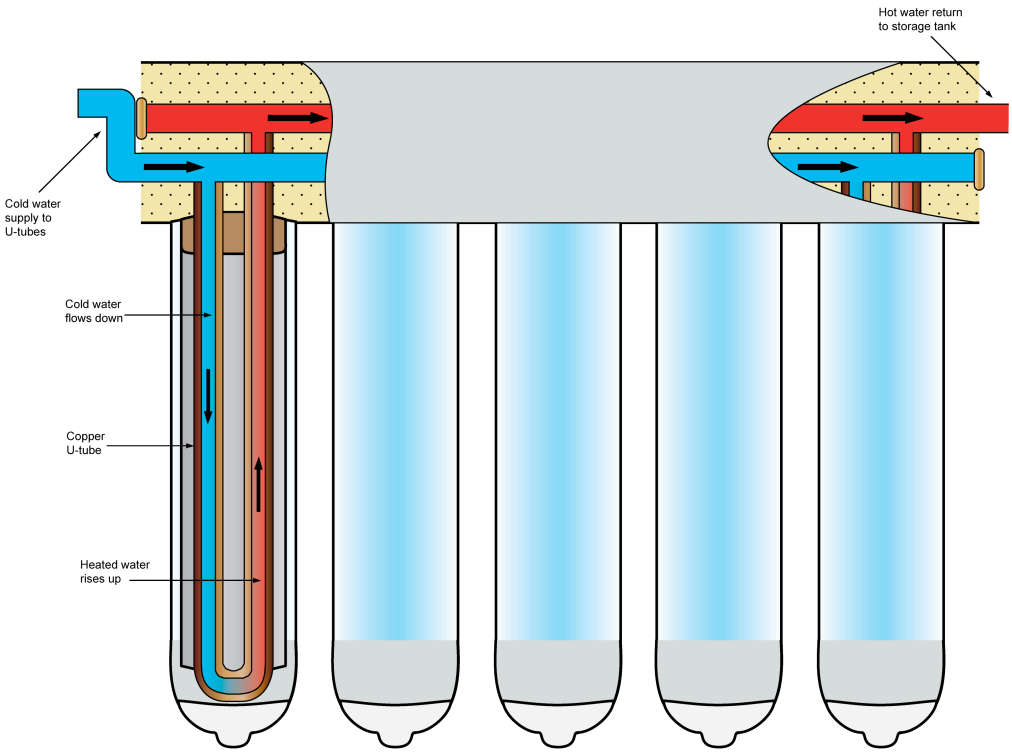
Figure 2.2: Typical heat pipe evacuated tube array



U-tube evacuated tube collector

Evacuated U-tube collectors have the fluid heated as it flows through a ‘U’ shaped copper pipe inside the glass tubes.

Figure 2.3: Typical evacuated U-tube array



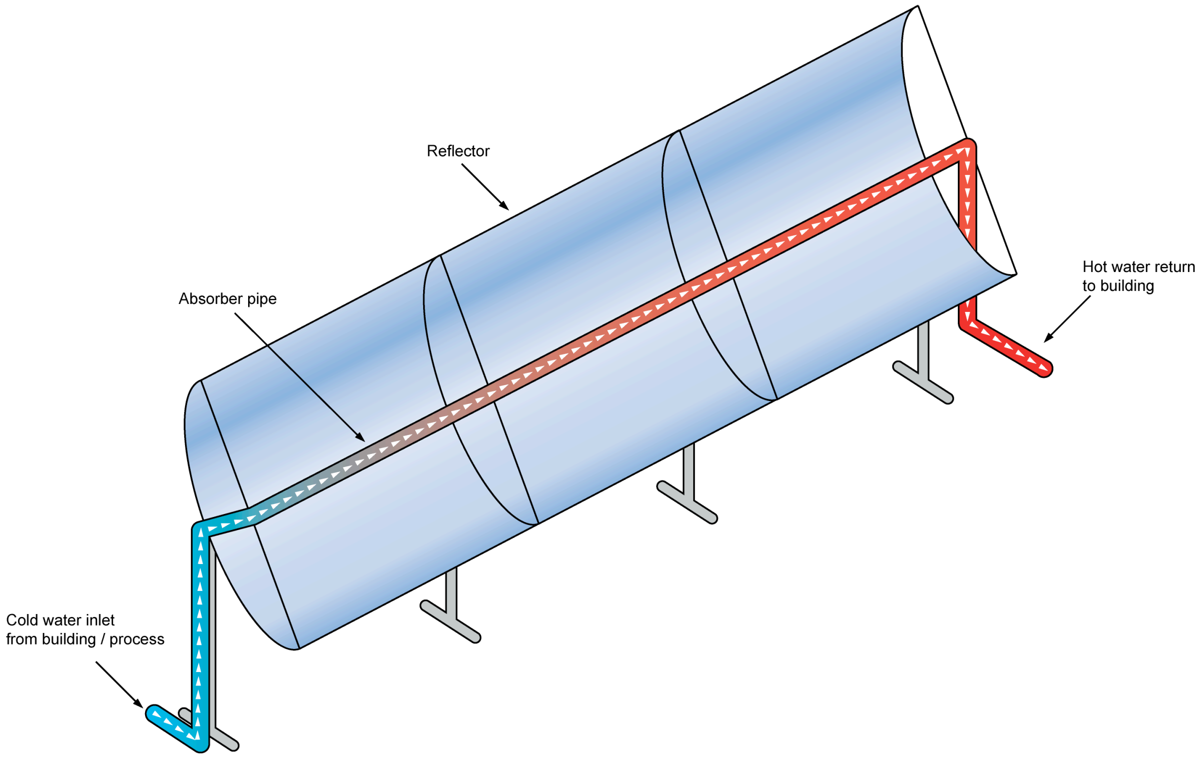
2.1.1.2 Concentrating collectors

Concentrating solar collectors use reflectors either as a trough (Figure 2.4) to focus on a line absorber or a dish to focus on a point absorber. They can reach far higher temperature levels than non-concentrating collectors. Concentrating collectors will collect only direct radiation (the solar energy coming directly from the sun) and consequently perform better in areas with predominantly clear sky (not cloudy) conditions.

The collectors are designed with either one or two axis tracking so that the concentrator can track the sun and the incident rays are always right-angled to the aperture areas. Common systems include the parabolic trough, linear Fresnel, parabolic dish and central receivers (solar tower). These collectors are typically used where temperatures above 100°C are needed, i.e. process heat or electricity generation.

Concentrating collectors are typically specified by their concentration ratio. The concentration ratio is the ratio of the area of the reflector to the absorber area. High concentration ratios are used for higher temperature collectors, but require more accurate tracking of the sun's path.

Figure 2.4: Typical concentrating collector



2.1.2 Collector performance comparison

Various types of solar collectors have been briefly described above. How do they compare with each other and what might be their areas of application? The standard method to evaluate the performance of solar collectors is to compare:

- instantaneous efficiency curve
- annual heat output.

When determining the annual heat output of a solar collector, the efficiency equation used must be consistent with the collector area used by the test laboratory to compute efficiency from the collector test results. It is distinguished between three collector areas:

- gross collector area
- aperture area
- absorber area.

The different collector areas for flat plate and evacuated tube collectors are shown in Figures 2.5, 2.6 and 2.7.

The gross collector area includes the outside dimensions of the product and defines the minimum amount of roof area of the collector.

The aperture area is the area that corresponds to the light entry area of the collector.

The absorber area is the area that receives solar energy. The absorber area of the heat pipe collector is the plan area of the array of tubes and does not include the gap between tubes. The area of tube arrays with a parabolic reflector behind the tubes is the area of parabolic reflector.

Figure 2.5: Cross-section of flat plate collector showing gross, aperture and absorber area

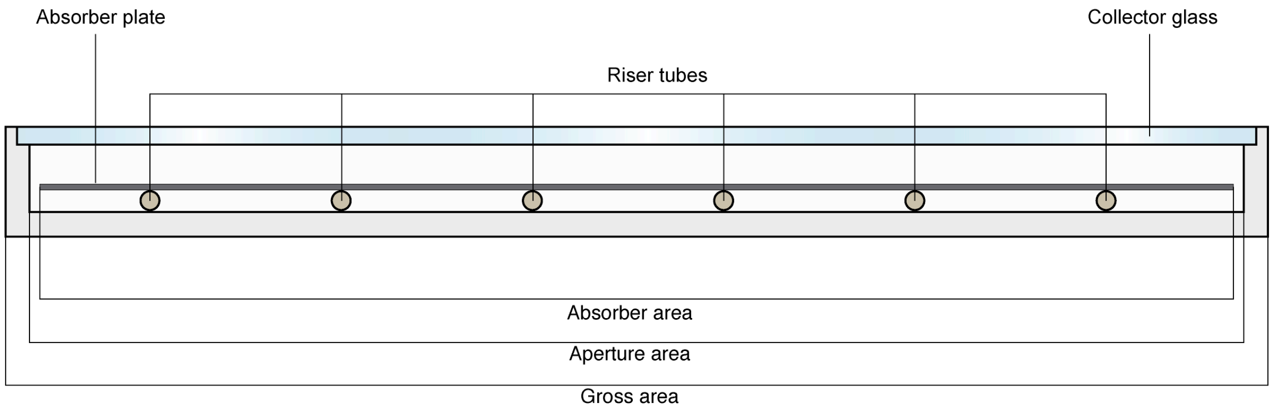


Figure 2.6: Cross-section of heat pipe evacuated tube collector without a backing reflector, showing gross, aperture and absorber area

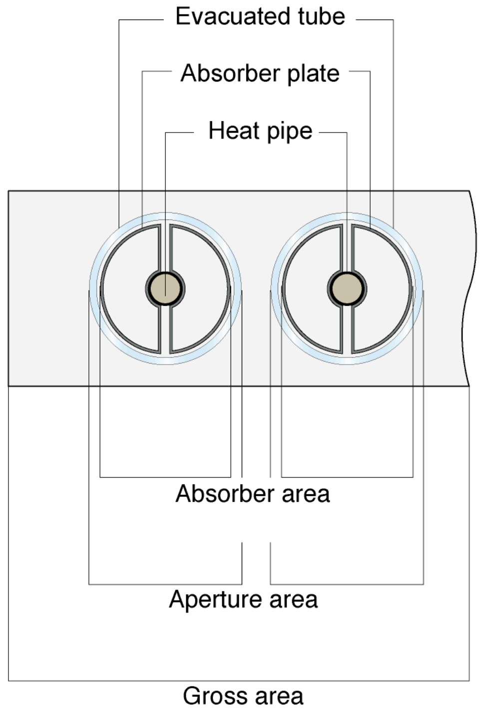
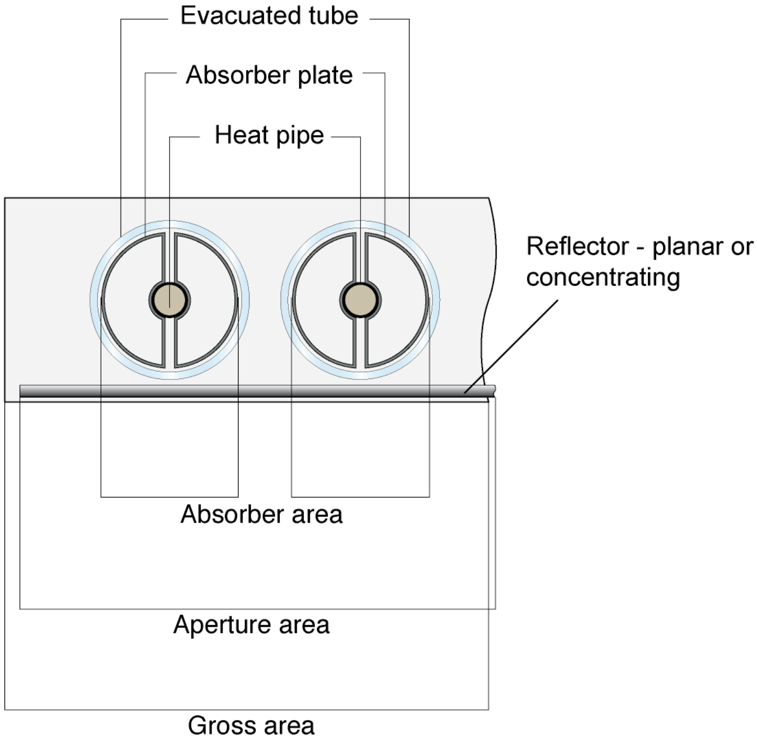


Figure 2.7: Cross-section of heat pipe evacuated tube collector with a backing reflector, showing gross, aperture and absorber area



The area basis for defining solar collector efficiency can be on the basis of gross, aperture or absorber area. If alternative solar collectors are compared on the basis of efficiency, care must be taken to use the efficiency with the collector area that was used by the test laboratory to compute the efficiency. Some test laboratories report all three alternative forms of collector efficiency.

Evacuated tube solar collectors that do not incorporate a reflector behind the tubes typically have efficiency reported on the basis of the aperture area. Such a report would imply a very high efficiency; however, it must be noted that the efficiency curve is based on a smaller area than an evacuated tube collector incorporating a reflector or a flat plate collector.

The choice of the appropriate pairs of values of efficiency and reference area has no effect on the computation of the energy delivery, as the product of efficiency times area is the same whether gross, aperture or absorber area is used.

To compare the heat output of different solar collectors, the product of efficiency times aperture area should be compared rather than efficiency alone due to the bias that can be introduced into efficiency specification by using the smallest area to define efficiency.

The most accurate way of comparing alternative solar collector performance is to determine the annual heat output for the range of inlet temperatures for the application and for the location of interest. This type of performance specification is referred to as a heat table (refer to Chapter 5).

The range of solar collector efficiency parameters for different product types can be compared on the basis of a linearised efficiency (equation 1) versus $(t_m - t_a)/G$ fit to the test data, as shown in Figure 2.10.

For the evaluation of the solar collector heat output, a three coefficient non-linear efficiency characteristic (equation 1) is required to accurately represent the high $(t_m - t_a)/G$ performance of glazed flat plate and evacuated tube collectors (refer to AS/NZS 2535).

$$\eta = \bar{\eta}_o - \bar{a}_1 \frac{t_m - t_a}{G} - \bar{a}_2 \frac{(t_m - t_a)^2}{G} \qquad (1)$$

where $\bar{\eta}_0$ = optical efficiency

$\bar{a}_1$ and $\bar{a}_2$ = positive coefficients from AS/NZS 2535 normal efficiency tests

G = incident solar radiation on the slope of the collector (from climatic data file)

t_a = ambient temperature (from climatic data file)

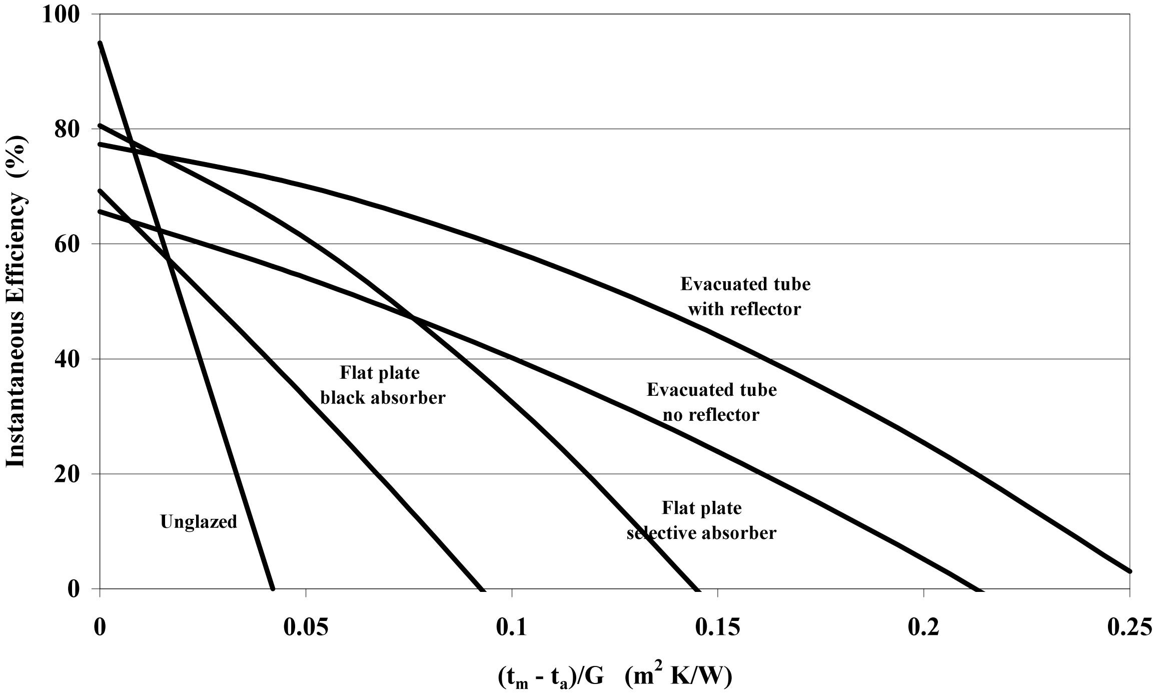
t_m = average fluid temperature in the collector

Typical normal incidence solar collector efficiency characteristics are shown in Figure 2.8.

The bottom axis, $(t_m - t_a)/G$, of the graph in Figure 2.8 represents the difference between the average fluid temperature in the collector (t_m) and the ambient air (t_a) divided by the incident solar radiation (G). Solar radiation under clear sky conditions is of the order of 1000 W/m^2. It can be seen that for a given value of solar radiation when the temperature difference is low, an unglazed flat plate collector performs better, i.e. has higher collection efficiency than a glazed flat plate or evacuated tube collector. As the value of $(t_m - t_a)/G$ increases, the glazed flat plate and the evacuated tube collectors perform better, i.e. have a higher efficiency. For high values of $(t_m - t_a)/G$, an evacuated tube collector with a backing reflector has the highest efficiency.

The implication of these observations is that if a solar collector is likely to be operating with a high $(t_m\text{-}t_a)/G$ value, then a collector with lower heat loss should be used. This is the case in many industrial applications where there is a closed process circuit loop and inlet temperature of the solar collector is always high. The exception to this general rule would be if the process circuit was open and significant amounts of cold make-up water were required to replace lost fluid. This would mean that the collector inlet temperature would be closer to ambient temperature and a less efficient collector might be adequate.

Figure 2.8: Instantaneous efficiency curves for various types of solar collectors



In addition to the normal incidence efficiency, the off-normal performance of a collector must also be considered. Typical off-normal performance of flat plate and evacuated tube collectors is shown in Figure 2.9. Flat plate collector performance decreases when the incident angle is not normal to the collector aperture due to reflection losses in the cover. Evacuated tube collectors normally show an increase in performance up to an incident angle of 60° due to the three-dimensional shape of the absorber and the losses at normal incidence due to the spacing of the tubes. The off-normal efficiency of a collector is given by equation 2 where $K_{\tau\alpha}$ is the incidence angle modifier.

$$\eta = \overline{\eta}_o K_{\tau\alpha} - \overline{a}_1 \frac{t_m - t_a}{G} - \overline{a}_2 \frac{(t_m - t_a)^2}{G} \qquad (2)$$

In the equation above:

- The $\acute{\eta}_0$ coefficient defines how a collector will perform when the ambient air temperature is the same as the mean collector temperature. Using this coefficient alone to calculate the efficiency can lead to inaccurate results.
- The $\bar{a}_1$ and $\bar{a}_2$ coefficients define how the collector will perform when the ambient air temperature is lower than the mean collector temperature. If a collector performs well in cold climates, or with high fluid temperatures, it will have very <u>low</u> $\bar{a}_1$ and $\bar{a}_2$ coefficient values.
- Evacuated tubes typically have very <u>low</u> $\bar{a}_1$ and $\bar{a}_2$ coefficients due to the vacuum layer that insulates the tubes against the ambient air temperature.
- Unglazed collectors typically have very <u>high</u> $\bar{a}_1$ and $\bar{a}_2$ coefficients, meaning that they lose efficiency when the ambient air temperature is below the mean collector temperature.

- $K_{\tau\alpha}$ defines how the collector will perform when the sun is not directly above the collector. For example, in the morning and afternoon (θ = 60°) an evacuated tube collector is operating at around 140% more than its rated η_0 efficiency, and a flat plate collector is operating at around 90% of its rated η_0 efficiency.

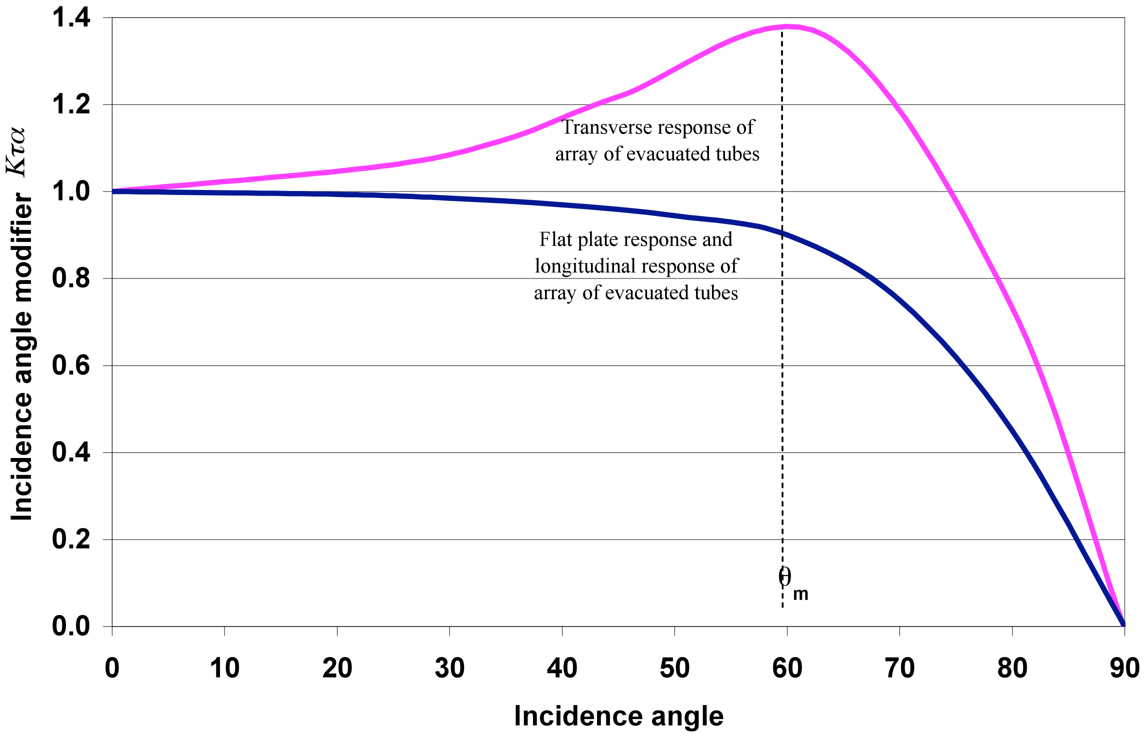
Note:

Care should be taken not to oversize the solar collectors. Systems with too much solar contribution can lead to prolonged stagnation conditions and very high temperatures (refer to Chapter 2.8).

If the hot water load is constant throughout the year, the collector area should be sized to meet the load during the period where the solar contribution is the highest – this usually occurs in summer when there are higher levels of solar radiation (refer to Chapter 3). The collectors should be sized to meet no more than 100% of the load requirements at any one time, right throughout the year.

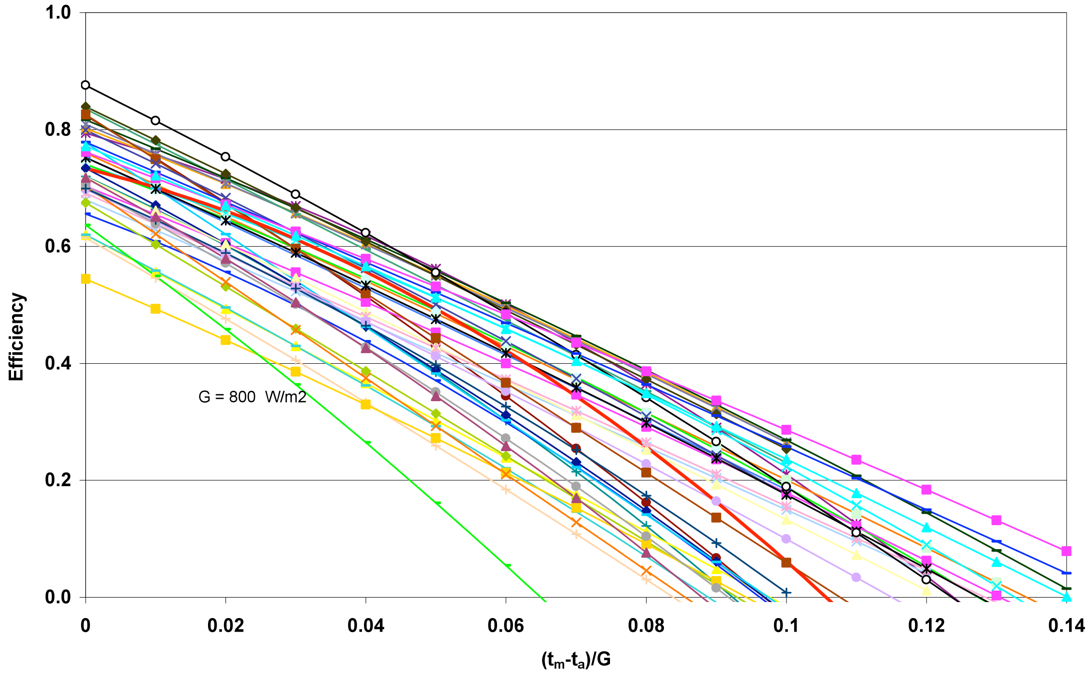
For LSTS with a non-constant load pattern, detailed analysis should be done to ensure that there are not long periods of time when there is no load placed on the collectors.

Figure 2.9: Incidence angle modifiers



The efficiency of different solar collector products depends on the product configuration and the methods used to limit heat loss. The range of efficiencies observed in commercially available flat plate collectors in Australia is shown in Figure 2.10. The low-efficiency products use black absorbers and low-transmission glass and as a result are less expensive compared to high-efficiency products that incorporate selective surface absorbers and high-transmission glass covers. The most appropriate solar collector is the one that can deliver the minimum energy cost over the life of the system at the required temperatures (refer to Chapter 5). In some cases, a low-efficiency product may be the most cost-effective solution.

Figure 2.10: Measured efficiency of flat plate solar collectors sold in Australia



2.1.3 Comparison of solar collectors on the basis of efficiency

To compare the heat output of different solar collectors, the product of aperture area times efficiency at the operating condition considered should be compared rather than efficiency alone due to the bias that can be introduced into efficiency specification by using the smallest area to define efficiency.

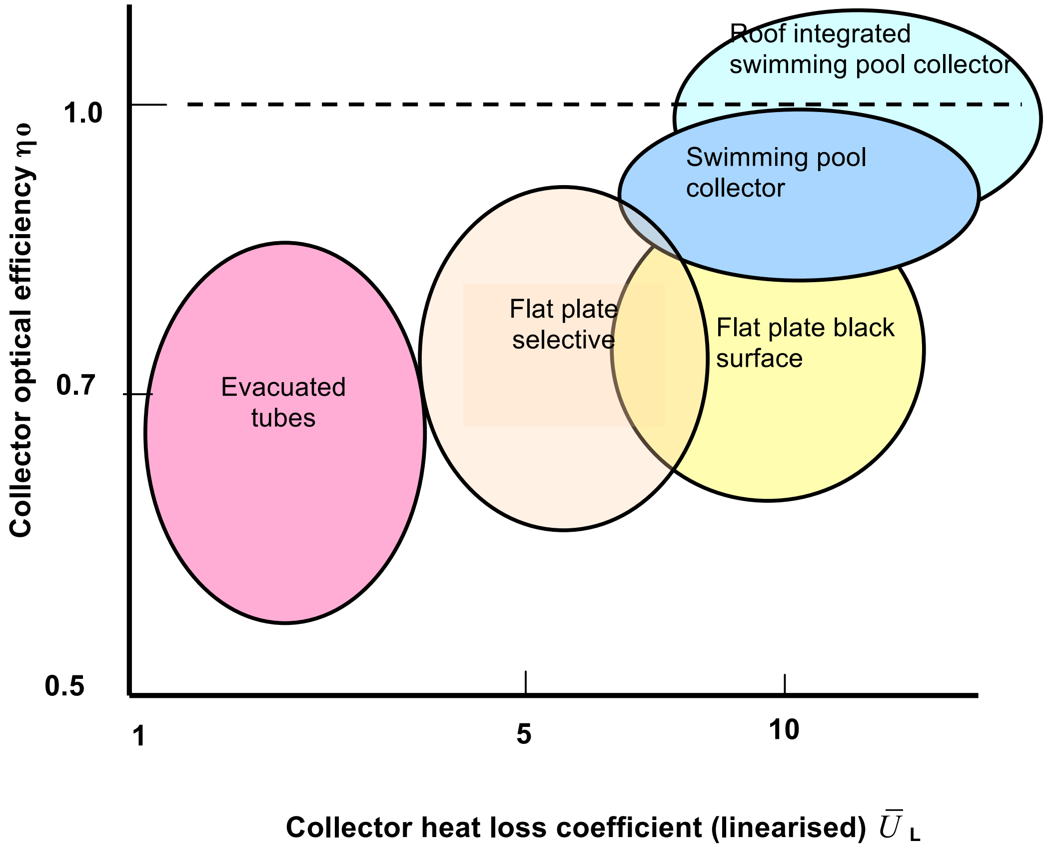
The most accurate way of comparing alternative solar collector performance is to determine the annual heat output for the range of inlet temperatures for the application and for the location of interest. This type of performance specification is referred to as a heat table (refer to Chapter 5).

The collector efficiency equation (equation 1) can be simplified into a linear equation (equation 3) that provides a reasonable approximation of the performance at low values of $(t_m\text{-}t_a)/G$. The range of linearised solar collector efficiency parameters for different product types is illustrated in Figure 2.11. The linearised equation is calculated by fitting collector test data to equation 3 to find the linearised heat loss coefficient (U_L) and the optical efficiency (η_0).

$$\eta = \bar{\eta}_o - \bar{U}_L \frac{t_m - t_a}{G} \qquad (3)$$

where $\bar{\eta}_0$ = optical efficiency
U_L = heat loss coefficient
G = solar radiation on the slope of the collector (from climatic data file)
t_a = ambient temperature (from climatic data file)
t_m = average fluid temperature in the collector

Figure 2.11: Solar collector efficiency parameters (linearised)



2.2 Storage tanks and heat exchangers

Temperature stratification in hot water storage tanks is the formation of layers of water of different temperatures within a storage tank. The hot water is at the top and gets cooler further down the tank. Temperature stratification can provide substantial operational performance benefits. Convection in the storage tank induced by collector loop or load side heat exchangers affects thermal stratification. Therefore, correct integration of the tank and heat exchangers in a low-flow system is essential.

Three configurations of heat exchangers are shown in Figures 2.12, 2.13 and 2.14. The degree of thermal stratification that can be achieved in tanks with collector loop heat exchangers depends on the location of the heat exchanger and the flow rate in the collector loop. Storage tanks with internal helical coil heat exchangers, either for a closed collector loop (Figure 2.12) or a load side heat exchanger (Figure 2.13), will have less stratification than storage tanks with an external heat exchanger based on low-flow design (Figure 2.14).

Figure 2.12: Tank with helical coil heat exchanger

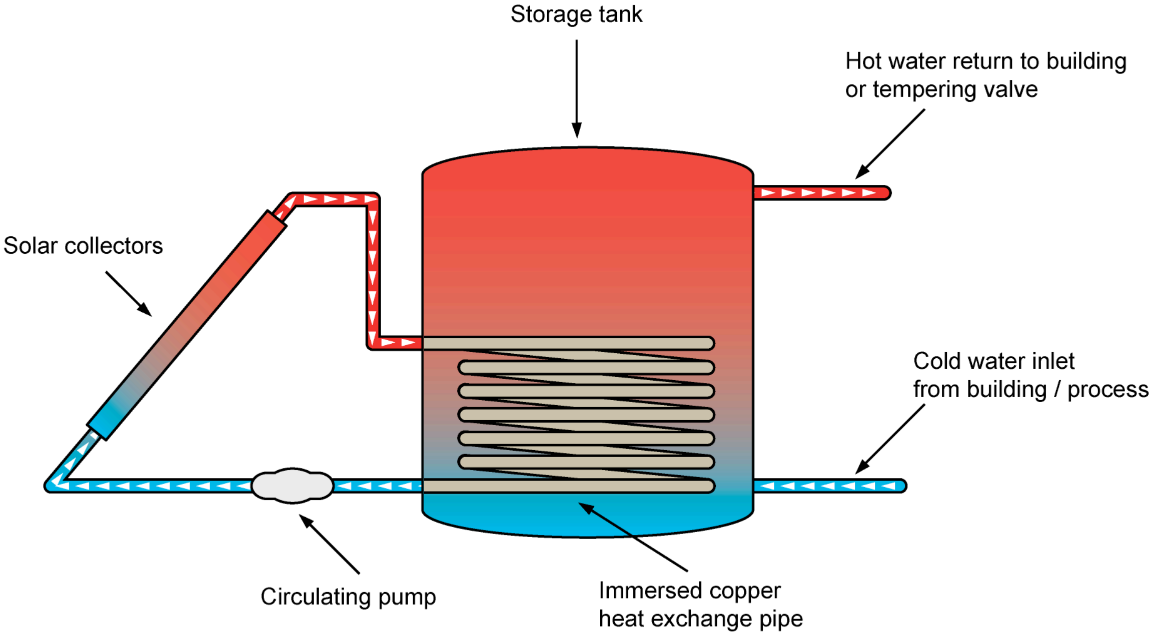


Figure 2.13: Load side heat exchanger tank

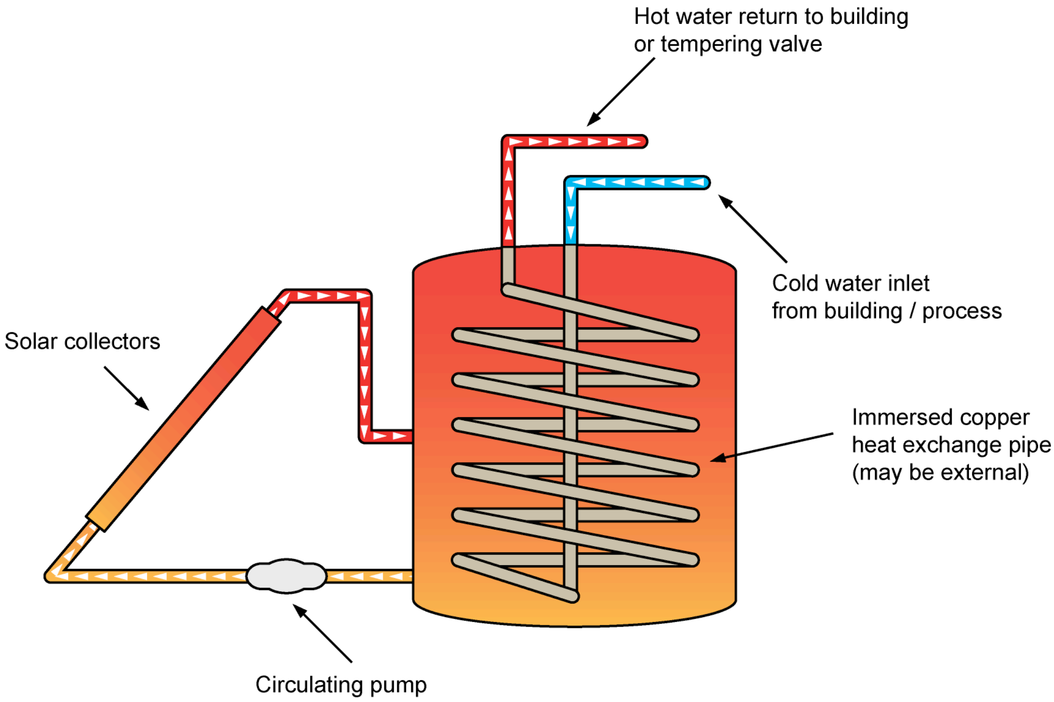
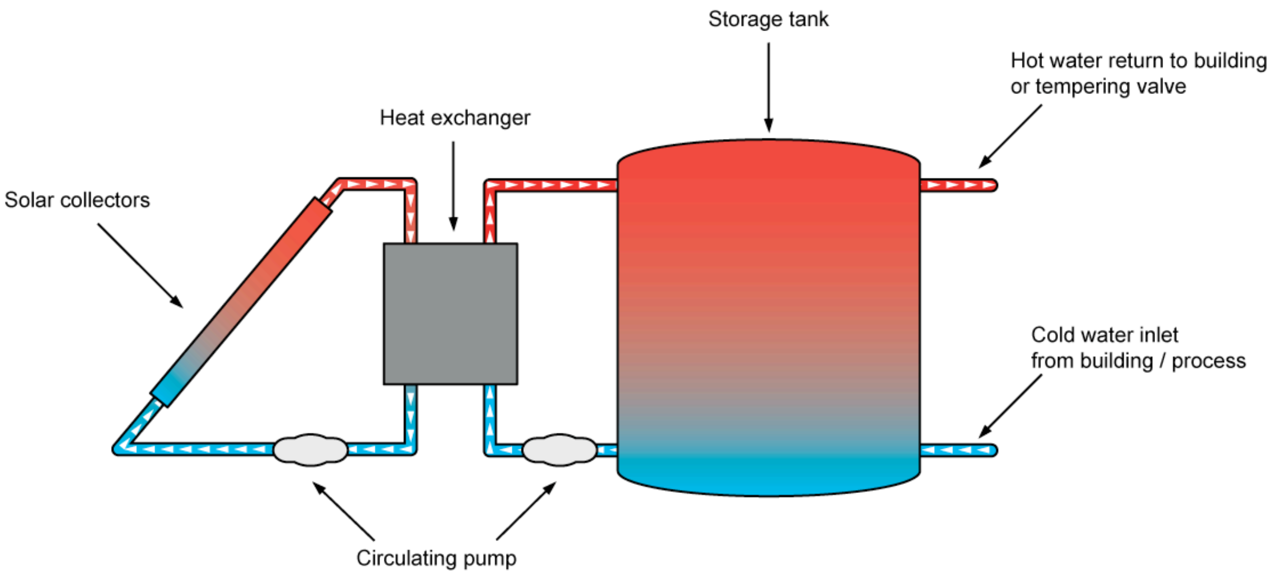


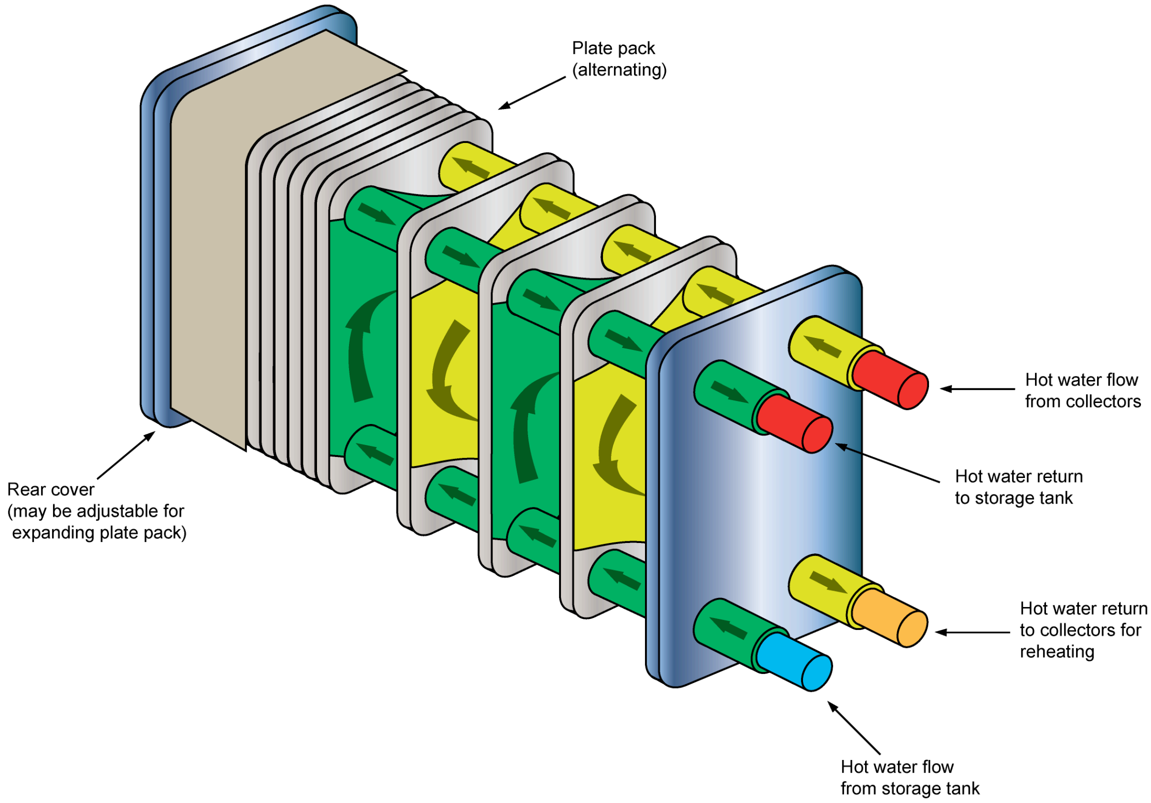
Figure 2.14: Tank with external heat exchanger



2.2.1 External heat exchanger configurations

External heat exchangers can be either plate or shell and tube heat exchanger configurations. Plate heat exchangers (Figure 2.15) operated in the counter flow mode have higher effectiveness and, as a result of a higher outlet temperature in the tank, loop flow can be configured to maximise thermal stratification in the tank.

Figure 2.15: Typical plate heat exchanger



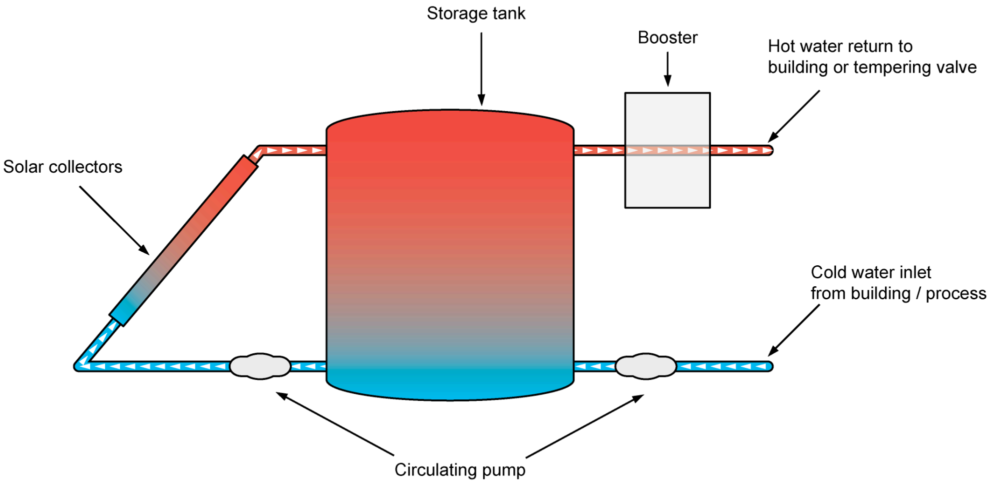
2.3 System layouts

There are two basic system layouts used in LSTS. These are the open and closed loop systems. The closed loop system is the most common one.

2.3.1 Open loop systems

In an open loop system, the sun directly heats the (potable) water and no heat exchanger is needed. The water is pumped from the storage tank to the collector array and then returned to the tank after it has been heated. The same water is taken from the tank to the process circuit (Figure 2.16).

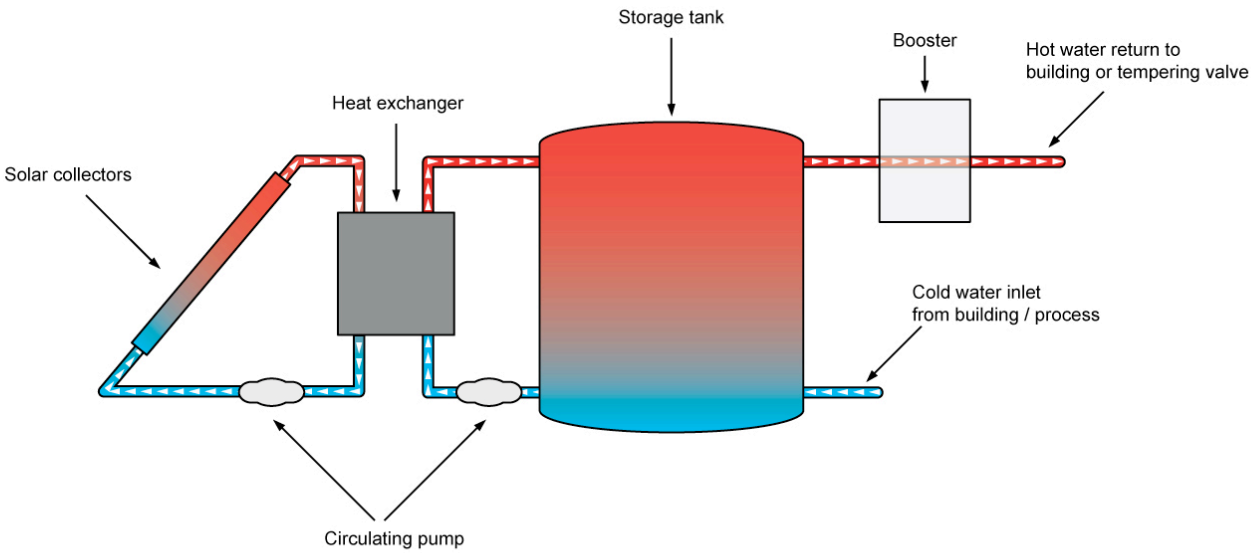
Figure 2.16: Typical open loop system



2.3.2 Closed loop systems

Closed loop systems use a heat exchanger to transfer the heat to a secondary circuit or thermal storage tank. The collector heat transfer fluid (water or water/glycol) remains in a sealed system. This configuration allows the use of non-potable water as the heat transfer fluid and anti-freezing agent may be added to the fluid in order to prevent damage from freezing (Figure 2.17).

Figure 2.17: Typical closed loop system



2.4 Collector loop design concepts

The most effective system design will depend on the selection of the most cost-effective solar collector for the application and careful system design. A system that is incorrectly configured may result in stagnation in some sections of the collector array and thus a significant reduction in heat output. The most common fault in designing LSTS is bad hydraulic design that results in uneven flow distribution or air locks in the collector array.

A high flow rate through a solar collector will maximise energy collection for a given collector inlet temperature, but the collector outlet temperature of the fluid may be too low to be useful. In addition, high flow rates require larger pumps and cause significant amounts of parasitic electrical energy. On the other hand, a flow rate that is too low will result in high fluid temperatures, high heat losses from the collector array and therefore a low heat collection efficiency.

The concepts that produce optimum heat output include:

- Design for thermal stratification in the storage which can be achieved by implementing the low-flow design concept (refer to Chapter 4.3).
- Balance the flow between parallel paths through the collector array which requires:
  1. equal friction (piping lengths) in all parallel paths in the collector array to ensure even flow – reverse return plumbing, also known as the Tichelmann principle
  2. all parallel flow paths are taken to the highest point in the array before entering the reverse return line.
- Incline all parallel flow paths in the collector array to the highest point for natural air lock clearance or fit air relief valves at all local high points in the plumbing.
- Optimise pump controller settings to avoid pump hunting (refer to Chapters 2.6 and 5.3).

2.4.1 Collector interconnection

LSTS require many collectors to be linked together. The objective of the collector arrangement is to achieve low pumping power requirements and a uniform heat production by all collector modules. The optimal collector configuration depends on:

- geometry of available collector installation area
- hydraulic characteristics of the collector modules.

Solar collectors may be connected together in series, parallel or a combination of series and parallel arrangements (Figures 2.18 and 2.19).

Figure 2.18 shows a series-connected collector array where all the heat transfer fluid passes through all of the collectors. In addition to the air relief valve at the collector outlet pipe, it may be necessary to install additional air relief valves at all local high points to avoid air locks. This depends on the system design (high or low flow) and pump selection.

In general, more electrical energy is required to pump the water through a series-connected array than a parallel-connected or multiple-parallel collector system because of the greater flow resistance from an equivalent number of collectors joined together in series.

Figure 2.18: Series-connected collector array

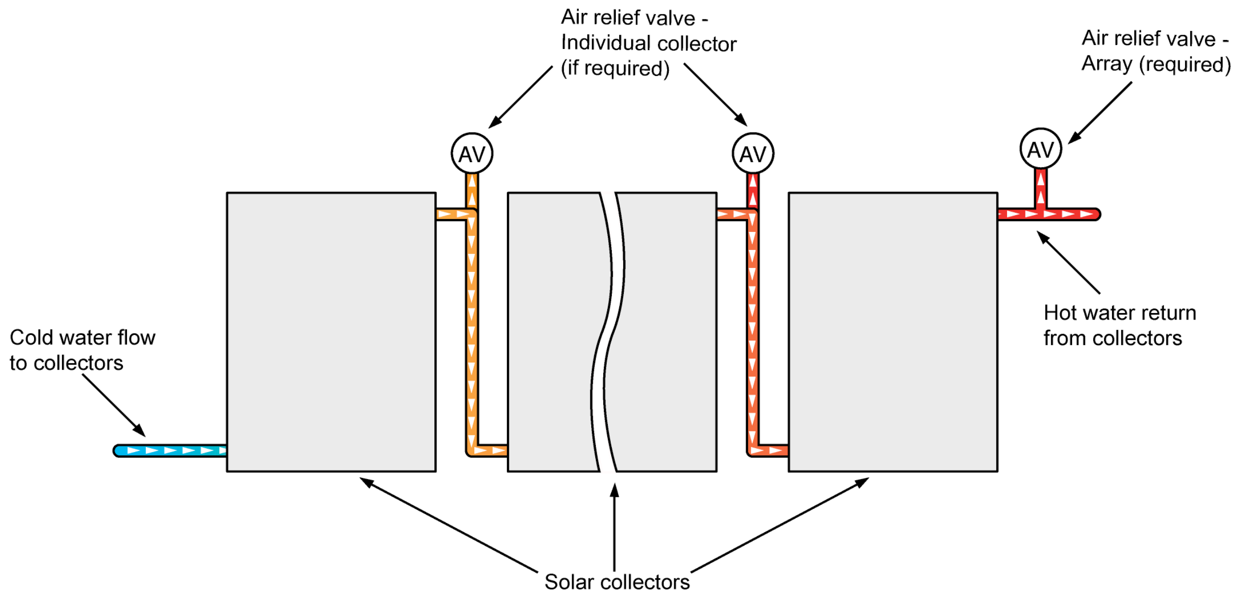


Figure 2.19 shows a parallel-connected collector array, where the flow of the heat transfer fluid is divided and a proportion goes through each collector. This collector arrangement only needs an air relief valve at the collector outlet pipe.

Figure 2.19: Parallel-connected collector array

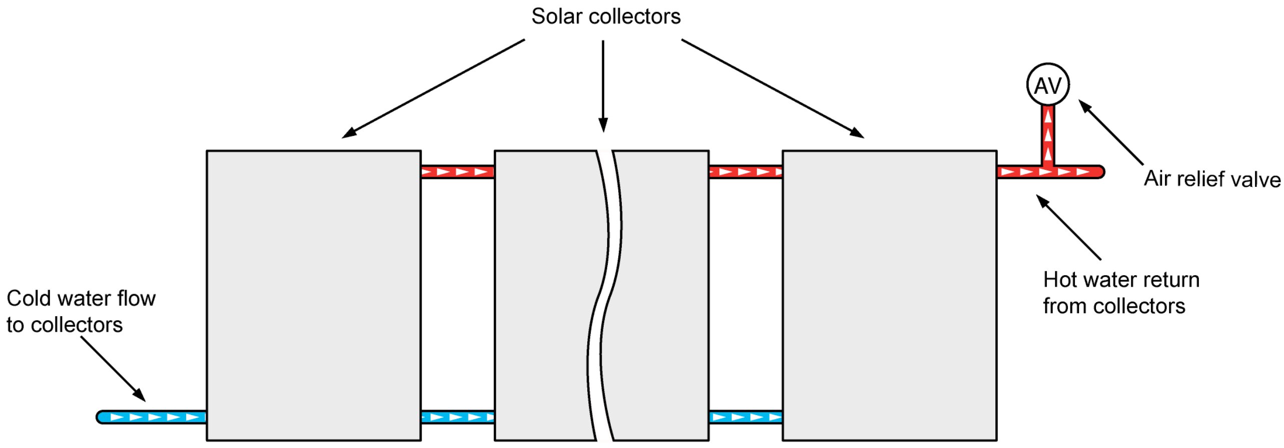
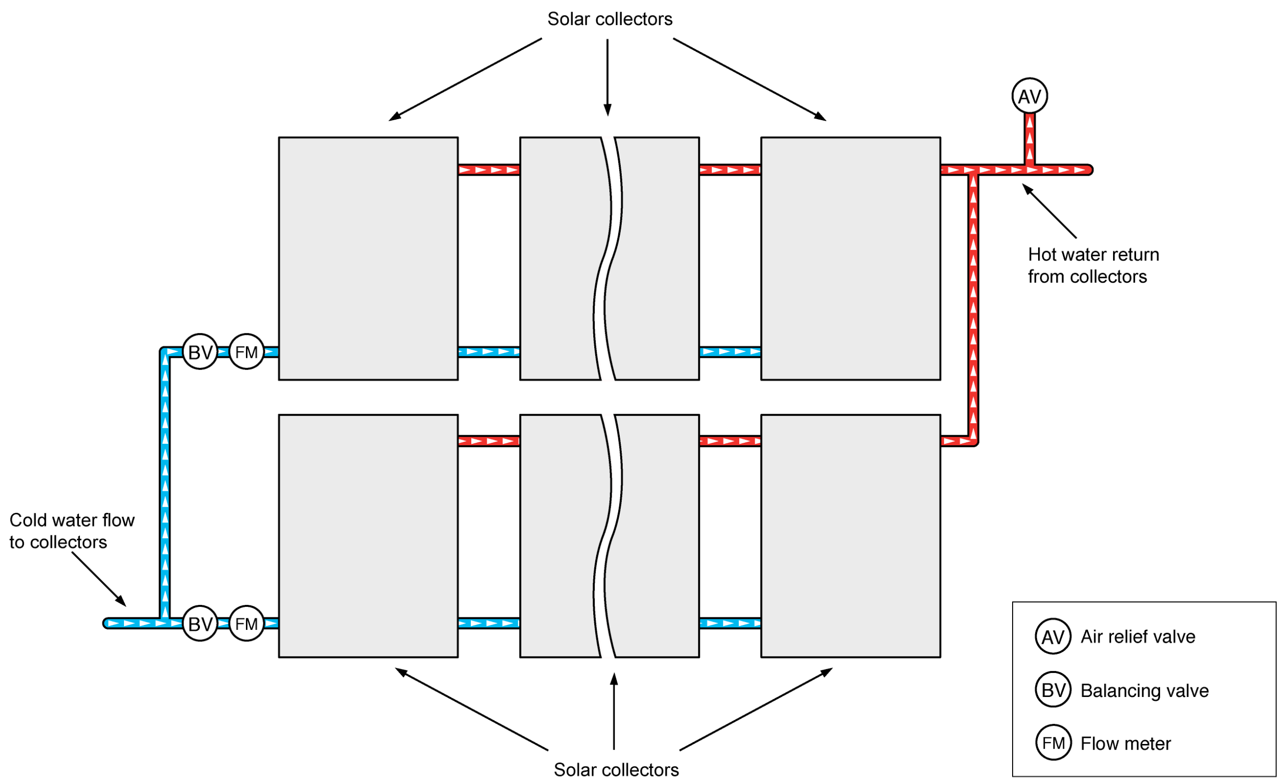


Figure 2.20 shows the recommended multiple-parallel collector arrangement, where a proportion of the heat transfer fluid goes through each group of collectors depending on how many rows are established. Collector groups connected in parallel should be plumbed such that the length of the flow and return paths are approximately the same for all flow paths through the array in order to achieve evenly distributed flows. If the number of collectors per row differs, balancing valves and flow meters are needed to be installed at the cold water flow pipes to ensure equal flows (refer to AS 3500). The air relief valve needs to be installed at the highest point after the different collector outlet pipes have been diverted together to avoid air locks.

Figure 2.20: Multiple-parallel collector array (recommended)



The optimal configuration depends on the geometry of the available area for collector mounting and the hydraulic characteristics of the collector modules. The objective of array layout is to achieve a low pumping power requirement and a uniform heat production by all collector modules.

Electricity consumption used for pumping is commonly known as the system's 'parasitic' energy. It is recommended that parasitic energy should not exceed 3% of the collected solar energy. If the parasitic energy is higher, it is an indication of poor hydraulic design.

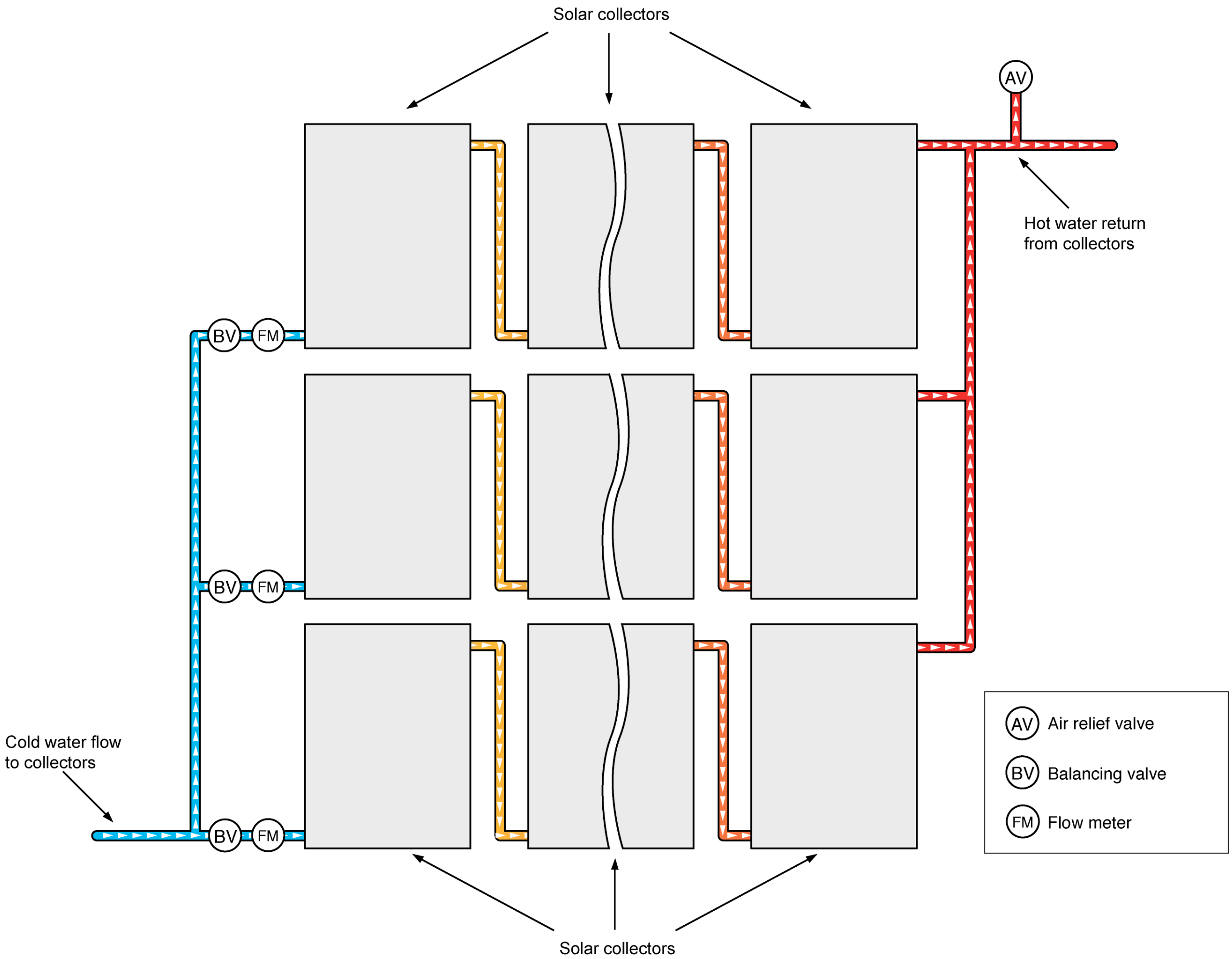
However, in large arrays, some collector modules may need to be connected in series so that the pressure drop in the header pipe does not exceed 10% of the pressure drop through a module in order to get uniform flow through parallel-connected collectors.

The starting point for optimising the collector arrangement is to aim for a high-irradiance temperature rise greater than 20 Kelvin through each series-connected collector group. This leads to a specific flow rate requirement of 0.2 to 0.4 L/(min.m^2 aperture area).

Connection of the flow and return lines to the same panel at one end of a parallel row will cause those panels at the near end to short circuit the flow, while those at the far end will receive less flow and suffer a reduction in performance. Such an arrangement should only be used where the pressure drop in the headers is much less than that in the fluid passages across the panels.

Multiple-parallel/series collector arrays as shown in Figure 2.21 should not be used, as one or more of the flow paths may air lock and significantly reduce the heat output of the collector array.

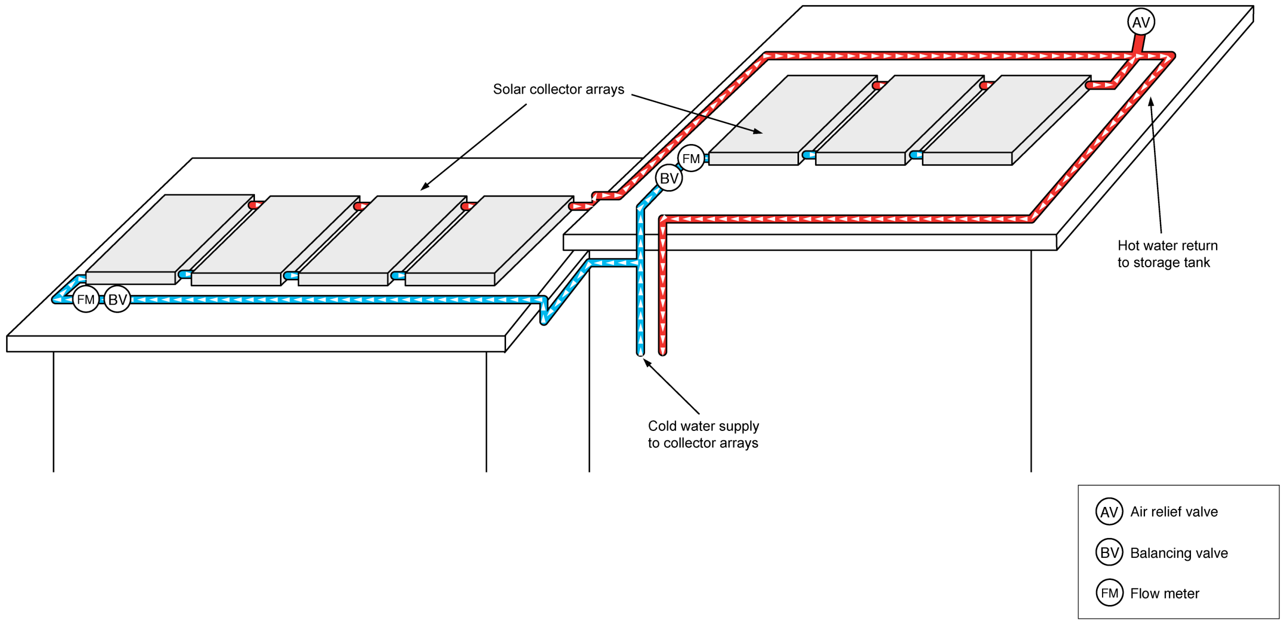
Figure 2.21: Multiple-parallel/series collector array (not recommended)



2.4.2 Collectors at different heights

Groups of collectors at different heights should be connected in such a way that they all receive water from the lowest point in the system and return it to the highest point. Figure 2.22 illustrates a system arranged in this way. The collector outlet pipe of the lower located collector array goes to the highest point in the system where it gets connected with the outlet pipe of the higher located collector array. Air trapped in the system gets relieved through an air relief valve at the main outlet pipe of the collector array. If the return lines do not come from a common height, flow through the different sections of the collector array may not be uniform, causing a reduction in performance. Flow meters and balancing valves at the collector inlet pipes are needed to ensure equal flows.

Figure 2.22: Collector array connections for collector panels at different elevations, illustrating common feed and return points at the lowest and highest points in the system



2.4.3 Sections of collector array with different orientation, slope or shading

If a collector array has sections with different orientation, slope or are subject to different shading effects, consideration should be given to independent control of the flow to each collector segment. This is to avoid heat loss from a section of the array receiving low radiation even though the overall mixed output flow may indicate positive output from the array. For such installations, the flow controller should monitor the outlet temperature of each collector segment and have the capability to isolate collector sections that have low output.

2.5 Energy conservation

The role of energy conservation in the design of LSTS is important and should not be underestimated for two reasons. Firstly, energy conservation reduces the energy consumption and saves scarce energy resources. Secondly, it is usually the most cost-effective way to reduce overall energy cost.

There are many energy-conservation measures in industrial process water heating processes that can be considered. These include:

- no-cost actions such as minimising the hot water storage temperatures
- simple and low-cost actions such as increasing insulation levels on pipework and storage tanks (discussed further below)
- complex and expensive actions such as the installation of more accurate control or heat recovery systems

Routine maintenance of boilers, thermostats, pumps and other components in a heat delivery system is also vital. There is little sense in installing an expensive LSTS to complement a poorly maintained conventional boiler and ancillary equipment. The second reason for reducing the demand for hot water for a particular process is that it will also mean that any LSTS installed subsequently can be either smaller or meet more of the demand than would have been the case prior to the conservation measures. In general, LSTS are capital intensive and any reduction in hot water demand will lead to a reduction in the size of the LSTS and a lower capital outlay.

It is critical that all pipework, fittings and storage tanks are optimally insulated. Failure to optimise the insulation level will either result in the unnecessary loss of collected solar heat (if there is too little insulation) or unnecessary expenditure (if there is too much insulation). The level of insulation on a storage tank and pipework in a conventional plant would normally be decided on the basis of an acceptable financial payback for the money spent on the insulation based on the annual energy savings.

When installing LSTS, the level of insulation on the storage tank, pipework and fittings should be increased to the point where the cost of the energy saved by the insulation is just less than the cost of the energy produced by adding more solar collectors to the system. In other words, the heat from the solar thermal system is cheaper than adopting further energy conservation measures.

If the low-flow optimum design approach is used, then a high level of insulation of the solar collector loop plumbing system (piping and fittings) is essential, as the collector outlet temperature will be high. However, as the piping diameter of the collector loop in low-flow designs is smaller than that of high-flow designs, a high degree of insulation can be achieved with less insulation thickness. The insulation material of pipework installed outside (e.g. between the collectors) should be weather and ultraviolet (UV) resistant and be able to withstand extreme temperatures (refer to Chapter 4.4).

2.6 Control systems

2.6.1 Pumps and controllers

LSTS require one or more pumps to circulate the heat transfer fluid around the system. In order to collect and deliver heat effectively and efficiently, an active control system is required to regulate the flow of the heat transfer fluid. Although it is possible to regulate pump operation using a time clock or photoelectric cell, these types of controllers are ineffective. The time clock cannot respond to variations in solar radiation and the photoelectric cell cannot respond to variations in storage temperature. As a result, differential or proportional controllers are used in LSTS.

A differential controller compares the difference between the collector inlet temperature, e.g. at the bottom of a storage tank, and the collector outlet temperature of the water at the top of the storage tank. If the difference is positive, then it is assumed that 'useful' heat may be collected and the pump is activated. If the solar radiation level falls below the level required to maintain a positive differential, then the pump is turned 'off'. In order to avoid the problem of a pump turning 'on' and 'off' repeatedly over a short period of time – known as 'hunting' – the controller incorporates hysteresis and on/off temperature differences must be matched to the collector type, size of collector array and flow rate.

Controller temperature difference settings required for evacuated tubes are different to those required for flat plate collectors, as evacuated tubes can reach a high stagnation temperature even in dull conditions. However, the heat gain from the collector may not be sufficient to achieve a steady state temperature greater than the controller turn off condition unless the sky condition is very clear. This means the pump runs until the heat is removed from the collector and then turns off and waits for the collector to reheat. The effect of this is to shunt hot water from the collector to the return pipe, which then cools off while the controller waits for the collector to reheat.

Typical on/off settings for a differential thermostat (DT) controller for a low-flow system supplying water at temperatures above 50°C are:

- 10/2 for a flat plate collector
- 20/2 for an evacuated tube collector.

However, the optimum controller settings depend on the size and flow rate of the collector array and are also influenced by the collector efficiency (refer to Chapter 5.3).

In closed loop systems, a second temperature sensor in the tank above the heat exchanger may be used to switch the pump between low and high speed and hence provide some control of the return temperature to the tank heat exchanger without using a proportional controller.

A proportional controller varies the speed of the collector array pump in order to maintain a relatively constant water temperature at the collector array outlet. As the solar radiation level increases, the pump speed is increased and, conversely, as the solar radiation declines, pump speed is reduced. This control concept has only a minor effect in systems using the low-flow concept.

Controllers using these strategies can be integrated within computerised building management systems.

Programmable controllers that can sense the temperature distribution in the tank as well as the collector outlet temperature can be used to optimise the system performance. Controllers with time-of-day clocks can also be used to minimise auxiliary energy use for applications that have a repeated daily hot water demand pattern.

There are few low-power pumps suitable for drain back solar collector arrays, as low-power centrifugal pumps do not have sufficient static head to start drain back systems. In such cases, it may be necessary to use two pumps or a dual-speed pump. The high head pump mode is used to refill the collector loop and the system then switches to the low flow rate pump or mode of operation. Positive displacement pumps readily control flow rate but tend to be noisy and expensive.