CHAPTER 3

Solar System Components, Configurations and Operating Principles

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3. SOLAR SYSTEM COMPONENTS, CONFIGURATIONS AND OPERATING PRINCIPLES

3.1 Collector types and operating principles

What this section is about

To install and maintain water heating systems for efficient operation, it is essential to understand the key physical principles underpinning their operation. This section is a summary of the key principles that apply to solar water heaters. These principles are covered in more detail elsewhere such as in the TAFE resource book, *Solar Water Heating Systems* (see Bibliography for details).

This section provides an understanding of:

- the concepts of conduction, convection and radiation as ways in which heat moves between hot and cold bodies
- the stratification principle in hot water storage tanks
- the changes in temperature, volume and pressure as water is heated
- the concept of thermosiphon flow for non-pumped water circulation in solar water heating systems.

Conduction, convection and radiation

Heat is another name for thermal energy, or energy stored in a body due to its temperature. We use temperature as a way to measure this thermal energy. The three processes by which heat is transferred in water heaters are conduction, convection and radiation. These processes determine:

- the rate of heat absorption and transfer by the solar collector to the water
- the rate of heat loss from the solar collector and storage tank back to the surrounding air.

These two processes control the overall effectiveness (or efficiency) of conversion of solar radiation into hot water. This in turn affects the size of the solar collectors and the water storage tank. For example, if a collector is poor at conducting heat in the absorber to the water in the riser tubes or manifold, then more heat will be lost back to the surrounding air. Alternatively, if too little insulation is wrapped around the storage tank or pipe work, then more heat is again lost to the outside air. Both these factors would reduce the performance of the solar water heater. To compensate, either a bigger system would need to be installed or more boost energy would need to be used. Let us now look at each process and how it affects solar water heater performance.

Conduction is the transfer of heat via atomic particles vibrating within a material and bumping into one another, giving some of their vibrational energy to neighbouring particles. The hotter the material, the faster the particles vibrate. It is the main way heat moves through solids and, to some extent, in liquids. Heat does not easily move through gases by conduction as the molecules are spread far apart compared with solids or liquids.

We know that some materials are good conductors of heat; e.g. copper, aluminium and steel. Other materials, such as plastics, are poor conductors. This is due to their differing atomic structures.

How does this heat transfer mechanism influence the performance of solar water heating systems? Firstly, performance is improved if the heat absorbed by the absorber plate can be quickly conducted to the water in the riser tubes or their equivalent. For this to happen we need materials that conduct well. Metals are far better conductors than plastics. Copper is roughly two times better than aluminium at conducting heat, which is two times better than steel. Hence, if using copper we can use one-quarter of the thickness of a steel plate; or if using aluminium we can use half the thickness of the steel to conduct heat over the same distance. So if we use steel instead of copper for our absorber plate, we need to either use a thicker plate or place the water passages closer together to get similar or better performance. This is why steel absorber plates use the flood-plate design compared with the fin and tube design of copper absorber plates.

Secondly, we need to use materials that are poor conductors around the sides and back of the collector to insulate the hot absorber plate from the surrounding area. This slows the rate of heat loss to the surrounding air, but does not prevent it completely.

Convection is the transmission of heat within a liquid or gas due to the bulk motion of the fluid. The rising of hot water from the bottom to the top of a saucepan as it is heated is one example. This occurs because the particles of water bump against one another more vigorously as they are heated and push themselves further apart, making the water less dense and hence lighter. This is called **natural convection** and is the main process of heat transfer in liquids and, to a lesser extent, in gases. We can also create convection by mechanical means, such as fans to blow cooling air across surfaces. The cooling fans in computers that help keep the electronic components operating at safe temperatures are one example.

In a solar water heater, convection heat transfer occurs in two main places. The first, in a flat plate collector, is under the glass cover between the hot absorber plate and the glass. The air immediately above the absorber plate heats up, becomes less dense and rises up to the glass cover above, where it heats the glass. The air is then cooled and sinks back to the absorber plate. This process is also happening on all outside surfaces of the collector box and glass cover. As a result, heat is lost to the surrounding air.

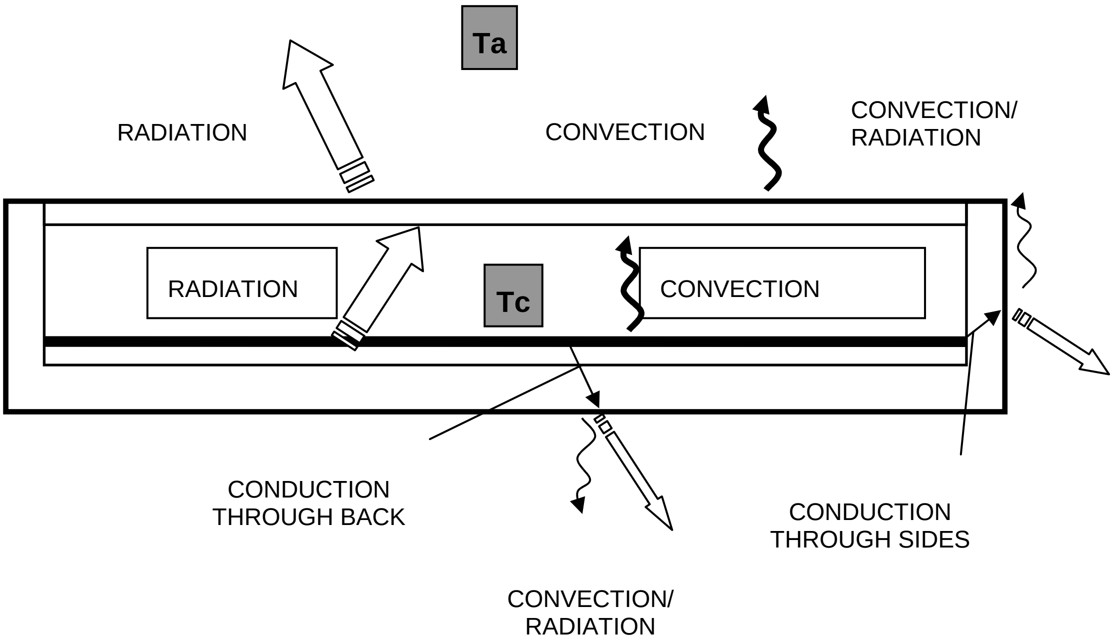


Figure 3.1.1 – Heat transfer via conduction, convection and radiation in a collector

Figure 3.1.1 shows all three heat transfer modes operating inside and from the outside surfaces in a solar collector with a glass cover on top, black absorber plate inside a box with insulated edges and back (note: Ta = air temperature, and Tc = collector absorber temperature).

Radiation is the transfer of heat via direct rays of electromagnetic energy. This is the main way heat is transferred through the air or even across vacuums. We feel this process when we stand in the sun or close to an electric radiator. In the sun, we feel all the electromagnetic parts of the sun's energy being absorbed into our skin and heating it. This includes the ultraviolet (UV) rays, which will eventually burn us, and short infra-red (IR) rays, both of which we can't see. And of course solar radiation includes the light rays that we can see. When we stand next to an electric radiator, we feel much longer infra-red rays.

In a solar collector, solar energy is transmitted as short-wave electromagnetic radiation to the absorber plate. Heat is also re-radiated to the surrounding space from all surfaces of the collector that are at a higher temperature than their surroundings. Mostly, the heat is re-radiated from the absorber plate to the glass above it, and then from the glass to the sky above, as these are the hottest surfaces in the collector.

In all the processes above, two important things occur. Heat always moves eventually from hotter to colder areas or objects, and the total amount of energy in the whole system remains the same. One way to think of this is as follows. If one litre of hot water at 60ºC is mixed into one litre of cold water at 20ºC, we will end up with two litres of hot water at 40ºC.

This means that heat collected by our solar heater and stored in our storage tank will always try to return and heat the surrounding air, which is at a lower temperature. By good design, we are able to capture some of the solar energy (typically about 40%) and transfer it to the taps as hot water. Even the energy in this hot water will eventually go back to heating our surroundings, after it has been used by us.

Pressure, temperature and expansion

Water is the main heat transfer fluid used in open loop water heating systems. It has some important properties that affect the design of water heaters. Firstly, when water is heated, several changes can occur (in closed loop systems the heat transfer fluid is a glycol-type fluid, which has many similar characteristics to water):

- an increase in temperature
- an increase in volume (hot materials expand)
- an increase in pressure if the volume is kept constant.

For example, one litre of water at 20°C will expand to 1.006 litres at 40°C. At 100°C that same litre of water would occupy 1.042 litres just before it boils. If this water is contained in an unvented cylinder (such as our hot water storage tank) and heated, then the volume of the tank cannot increase as the tank is not a very flexible material, and so the pressure inside will increase. The cylinder of our storage tank must be able to handle a certain amount of this pressure without making the tank too heavy and too costly. If the pressure becomes excessive, then there must be a system to relieve that pressure. Failure of that system could result in the explosive bursting of the cylinder.

To cope with this increase in pressure, **mains pressure tanks** must be designed to operate up to a maximum pressure that is specified in engineering Standards such as AS/NZS3500. As well, a safety valve, such as a pressure and temperature relief valve, may be fitted that will relieve pressure in the tank at a preset temperature and pressure by draining some water out of the tank to ground. **Gravity feed tanks** operate at atmospheric pressure. These require an expansion tank above the storage tank. This small tank also contains a float valve to top up the tank as hot water is drawn off. Details of these systems are shown in subsequent chapters.

It should also be remembered that water boils at 100°C at atmospheric pressure (101 kPa), but at 200 kPa the boiling point is 121°C. If water at this temperature is released to the atmosphere it will immediately turn to steam – explosively! These high temperatures and resulting pressures could injure people or damage equipment.

Secondly, when water cools, it initially contracts in volume (under constant pressure) until about 4ºC when it expands. This has practical impacts upon the design of solar water heaters for freezing conditions, as this expansion of water can crack pipes and tanks. System design features and precautions to cope with freezing are explained in subsequent chapters.

Principles of thermosiphon flow

In a thermosiphon solar water heating system, there is no pump to circulate the water from the collectors to the storage tank. Yet the water heated in the collectors flows to the storage tank and the cold water from the bottom of the storage tank flows to the bottom of the collectors. What causes this circulation?

The circulation occurs because the water expands and becomes less dense as it is heated. This makes the water lighter than the cold water, so it floats on top of the colder water. Due to the location of the storage tank above the collectors and the continuous upward rise of the collector riser and header tubes, and the return pipe from the collector to the tank, the less dense hot water can rise to the top of the collector, up through the return pipe to the hot water storage tank. Its place is taken by the colder, denser water from the bottom of the tank that will sink slowly down the collector supply pipe. **Thermosiphon** flow is the name given to this flow and it is an example of natural convection. The driving force is due to the change in density of the water as it is heated. Figure 3.1.2 below shows this circulation in a typical close coupled thermosiphon system.

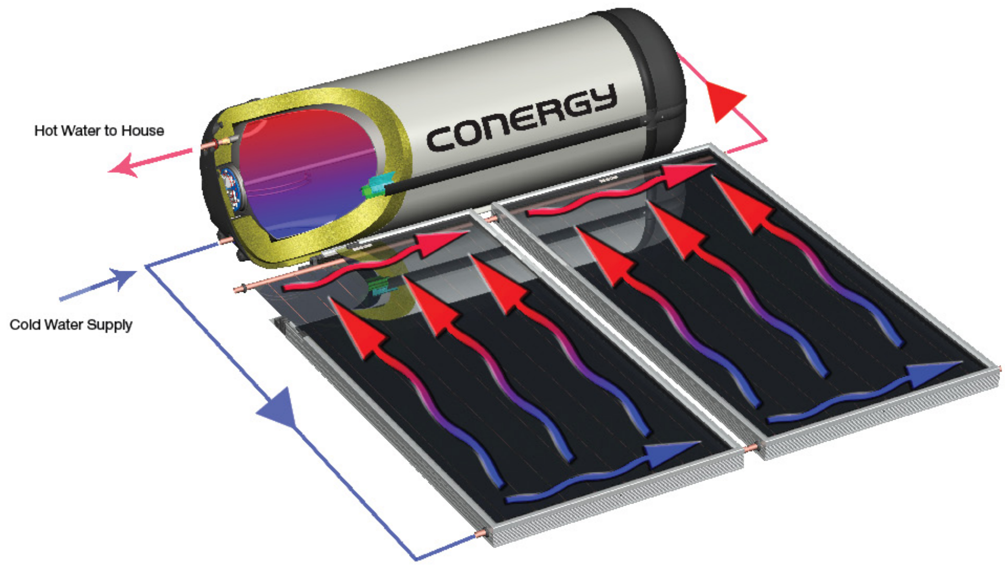


Image: Courtesy Conergy

Figure 3.1.2 – Thermosiphon flow in a close coupled system

A thermosiphon system has a cost advantage over a pump-circulated system. A pumped system requires a pump and a pump controller as well as a power supply to run the pump. Pumps and controllers can add some extra complexity to a solar water heater system.

Stratification in hot water storage tanks

Stratification is the tendency for stored water to remain in layers of different temperature, with hot water at the top layer and cold at the bottom. Heated water expands, becomes less dense and can float on colder denser water. Since water is a poor conductor of heat, the water can remain in different temperature layers until it is agitated:

Relative density of water at 20°C = 0.998kg/m^3

Relative density of water at 60°C = 0.983kg/m^3

The stratification in a tank of hot water allows the hottest water to be drawn from the top of the tank. Incoming cold water is fed through a baffle or spreader pipe so that it will create the least disturbance to this stratification. Figure 3.1.3 below shows a cut-away through a typical close coupled, thermosiphon solar system tank.

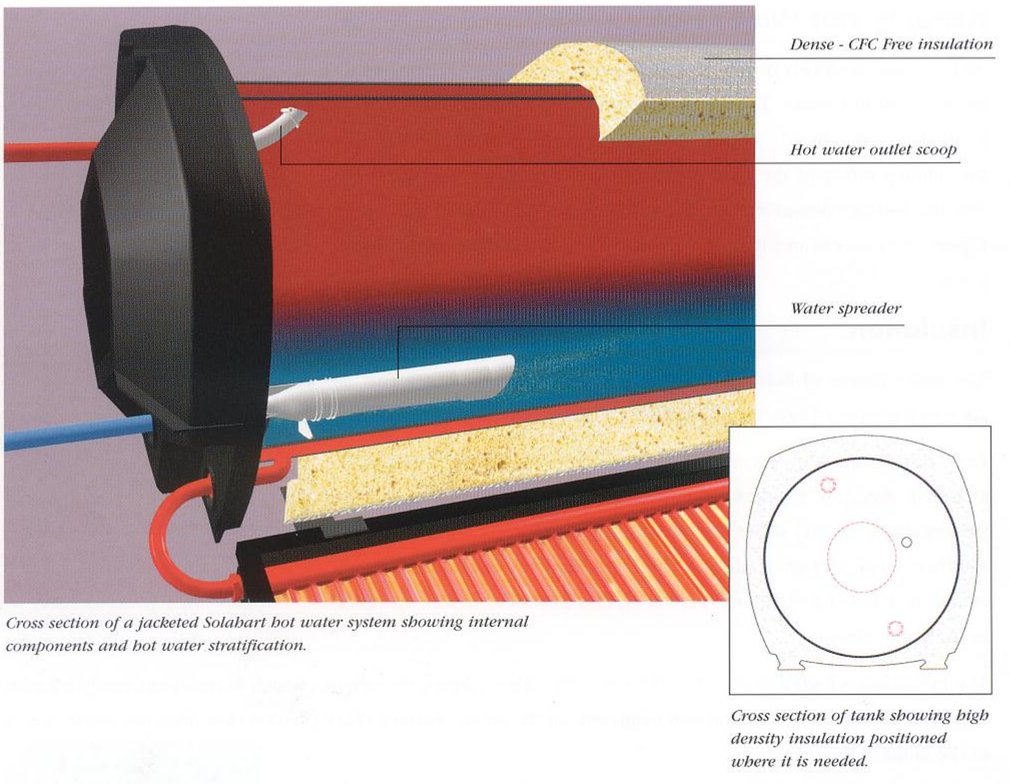


Image: Courtesy Solahart

Figure 3.1.3 – Cross-section through a close coupled system storage tank

This diagram shows the stratification of the water in the tank with the hotter water at the top and the colder water at the bottom. To prevent or minimise mixing of hot and cold water, cold water is brought into the bottom of the tank through a specially designed spreader pipe that slows the water velocity and spreads it along the bottom of the tank.

Conversely, at the top of the tank the hot water outlet pipe is scooped upwards inside the tank to draw water from the hottest level. Note also that good insulation is wrapped around the tank, and the tank is located further to the bottom of the insulation so that the insulation is thicker at the top where the hottest water is located.

Key points

- Heat is thermal energy due to the vibratory motion of atomic particles within a solid material, liquid or gas. We measure heat energy by measuring temperature.
- Heat always flows from hotter to colder areas or materials and the total amount of energy in the whole system remains the same.
- Heat is transferred in all solar energy systems via conduction, convection and radiation.
- As they heat up, solar collectors and storage tanks try to lose heat back to the surrounding air via conduction, convection and radiation. Good system design tries to limit this.
- The choice of materials in the construction of solar collectors affects their performance. For example, absorbers need to be good conductors of heat to efficiently transfer solar energy to the heat transfer fluid (often water). The absorber plate and the storage tank need to be insulated to prevent heat loss to the air.
- The properties of the heat transfer liquid affect the construction materials of the collector and storage tank. Water is the most common heat transfer liquid used and designers must account for its properties, or for the properties of other heat transfer fluids if they are used.
- Water expands as heated, and in closed mains pressure systems exerts a pressure on the inside of the storage tank and collectors. Both must be strong enough to cope and have some form of safety protection to prevent rupture if the pressure is too high. This is usually a pressure/temperature relief valve that drains some water from the tank to ground if the pressure or temperature exceeds set limits.
- Water boils at about 100ºC at atmospheric pressure and at higher temperatures as the pressure increases. If steam forms inside the system, it could cause tanks to rupture and cause injury to people.
- Water contracts in volume at constant pressure until about 4ºC when it expands again. This can cause cracking of pipes if the design does not take this into account.
- Thermosiphon flow is used in many systems to transfer the heated water in the collector to a storage tank. It uses the natural convection principle that a heated fluid will expand and become lighter, and so rise to the top of the container that encloses it. This means that the storage tank must be higher than the solar collector and the pipe work must all rise continuously upwards from the collector to the tank.
- Stratification of hot water occurs when hot water is stored in a stationary condition in a tank. The hottest water rises to the top and the coolest falls to the bottom. A small amount of conduction will occur between layers. This stratification assists the operation of the hot water system by allowing the hottest water to be drawn off from the top of the tank.
- To prevent mixing of hot and cold water, specially designed pipes are used to feed and spread the cold water into the bottom of the tank at low speed. At the top of the tank, the draw-off pipe is scooped upwards to take water from the hottest level.

3.2 Collector types and operating principles

What this section is about

Different solar collectors are designed to operate efficiently over different temperature ranges and using different heat transfer fluids. For example, pool heating collectors look different from residential hot water collectors because they only have to heat water to a maximum of about 30ºC. Residential hot water collectors, however, need to be able to heat water to 60ºC or higher. In this section, we examine the features and construction of different collectors for domestic hot water supply, including:

- the construction and components of flat plate collectors and evacuated tube collectors
- the effect that each of the structural components has on the operation of the collector as a whole, in relation to maximising absorption of solar radiation and minimising heat losses by conduction, convection and re-radiation
- selective absorber surface coatings and their effect on the performance of a solar collector
- the effect that winter and summer conditions have on the solar collector.

Flat plate collector systems

Flat plate collectors have been used since 1950 in Australia. Their principle of operation is relatively simple, but there have been advances in the construction technology, materials and absorber surface that are used by different manufacturers. All have a box, usually made of steel or aluminium sheet. The absorber plate, with tubes attached for a heat transfer fluid to pass through, is in the middle of the box. Beneath the absorber plate is insulation to prevent the loss of heat out through the bottom of the box. Above the plate is a transparent cover, usually glass, which is designed to trap solar radiation and convert it to heat in the absorber plate. It also prevents cold air from blowing over the plate and taking this heat away. Figures 3.2.1 and 3.2.2 show the various components.

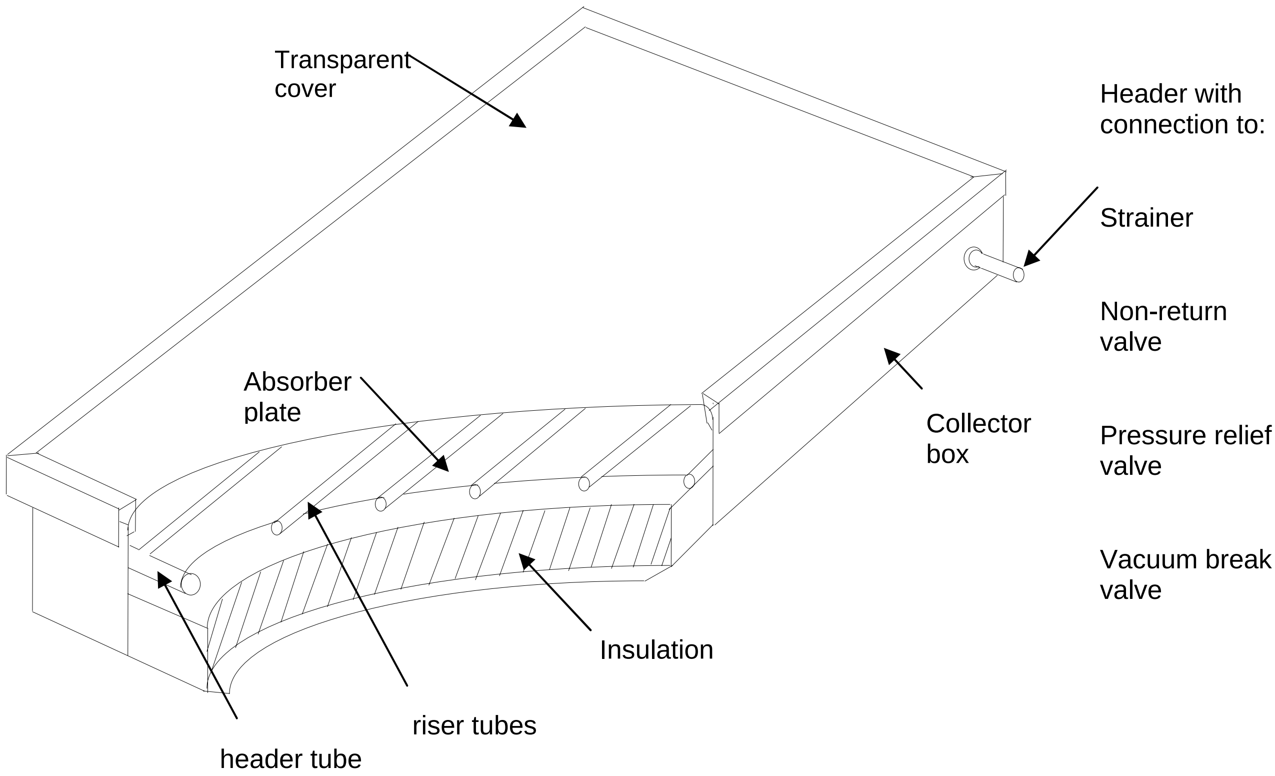


Figure 3.2.1 – Construction details of a flat plate collector

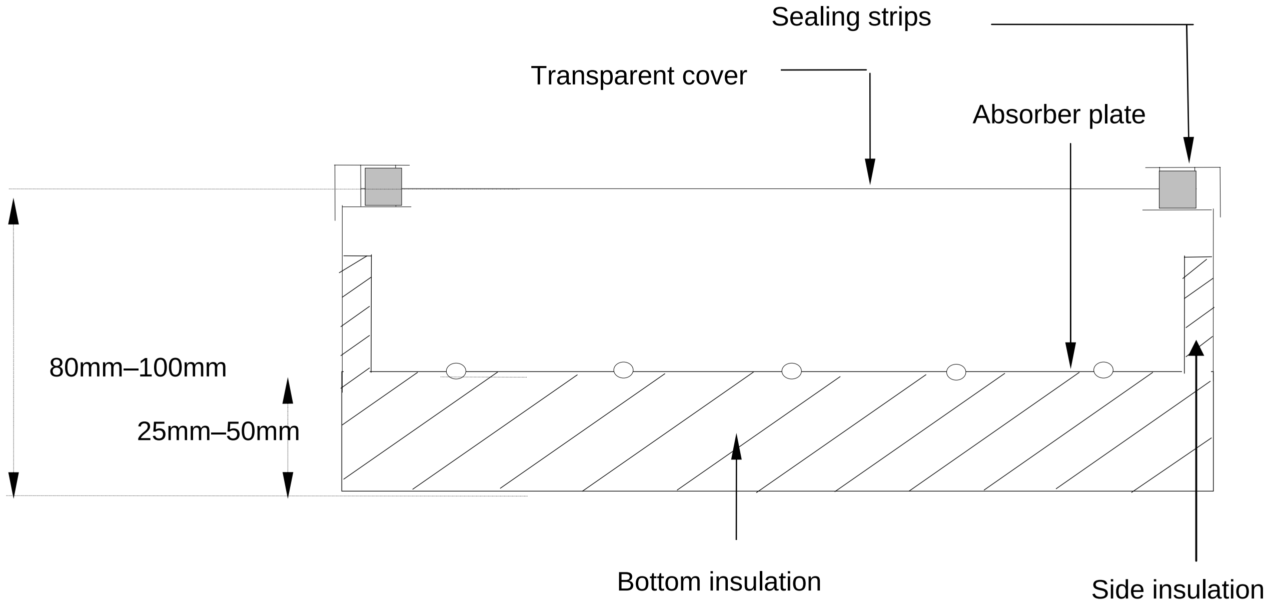


Figure 3.2.2 – Cross-section of a flat plate collector

Principle of operation

Two processes happen at the same time inside a solar collector:

- When the sun shines through the glass cover, **the solar radiation**, both the direct and diffuse parts*, is absorbed by and heats the absorber* *plate.* The absorber plate conducts heat to the water in the riser tubes connected to it.

- *Heat is lost from the absorber plate back to the surrounding air via the transparent cover.* This is because heat always tries to flow from hotter to cooler areas. As well, the transparent cover is not a good insulator so it allows heat to escape from the top surface.

Heat is, in fact, lost from all external surfaces of the collector via convection, conduction and re-radiation. These energy losses can be reduced by:

- for conduction – bulk insulation such as rock wool or fibreglass around the sides and back of the collector
- for convection – a transparent cover to protect the absorber plate from winds
- for re-radiation – a transparent cover to trap energy re-radiated from the absorber plate, and selective surfaces on the absorber plate to reduce the amount of re-radiated energy from the absorber surface.

The function and design of the components of flat plate collectors are discussed in more detail below.

Absorber plate

For best performance, the absorber plate should have the following features:

- highly absorbing surface for the incoming solar radiation (typically a dark colour); that is, a high **absorptance** factor (such as 0.95; i.e. 95%)
- re-radiation of very little heat (infra-red) radiation from the absorber surface as it gets hotter; that is, a low **emittance** factor (such as 0.05; i.e. 5%)
- high conduction of heat to the heat transfer fluid (typically water or water/glycol)
- suitable mechanical strength and corrosion resistance.

How the heat transfer fluid (water or water/glycol) is brought into contact with the plate also affects the efficiency of heat transfer from the plate to the fluid. It is typically done in one of three ways:

- Header pipes at the top and bottom of the collector are joined by risers. The risers are in thermal contact with the absorber plate. These are called **fin and tube collectors**.
- The absorber plate is made of two sheets with welded seams joining the two together. Waterways are formed between the welded seams and the fluid passing through is heated directly by the sun. These are called **flooded-plate collectors**.
- There are also available plastic, rotationally moulded systems that integrate collectors with a storage tank. These require less protection from over-heating and ‘hard’ water quality (see Chapter 5 for details of water hardness).
- **Serpentine collectors** have a pipe coiling backwards and forwards across the absorber plate. This pipe is thermally bonded to the absorber plate and as the water passes through the pipe it absorbs heat from the plate.

- The '**heat sheet**' collector is a lightweight, flat-plate heat pipe, consisting of two sheets of steel seam-welded together at the edges and carrying a pattern of indentations. The indentations create a vapour space within the heat-sheet that is evacuated and into which a working fluid is introduced, providing a two-phase thermosiphon process. The working fluid collects heat from the collector, transfers it to the water via a copper tube heat exchanger and the condensate returns via gravity from the condenser end to the evaporator end.[1]

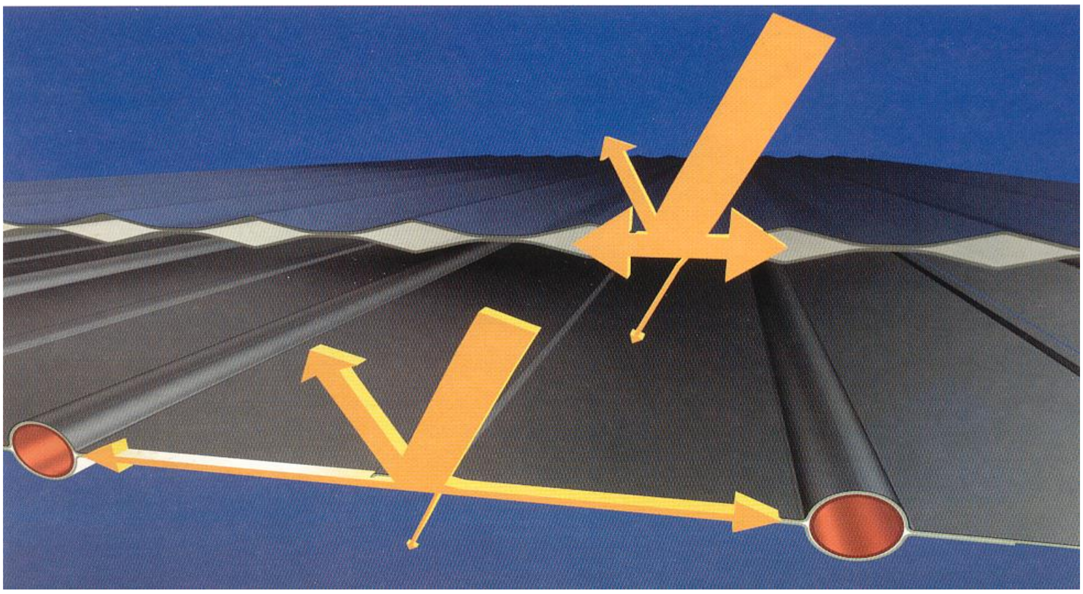


Photo: Courtesy Solahart

Figure 3.2.3 – Types of absorber plates

Figure 3.2.3 shows a cut-away of typical absorber plates including a fin and tube collector (lower) and a flooded plate collector (upper). The fin is wrapped around the tube to better conduct heat to the tube. A thermal paste is used between the fin and tube to prevent corrosion if different metals are used. Typically, either the fin is aluminium and the tube is copper, or both are copper. See Figure 3.2.4 (below) for more examples.

The flooded plate collector uses two pressed metal sheets that are then spot welded together to form passageways for the heat transfer fluid. Because the fluid is in contact with almost the whole absorber inner surfaces, the heat transfer to the fluid is improved, and cheaper, lower conductivity absorber materials can be used such as steel or even plastic.

Serpentine collectors are less frequently used due to their lower efficiency of transferring the absorbed heat to the heat transfer fluid. But they are a little cheaper to make.

[1] Information courtesy Thermocell Ltd New Zealand (www.thermocell.co.nz).

Photos: Andrew Blair

Figure 3.2.4 – Fin and tube collectors – a stack of riser/headers (left) and absorber plates (right) ready for assembly

Absorber plate surface coatings

Simple coatings, such as black paint, work satisfactorily to absorb solar radiation but they are also high emitters of heat from the absorber surface as it gets hotter. This heat leaves the absorber surface as infra-red radiation and is absorbed by the glass above. This glass gets hot and loses heat to the surrounding air. This makes the collector less efficient at heating water.

To improve the performance of the absorber surface, special surface coatings have been developed called '**selective surfaces**'. Common selective surfaces include chromium, copper, nickel or titanium oxides that are electro-chemically or chemically applied to the absorber surface. They provide close to the ideal characteristics required for the absorber plate; i.e. high absorptance of solar radiation and low emittance of infra-red re-radiated energy from the hot absorber surface.

Selective surfaces improve the efficiency of solar radiation collection and reduce heat losses from the collector's transparent cover to the surrounding cooler air. They are therefore most beneficial in colder climates. They are also used in commercial applications where higher water temperatures may be required.

Transparent collector cover

The essential purpose of the transparent cover is to:

- transmit the maximum amount of solar radiation to the absorber plate to heat it
- trap the re-radiated infra-red (heat) radiation that is emitted from the absorber plate towards the transparent cover
- prevent wind from blowing directly over the absorber plate and removing heat
- be strong and long lasting

- be cheap and readily available.

Some glasses and plastics contain these characteristics. The most common material for the transparent cover is toughened, low-iron glass. Compared with normal window glass and many plastics, low-iron glass has the following improved qualities:

- It has very high transmittance and hence reflects and absorbs less solar energy as the sun's rays pass through it. More energy gets to the absorber plate.
- Less energy is re-radiated and lost from the cover to the surrounding air because it stays cooler due to its lower absorptance.
- It can be etched on one surface to further reduce reflection of solar radiation.
- It is very long lasting and strong, and will resist hail damage and many other 'neighbourhood' projectiles.

Collector box

The outer box of the collector must be able to do the following:

- protect the absorber plate from water ingress, hail, snow, dust and corrosion
- provide sufficient mechanical strength against both thermal stresses and wind forces, and be UV-resistant
- support and protect the insulation around the sides and back of the absorber
- be light enough to handle and easy to install
- provide a long, low-maintenance life.

Aluminium is now a commonly used box material.

Evacuated tube collectors

In flat plate collectors, significant heat is lost mostly by convection and re-radiation through the top surface of the collector. This heat loss increases as the water temperature in the collector gets hotter during the day. So while the collector is highly efficient at the beginning of the day (e.g. 70%), the efficiency decreases as the water circulating through the collector gets hotter.

In evacuated tube systems, this heat loss is reduced by almost totally eliminating conduction and convection heat losses. This is because the space between the absorber and the glass outer tube is evacuated. With little air to move and transfer heat by conduction and convection, heat loss is further reduced. Radiation losses are reduced by incorporating a selective surface on the absorber, similar to flat plate collectors. As a result, evacuated tube collectors can operate at temperatures above 100ºC, compared with about 100ºC for flat plate collectors.

The principle of operation is similar to a flat plate collector in that solar radiation (both direct and diffuse) enters through the glass tube and is absorbed by the absorber plate, which transfers the heat into a heat transfer fluid inside the collector tube. The heat transfer fluid (generally an anti-freeze liquid) can be passed in one of three ways through the evacuated tube collector:

- in one direction only between top and bottom manifolds
- into (down) and out (up) the collector through concentric tubes or a U-shaped tube,
- up (as vapour) and down (as liquid) in the same inner sealed tube, often copper which is itself evacuated. This is known as a heat pipe.

Cross-sections of a heat pipe and concentric tube types are shown in Figure 3.2.5 (below).

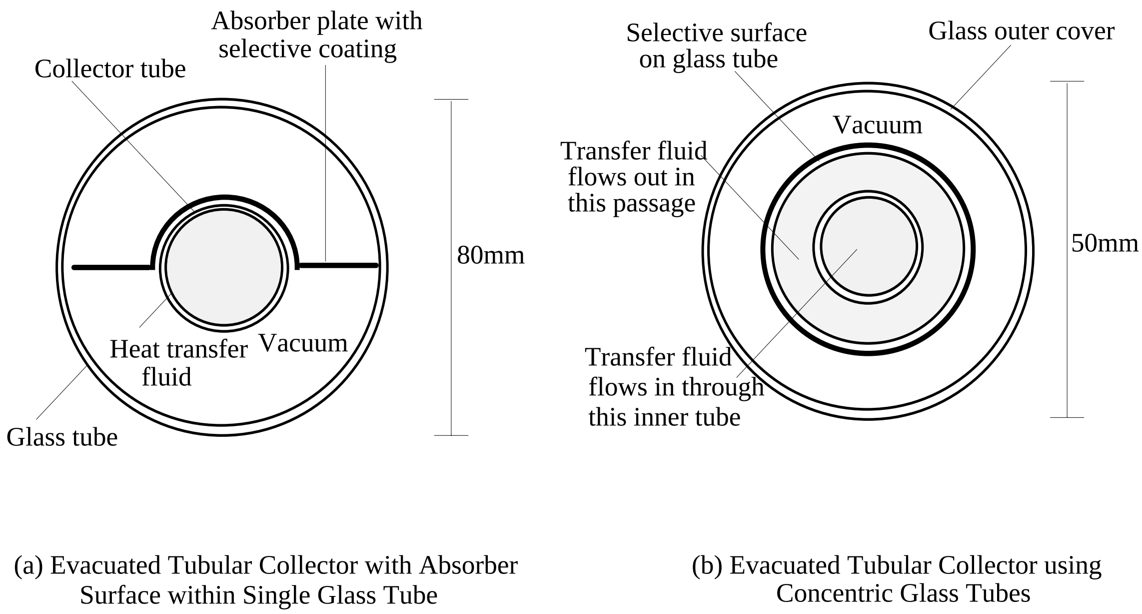


Figure 3.2.5 – Cross-section of evacuated tube collector types

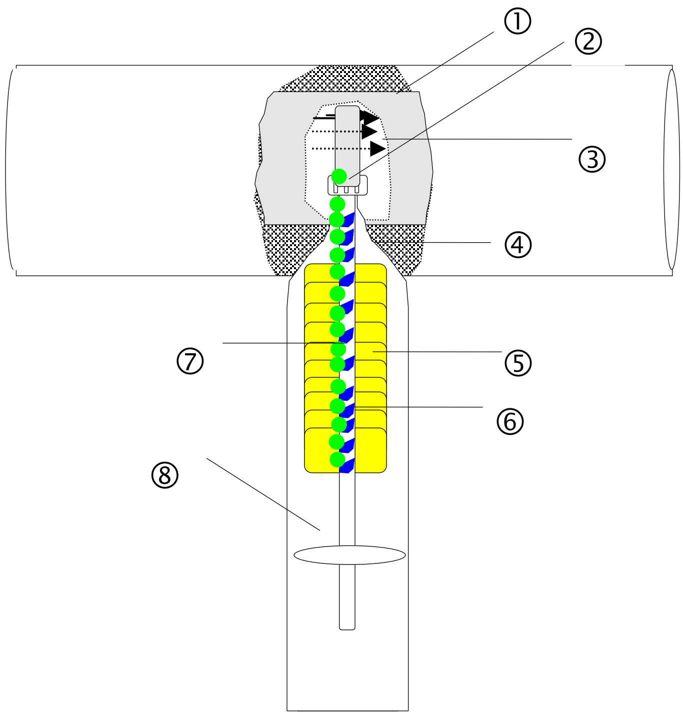
The U-tube type of construction is shown in Figure 3.2.6 (below). The photographs show the copper U-tube with an aluminium fin mounted inside to form a roughly cylindrical shape. This is then inserted in an evacuated glass tube shown to the left in each photograph. Each tube is inserted into an insulated manifold box at the top, which captures the heat and transfers it to a storage tank.

Photos: Andrew Blair

Figure 3.2.6 – Constructions details for a U-tube type evacuated tube collector

Figure 3.2.7 (below) shows the principle of the heat pipe in action. The heat pipe is the sealed copper tube in the centre of the evacuated tube. An absorber fin is attached. The tube contains a refrigerant (often water) at a reduced pressure. The water in the tube will boil well below 100ºC. For example, depending on the pressure, it may boil at 40ºC. When it boils it forms water vapour that fills the tube and rises rapidly to the top. Heat is removed at the top of the tube as a fluid passes over the heat exchanger at the top of the heat pipe.

The vapour condenses to a liquid and flows back down the tube where it is reheated. The heat pipe must be inclined to transfer heat up the tube. The heat pipe is like an electronic diode or a plumbing non-return valve. The heat is transferred up but not down the tube.



(1) Insulated manifold
(2) Condenser
(3) Water flow
(4) Heat pipe
(5) Absorber plate
(6) Liquid coming down
(7) Liquid going up
(8) Glass tube

Image: Courtesy Endless Solar

Figure 3.2.7 – Heat pipe evacuated tube system

Winter and summer performance of collectors

What are the factors that affect winter and summer performance of collectors? Firstly, as the collector heats up during the day, hot air rises from the absorber to the glass cover of the collector. If the air above the glass is warm, as in summer, then the heat stays beneath the cover as heat flows from hot to cold areas. If the air above the glass is cool, then heat is lost to the atmosphere by conduction of heat through the thin layer of glass, and then by convection and re-radiation from the cover surface to the surrounding air. This means that in winter when the day is cold, a lot of heat is lost to the atmosphere through the glass, even on a bright sunny day.

Secondly, the weather patterns vary throughout Australasia. This includes periods of rainfall, cloud and solar radiation, ambient temperatures, wind speeds and dust. For example, in Melbourne, Adelaide and Perth the climate tends to bring most rain in winter, day lengths are much shorter than in summer and the sun is lower in the sky all day. These factors reduce solar radiation levels. By comparison, in Brisbane, Rockhampton, and Alice Springs the winters are often sunny with most rain falling in summer. Days are not much shorter and the sun is higher in the sky than it is further south.

Overall, this means that in most parts of Australasia, solar collectors produce more hot water in summer than in winter for the following reasons:

1. The days are longer and the sun shines for more hours, heating the water for a longer period.
2. In southern coastal parts of Australia, there is less cloud during the summer and more in winter due to winter rains. So again the water is heated for a longer period of time.

3. Because New Zealand is an island, cloud cover is persistent year-round. However, winter rains and low temperatures reduce solar gain in winter.
4. The air surrounding the collectors is warmer in summer so there is less heat lost through the glass, back to the atmosphere.
5. The cold water supply is usually warmer in summer than in winter. Because it is warmer before heating starts, it is possible for it to reach a higher final temperature.

Key points

- **Flat plate collectors** consist of the following components:
    - a transparent top cover (typically glass) to allow solar radiation to pass through to an absorber plate
    - an absorber plate to absorb solar radiation and convert it to heat
    - a series of passageways through, or attached to, the absorber plate through which a heat transfer fluid passes to collect the heat energy
    - an insulated box to prevent weathering and reduce heat loss from the absorber plate.
- **Evacuated tube** collectors consist of the following components:
    - a cylindrical glass tube to allow solar radiation to pass through to an absorber plate
    - an evacuated space between the glass tube and the absorber surface
    - a long, thin absorber plate either as a flat metal fin, cylindrical metal fin or cylindrical glass tube within the outer clear tube
    - a glass passageway, metal U-tube or one-way metal tube on the inside of the absorber to pass a heat transfer fluid through to collect the heat.
- The principle of operation is that solar radiation passes through and is trapped by a transparent top cover in a flat plate collector. This trapped radiation is absorbed by the absorber plate, converted to heat and conducted to a heat transfer fluid circulating through the collector. This heat is then circulated and stored in an insulated storage tank for later use.
- The heating ability of a collector is determined by how effectively it collects solar radiation and how little heat is lost from the hot collector back to the surrounding air.
- To maximise collection of incoming solar radiation from flat plate collectors:
    - use highly transparent top covers that allow maximum solar radiation through but limit re-radiated energy from the absorber plate
    - use highly absorbing surfaces on the absorber plate.

- To minimise heat losses from the absorber plate of a flat plate collector:
  - insulate the back and sides of the box
  - use absorber surfaces that limit re-radiation from the absorber plate
  - use one or more transparent covers to reduce heat loss by wind from the top of the collector
  - evacuate the space between the transparent cover and the absorber plate.

Sections 3.1 & 3.2 questions

1. Solar radiation passes through the transparent surface of solar flat plate collectors and is absorbed on the absorber plate.

   a. How does the heat energy reach the water in the collector?

   b. Not all of the heat energy heats the water in the collector. What happens to the heat that is not transferred into the water?

   c. What purpose does the glass serve in flat plate solar hot water collectors?

   d. Modern flat plate collectors use low-iron glass rather than window glass used in some older collectors. Low-iron glass is more expensive than window glass so why is it used?

   e. Solar swimming pool heating collection material does not have glass covering it. Why is glass covering comparatively unimportant for pool heating?

2. Flooded collectors are able to be used for solar hot water systems where the absorber material is plastic or steel. Why would plastic be unsuitable for fin and tube flat plate collectors?

3. Australian scientists invented the use of ‘selective surfaces’ for solar hot water systems. Why is a selective surface so much better than just plain black paint for the plates (fins) of solar collectors?

4. Why are evacuated tube collectors cylindrical? Why aren’t flat plate collectors made with a vacuum between the absorber plate and the glass cover?

5. What is a ‘heat pipe’?

3.3 Storage tanks

What this section is about

Storage tanks should be robust, long lasting and well insulated to store the heat energy from the solar collectors. This section examines some of the features of storage tanks for solar water heating systems. It covers the following topics:

- tank materials and construction requirements
- insulation
- outer casing
- stratification and preventing mixing
- tank shape
- draw-off
- tank connections for solar collectors and/or solid fuel heaters
- heat exchangers and tanks.

The storage tanks can be subjected to harsh water conditions and thermal stressing. To be robust and provide good life, they must be constructed of materials that are:

- durable
- safe to use and handle
- cost-effective
- low impact environmentally.

The most **common materials** used are:

- low-pressure tanks
    - o copper
    - o plastics such as polyethylene and ABS
- mains pressure tanks
    - o vitreous enamel-lined mild steel
    - o 316 stainless steel

Tank construction

Durability and safety

Domestic storage tanks must be light enough to be handled by two people. They must be strong enough not to rupture and expose workers or users to scalding hot water. They must be able to handle the stresses of expanding water, cyclic thermal stresses of daily expansion and contraction, partial vacuum conditions, corrosion, hail, snow and ultra violet (UV) radiation attack.

There are pros and cons of using different materials. For example, stainless steel forms a thin oxide layer that is generally very corrosion resistant. But it can be corroded around stresses in the welds, for example, under exposure to chlorinated water. By comparison, mild steel does not have the corrosion resistance of stainless steel and must be coated with a glass vitreous enamel lining to stop direct contact with water. Generally two layers are used: one that bonds with the steel well and the other that resists cracking or crazing at higher temperatures and cycling thermal stresses.

Sacrificial anodes that will corrode in place of the steel are also used in vitreous enamel-lined tanks for further protection. This may increase maintenance costs. Copper can also be corroded, particularly when in contact with other metals or via stress corrosion cracking. Plastics, while highly corrosion resistant, are subject to attack by UV radiation and may become unstable at high temperatures.

All tanks in the Australian and New Zealand market have to meet stringent engineering Standards such as AS/NZS 2712 – Solar and Heat Pump Water Heaters: Design and Construction. As a result of these Standards, all systems on the Australasian market provide long life when properly installed and maintained. In all cases, maintenance of tanks and collectors increases and system life decreases when conditions are extreme; e.g. very harsh water supplies.

Insulation

Insulation reduces the heat loss to the air. This is wasted energy that is no longer available at the hot water taps. The insulation requirements and allowable heat loss rate from storage tanks are specified in AS/NZS 4692 – Storage Water Heaters. In the past, this Standard has allowed excessive heat losses from storage tanks, in excess of 30%. In recent years, these Standards have been improved with the introduction of Minimum Energy Performance Standards (MEPS). Solar water heater tanks have generally been better insulated than normal electric or gas water heater tanks.

Typically, high density polyurethane foam insulation is injected between the inner tank containing the **drinking (potable) water** and the outer weatherproof shell. The inner tank is located within the outer shell to increase the thickness of the insulation at the top of the tank. Figure 3.3.1 shows this in a cut-away view of a horizontal storage tank.

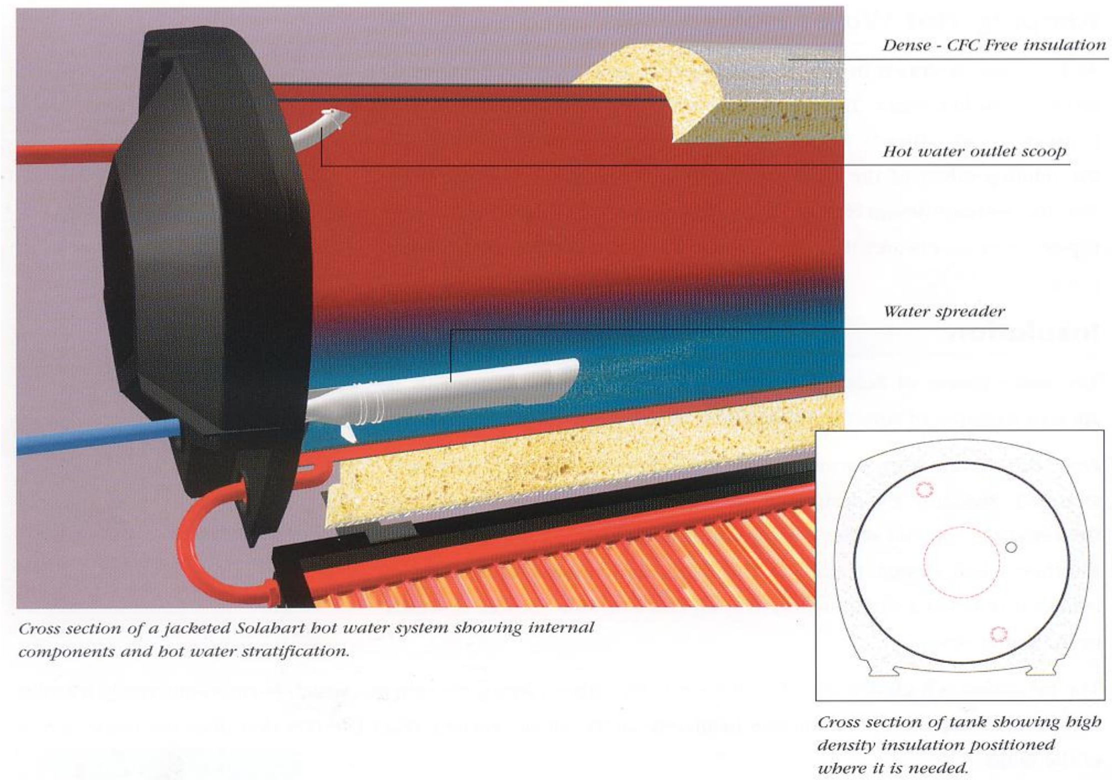


Image: Courtesy Solahart

Figure 3.3.1 – Cut-away view of a typical horizontal storage tank

Environmental impact

All water heaters have some environmental impacts, either as a result of their construction materials or the energy used in service. Ideally, the materials used for the construction of solar collectors and tanks should be:

- made in production processes that minimise use of energy and toxic materials
- easily reusable or recyclable at the end of their service life.

These criteria are now being written into Australian and international standards.

Outer casing

The outer casing must protect the insulation and inner tank from the weather. The most common materials used are:

- anodised aluminium
- colour bond aluminium
- UV-resistant plastic.

The outer casing must also be strong enough to handle and provide protection during transport. It must also protect the electric boost element.

Tank use

Stratification and preventing mixing

Stratification is explained in an earlier section – 'Principles of Water Heating'. It assists with the delivery of hot water by allowing the hottest water to be drawn off from the top of the tank. To prevent or minimise mixing of hot and cold water, cold water is brought into the bottom of the tank through a specially designed spreader pipe that slows the water velocity and spreads it along the bottom of the tank (see Figure 3.3.1).

Tall tanks have much better stratification, and maintain this stratification better than long, low or squat tanks. This is because it is easier for heat to be conducted between hot and cold layers and the tank walls in a long, low tank since the surface area for conduction is much greater. Figure 3.3.2 (below) shows two tanks of the same shape and volume. One is mounted horizontally (tank A) and one vertically (tank B). The shaded area marks the size of the surface area of conduction between hot and cold layers halfway up the tanks. Tank A clearly has a much larger area across which heat is conducted. Hence the lower layers become warmer and the hot upper layers cool a little.

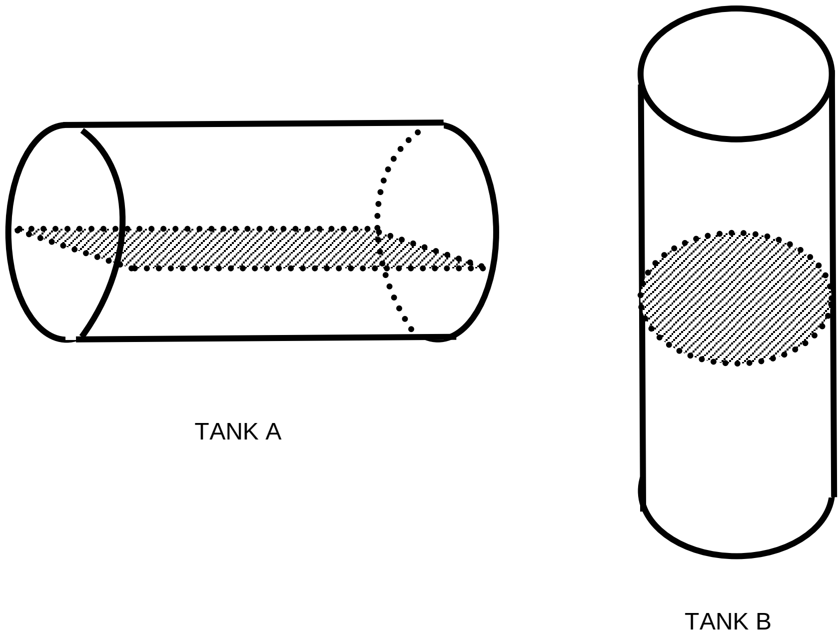


Figure 3.3.2 – Surface area for conduction between layers in storage tanks

Tank shape and size

Tank shape affects the following:

- the rate of heat loss from the tank
- heat transfer between hot upper layers and cooler lower layers by conduction
- the mixing between hot and cold layers in the tank as water is circulated through the tank and/or drawn off from the tank.

Long, thin tanks have a larger surface area for a specified volume and this increases the rate of heat loss for the same thickness and type of insulation. Squat tanks have a smaller surface area and less heat loss.

As water either circulates through the tank due to thermosiphon heating by the collector, pumped circulation from the collector, or draw-off of hot water, then some mixing of the hot layers with the cooler layers can occur. This can reduce the temperature of the water at the hot outlet, making it appear as though the tank has lost a lot of heat.

Tank size is chosen to meet the requirements of the user. Most solar water heater tanks are sized to roughly 75 litres volume of hot water for every $1m^2$ of collector area – or about one-and-a-half to two days' demand of hot water – to cater to some extent for bad weather conditions. These figures have been determined by testing and optimisation of solar water heating system configuration and costs for various hot water loads. This is explained in more detail in Chapter 6.

System performance, draw-off volume and recovery rate

The performance of solar water heating and heat pump systems can be determined from Standards; in particular, AS/NZS 4234 – Water Heaters: Domestic and Heat Pump – Calculation of Energy Consumption; and AS/NZS 2984 – Solar Water Heaters – Method of Test for Thermal Performance – Outdoor Test.

The latter gives the volume of hot water (draw-off) and energy that a system with a given collector area and storage tank size can deliver above 57ºC or 45ºC.

AS/NZS 4692 covers the hot water delivery rating (or draw-off volume) of a given tank size. This is the volume of hot water that can be drawn off at a set flow rate until the temperature falls to a specified temperature. For example, a 300 litre tank may be rated for a draw-off of 280 litres down to 60ºC. They are tested at a 12 litre per minute flow rate and a temperature drop of 12ºC.

Manufacturers also specify the rate of recovery for their tanks. This is the volume of water that the tank can continue to deliver per hour for a specified temperature rise of the water; say 15ºC to 60ºC (i.e. a rise of 45ºC) for each tank and booster heating element size. For example, the heat recovery rate of the gas-boosted tank may be rated at 200 litres per hour for a 45ºC temperature rise.

Tank connections for solar collectors and/or solid fuel heaters

Solar collectors and solid fuel heaters operating under thermosiphon flow require connections to the storage tank that are larger than 13mm and are typically 20mm to 25mm diameter. The connection also has to be located appropriately. The supply pipe from the storage tank to the collector must be located as close as practicable to the tank bottom to draw off the coolest water. With vertical tanks used with either remote thermosiphon storage or split (pumped) storage systems, the return pipe from the collectors to the tank can be returned at about one-third to two-thirds of the tank height. This arrangement helps to create a stratified pocket of hot water at the top of the tank that is largely undisturbed by the thermosiphon flow. However, piping arrangements vary from manufacturer to manufacturer.

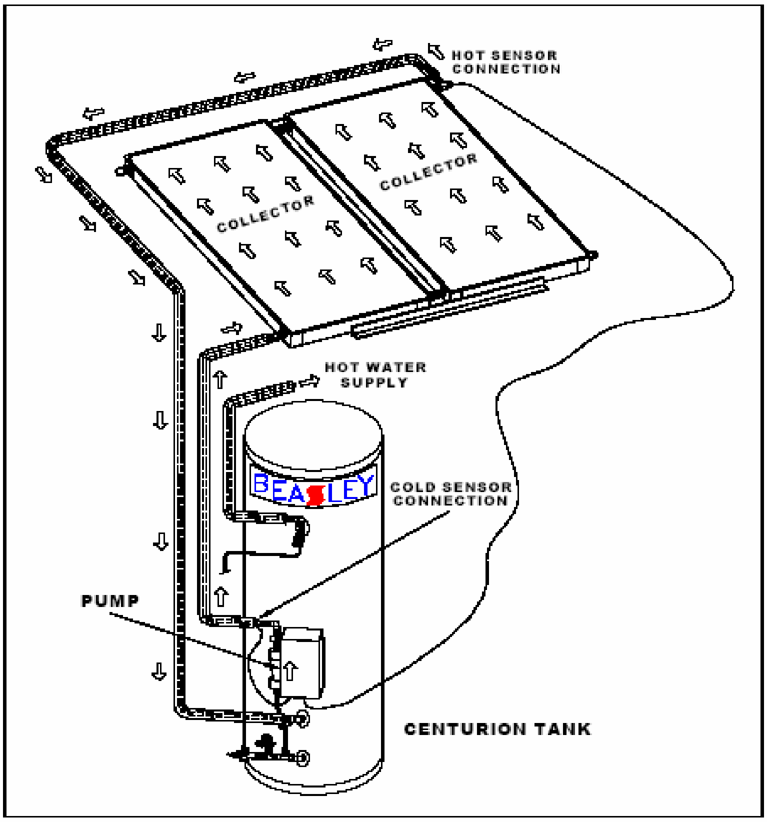


Diagram: Courtesy Rinnai

Figure 3.3.3 – Pipe connections between collector and tank – split system

Retrofitting of existing tanks requires the use of a five-way RMC connector that fits into the cold inlet fitting at the bottom of the tank. This special connector allows cold water to be drawn off to the collectors and the hot water returning to the tank to be injected into the tank through the centre of this connector. This is not an ideal arrangement unless the hot water inlet pipe is bent up to allow the hot water to be above the cold, as it tends to causing mixing of hot and cold water at the bottom of the tank, hence increasing the temperature of the water circulated to the collectors. This in turn reduces the efficiency of the collectors.

For close coupled thermosiphon systems, the collector supply and return pipes exit from the bottom and top of the tank respectively to try to avoid the mixing of hot and cold water inside the tank. Cold water spreader pipes are essential in this design as hot–cold mixing can easily occur.

Heat exchange tanks

In some environments, the water quality is very poor. As well, freezing conditions can cause the water in collectors and connecting pipes to freeze and burst. To overcome these problems, heat exchangers are used to separate the drinking (potable) water from the water circulating through the solar collectors. This allows the use of water/glycol anti-freeze and corrosion inhibiting fluids to be used in the separate collector circuit. Heat exchangers come in many forms. The most common types used in solar water heating system tanks form an integral part of the tank. This is achieved by having an outer tank around the outside of the main inner, drinking (potable) water, horizontal cylindrical tank (see Figure 3.3.4). The section on frost protection will cover heat exchangers in more detail.

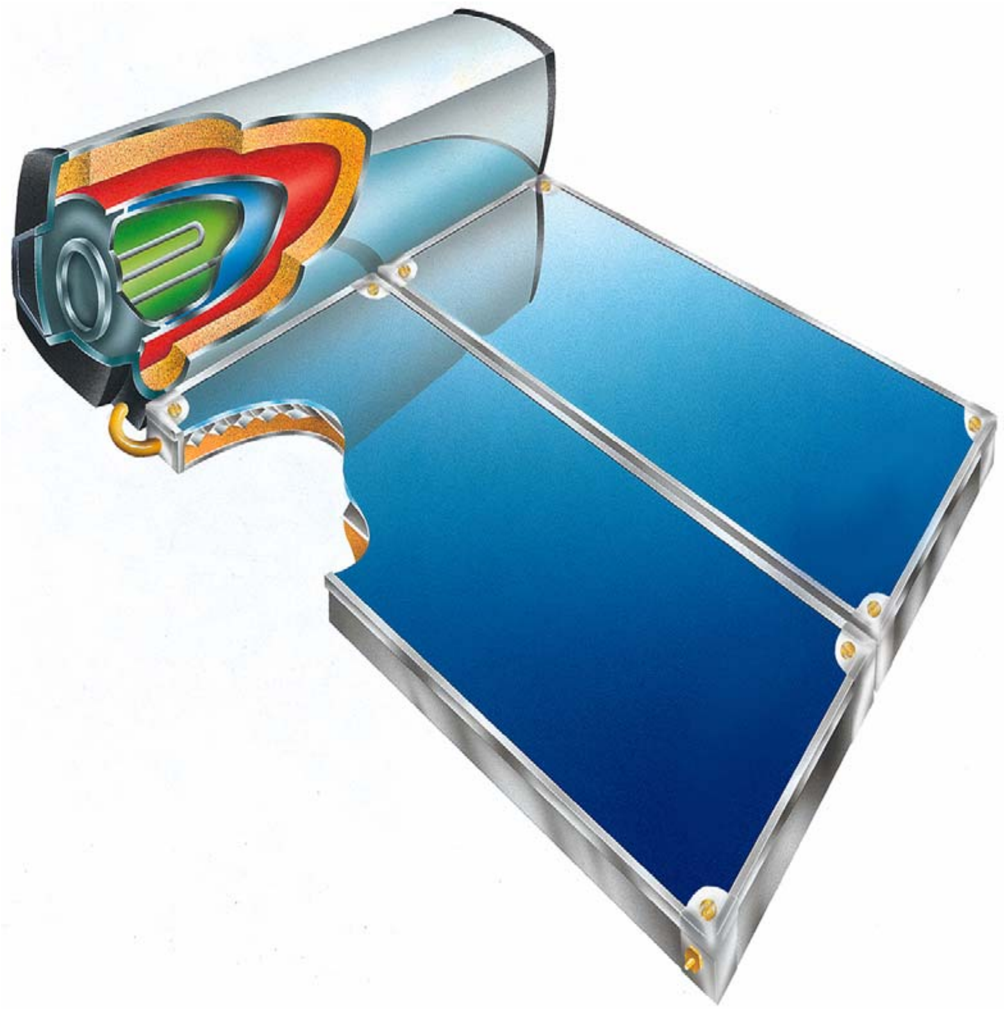


Image: Courtesy Solahart

Figure 3.3.4 –Heat exchanger as a tank around the inner drinking (potable) water tank

For split systems, a copper coil (or calorifier) can be set inside the storage tank through which the drinking (potable) water is passed (see Figure 3.3.5). This is mostly done for larger commercial systems.

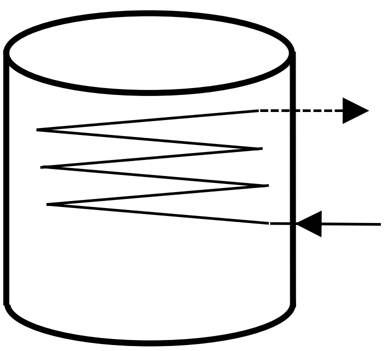


Figure 3.3.5 – Mains pressure copper coil heat exchanger inside the storage tank

Key points

- To be robust and provide good life, storage tanks must be constructed of materials that are:
    - durable
    - safe to use and handle
    - cost-effective
    - low impact environmentally.
- The most **common materials** used are:
    - low-pressure tanks – copper, and plastics such as polyethylene and ABS.
    - Mains pressure tanks – vitreous enamel-lined mild steel and 316 stainless steel
- Good quality, thick insulation will ensure low heat loss from the tank to the surrounding air.
- Consideration should be given to minimising the life cycle environmental impact of storage tanks and solar collectors by reducing toxic material and energy use during construction and using recyclable materials.
- The outer casing of the tank should protect the system from the weather and allow ease of handling.
- Tall, vertically mounted tanks increase temperature stratification within the tank. However, the larger surface area can increase heat losses if not adequately insulated.
- Long, horizontally mounted tanks are prone to mixing of hot and cold layers and require spreader pipes to minimise this adverse effect.
- In poor water quality or freezing environments, heat exchangers are used to separate the drinking (potable) water from the water circulating through the solar collectors. This allows the use of water/glycol anti-freeze and corrosion inhibiting fluids to be used in the separate collector circuit.

Section 3.3 questions

1. Hot water storage tanks are much the same whether they are for solar hot water systems or electric or gas storage systems. They all consist of an inner tank in which the hot water is stored and an outer case. Between the inner and outer cases is insulation designed to reduce heat loss from the stored hot water.

    a. What materials are commonly used for the inner hot water storage tank?

    b. Suggest a reason why the insulation is thicker at the top of a Solahart hot water storage tank than at the bottom, as shown in the small inset in Figure 3.3.1.

    c. The outer case must be able to withstand various environmental factors. What are these factors that might otherwise damage the hot water storage tank?

2. What does the word ‘potable’ mean when used to describe water?

3. Hot water storage tanks are nearly always cylindrical. Why?

4. Most non-solar hot water storage tanks are cylinders, standing on end. Close coupled solar storage tanks are cylinders that are mounted horizontally.

    a. Why are the tanks mounted horizontally?

    b. What problem does this present in terms of stratification?

    c. Suggest why a person with a close coupled solar hot water system may find that their hot water is a lot cooler in the morning than it was when they went to bed.

5. A standard 315 litre hot water storage tank is likely to contain 340 litres of water. Why do we call the tank a 315 litre tank and not a 340 litre tank?

6. What is a heat exchanger and why are they commonly used in solar water heating systems?

3.4 Close coupled solar water heater systems

What this section is about

The close coupled solar water heating system has become the most popular domestic solar hot water system in Australia. This is because of the advantages listed below, and the fact that the product has been vigorously marketed, particularly by Solahart. After significant research, development and market research, Solahart has concluded that a 300 litre unit with $4m^2$ of collector area is the most practical option.

This section covers the following aspects of close coupled solar water heaters:

- the layout of a typical close coupled system
- principles of operation
- the components of a close coupled system
- heat exchanger type of system and the benefits
- methods of boost heating, including electric and gas boosting
- advantages and disadvantages.

Principle of operation

Close coupled systems are so called because the collectors and the storage tank are close together. The storage tank is mounted directly above the collectors. The most common installation has the collectors and the storage tank mounted on the roof. The hot water from the collectors rises by thermosiphon flow through the very short connecting pipes and into the storage tank. The storage tank is able to withstand higher pressures than a gravity-feed, in-ceiling tank, providing hot water at ‘mains pressure’.

Close coupled systems – features

The low-profile storage cylinder is a feature of all Australasian manufactured close coupled solar water heating systems. This has the advantages of:

- Not being too prominent on the roof,
- Spreading the load across a number of roof rafters,
- Being stable on the roof,
- Being relatively easy to install.

Figure 3.4.1 (below) shows typical components of a close coupled system including:

- storage tank (direct heating or integral heat exchanger types available)
- collectors
- auxiliary heating or booster element
- sacrificial anode (vitreous enamel tanks only)
- hot water pressure/temperature relief valve
- cold water valves

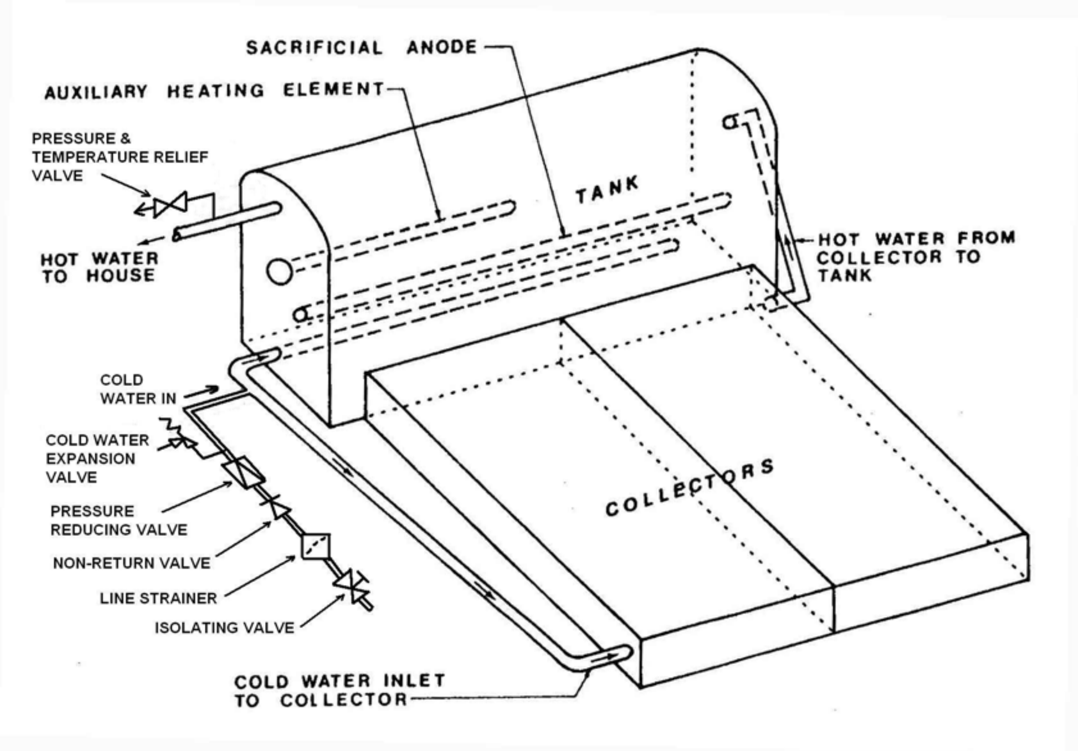


Image and photo: Courtesy Charters & Prior and Solahart.

Figure 3.4.1 – Typical close coupled system and components

Storage tank

Typical storage volume is about 300 litres. Tank sizes vary from 150 to 440 litres.

Tanks may use:

- direct heating of the potable water
- indirect heating of potable water via an integral heat exchanger shell tank that surrounds the inner potable water tank

- indirect heating of potable water via a heat exchanger external to the tank and collectors.

The tank may be supplied with cold water at:

- full mains pressure
- reduced pressure via a pressure reducing valve
- low pressure via a float control valve (vented systems only).

Depending on the operating pressure, the tank may be made from:

- vitreous enamel-lined mild steel (high-pressure systems)
- stainless steel (high-pressure systems)
- moulded plastic (low-pressure systems).

Tanks are reasonably well insulated with about 50mm thickness of high density polyurethane foam insulation.

Collectors

For domestic applications, one, two or three collectors of approximately $2m^2$ area each are used depending on storage tank size. A rule of thumb is $2m^2$ of collector per 150 litres of storage (for construction details, see Section 3.2 – Collector types and operating principles).

Absorber

The absorber is enclosed in a glass-covered metal box made from zinc-alume or aluminium sheeting, insulated at the back and sides. The absorber surface may be painted matte black or finished with a selective surface (e.g. AMCRO or Black Chrome). The glass cover may be toughened low iron, anti-reflective (higher transmittance) or plain window glass (cheaper models).

Absorbers are made from:

- copper pipe attached to copper or aluminium sheeting (fin and tube design)
- all moulded plastic (low-pressure design)
- mild steel (flooded plate design – heat exchange systems only).

The number of collectors and the storage tank size can be changed to meet the demand for hot water.

Cold water entry

Cold water from the mains supply enters the bottom of the tank via a series of valves specified in AS/NZS 3500 (see Figure 3.4.1). These are often in a cluster called a **combination set.** Their purpose is as follows:

- **Isolating valve** – allows isolation and maintenance of the system.
- **Line strainer** – filters larger particles in the water.
- **Non-return valve** – prevents back-flow of water into mains (not required for a low-pressure system with float valve).
- **Pressure reducing valve** – reduces mains pressure to below the maximum rated pressure of tank and collector (not required in all situations or on low-pressure, vented systems).
- **Cold water expansion valve** – releases cold water rather than hot water due to pressure build-up as the water in the storage tank is heated and expands. This prevents wastage of hot water and protects the tank from excessive pressure. Pressure setting should be about 200kPa less than the

pressure/temperature relief valve (typical cold water expansion valve pressure setting is 500kPa).

- **Diffuser or spreader pipes** – the cold water inlet pipe connects to a diffuser or spreader pipe running part way or the full length of the tank at the bottom. It reduces the water velocity and limits mixing of hot and cold layers in the tank. This helps maintain stratification of water temperature and hence keep the hottest water at the top of the tank.

Hot water exit

After water is heated in the collectors, the hot water passes into the tank through the hot water inlet at the opposite side of the tank to the cold water inlet. It is usually located about halfway up the tank.

The hot water entering the tank rises to the top of the tank, causing some mixing of the water in the top half of the tank as it enters, though the hottest water will always rise to the top of the tank. Hot water is drawn off from the very top of the tank through either a top diffuser pipe or scoop.

The water exits via a **pressure/temperature relief (PTR) valve**. Its purpose is to protect against excessive temperature (>99ºC) and pressure (>1MPa) (typical pressure setting is 700kPa). If either of these conditions is exceeded, the valve opens and dumps a large quantity of hot water through a drain to ground (or via the roof).

Other system features

Heat exchanger systems

Some manufacturers provide heat exchangers to provide:

- frost damage protection in frost prone areas
- protection from hard water supplies, particularly bore water in outback regions.

Details of their construction and installation requirements can be found in Section 3.3 (Storage tanks) and Section 5.2 (Frost protection).

Sacrificial anode

Storage tanks made of mild steel and lined with vitreous enamel must be fitted with a sacrificial anode to prevent corrosion of the tank. The anode runs horizontally along the inside of the tank. It is made from either aluminium or magnesium alloys, depending on water quality. It corrodes over time and must be replaced periodically. Manufacturers specify replacement periods according to site water quality.

Stainless steel tanks and plastic lined tanks do not require a protective anode.

Over-temperature heat dissipater or dump

Some older systems used a heat dissipater device to reduce the likelihood of overheating in summer if the system is not used for some weeks (e.g. a summer holiday). This comprises a finned copper heat pipe, positioned at the back of the storage tank and running into the middle of the tank as shown below. The heat pipe is sealed and partially evacuated with a little water in it. This water boils at about 75ºC. The steam rises up to the radiator fins and condenses, giving up its heat to the air via the fins. The cooled water trickles back down the pipe to be heated again. Once the temperature falls below 75ºC, it ceases to boil, transfer heat and lose heat from the storage tank. Figure 3.4.2 shows how this works. More detail is provided in Section 5.1.2 (Over-temperature protection).

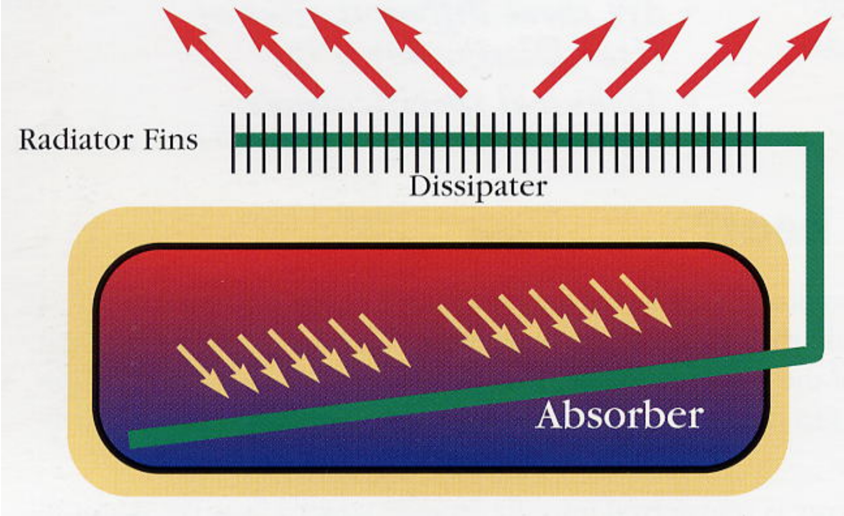


Image: Courtesy of Solahart.

Figure 3.4.2 – Over-heating dissipater

Supplementary heater or booster types

A booster element can be either electric or gas. Electric boosters are usually located in the middle of the tank so that they heat the water above. Elements fitted to tanks for the colder regions have a curved or 'sickle' element fitted with the sickle pointing down to boost heat more water when connected to off-peak electricity tariffs. A thermostat switches the element off when the water reaches the desired temperature, typically about 60ºC. They are generally rated at 2.4 or 3.6 kilowatts of power.

Gas boosters can either be tank mounted to heat the tank water directly or a separate in-line instantaneous gas booster after the storage tank. Gas boosters are generally rated at between 13 (tank mounted) and 200 Megajoules per hour (in-line instantaneous type), providing fast recovery time. Electronic ignition systems are used to avoid wasting gas with a pilot light. Electricity is required to operate the electronic control, which turns on the gas when the water temperature drops and a spark ignites the gas. A big advantage of the electronic ignition is the ability to control it from a remote location and disable the burner during daylight hours. Figure 3.4.3 shows details of a close coupled system with integral tank gas boosting and a heat dump pipe at the rear of the storage tank. The inlet and outlet valves are also shown. This system provides 97% of the hot water to the Brisbane home of the author and his wife.

Details of booster operation and control are given in Chapter 4 (Boost Heating).

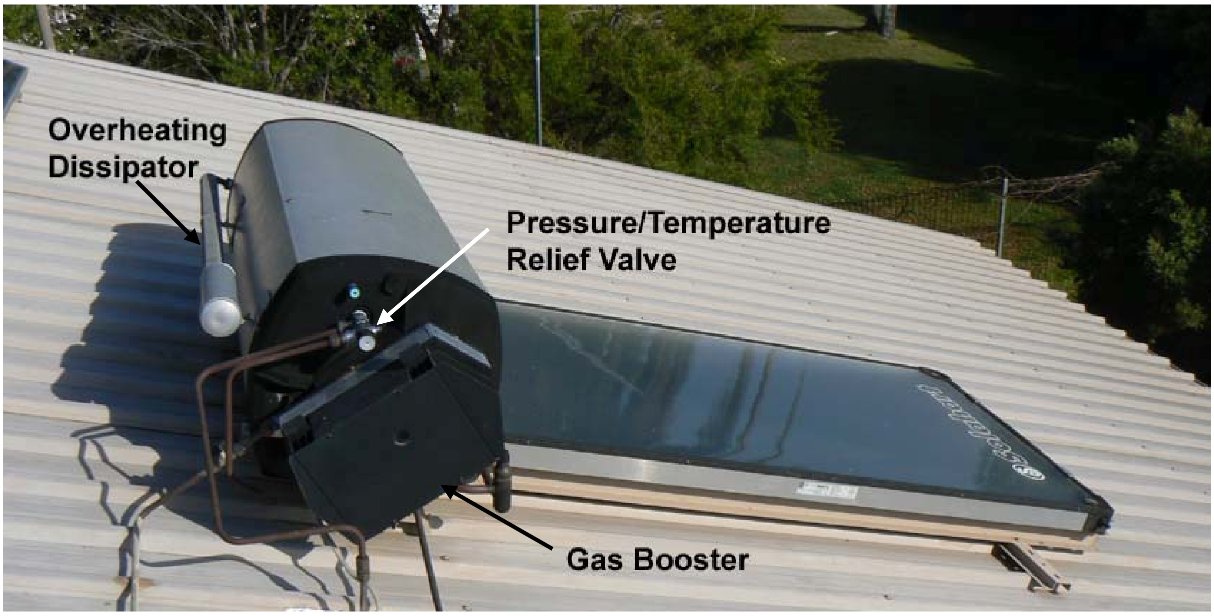


Photo: Courtesy of Trevor Berrill.

Figure 3.4.3 – Close coupled system with integral gas boosting and heat dissipater

Other system types

Most solar water heaters use collectors with metal absorber plates that maximise conduction of heat to the water. However, in regions of high solar radiation all year, such as northern Australia and SE Asia, these systems can overheat in summer. As well, in many regions, hard water supply can lead to shortened life of metal tanks and collectors. One solution is a plastic, rotationally moulded, integrated collector and tank system. This aims to be a low-cost, low-maintenance system in regions of high annual radiation and hard water. As the absorber plate is less conductive, the collector is less efficient than conventional metal absorber designs, so overheating is less of a problem and performance is satisfactory. The systems have electric boosting.

These all plastic systems are low-pressure systems. They can be used as pre-heaters in cooler regions. Figure 3.4.4 (below) shows a cut-away through such a system.

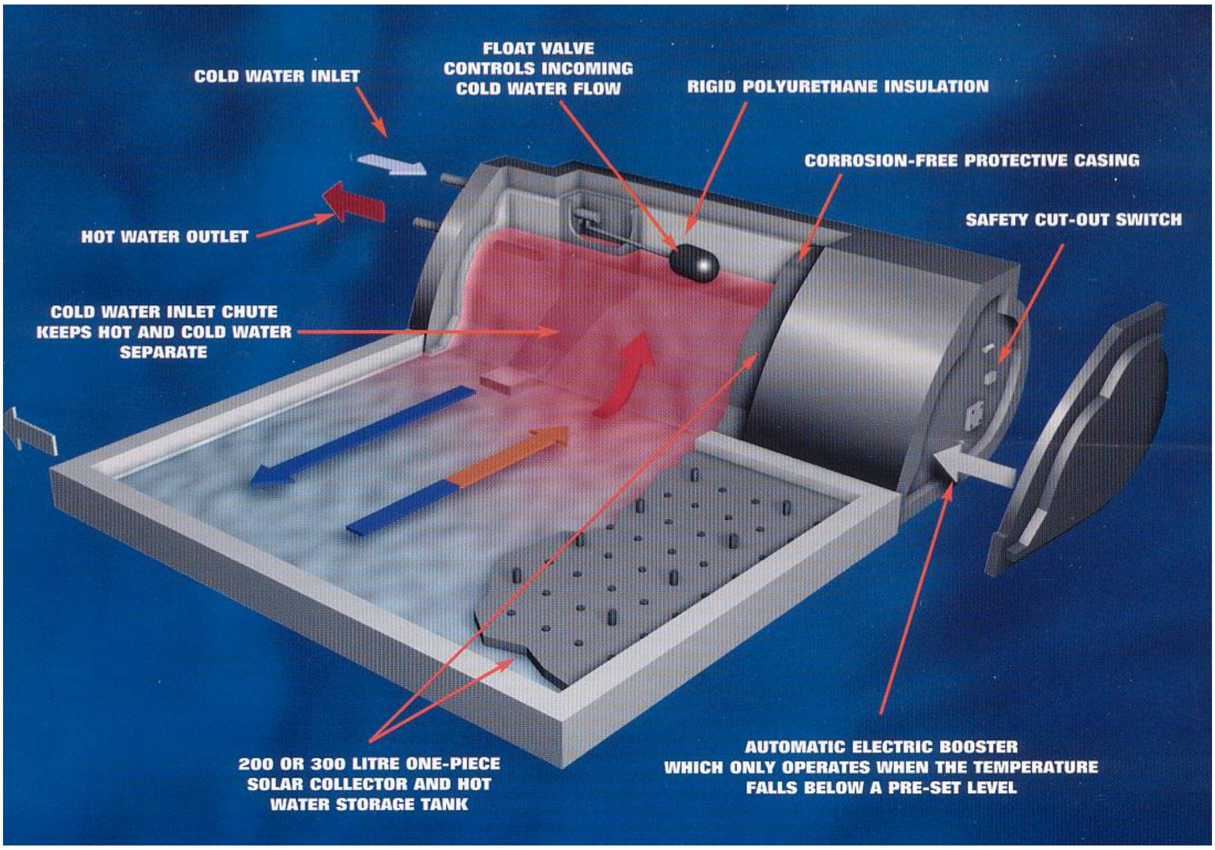


Diagram: Courtesy of Solco.

Figure 3.4.4 – Close coupled low-pressure, plastic system

Advantages of close coupled systems

- The collectors and storage tank being close together means that there is less heat loss in the pipe work connecting the two.
- Installation is reasonably straightforward. It is more likely to be installed correctly. There is no difficult roof flashing to be undertaken. The entry of the cold water supply, and the hot water delivery pipes and the electric power cable or pipe for gas boosting, is fairly simple.
- There is no scrambling in restricted ceiling spaces. The installation is out in the open.
- The system can be installed on houses where there is no ceiling space at all; for example, houses with cathedral ceilings.
- As long as the roof has sufficient slope, there is no problem with reverse thermosiphon flow at night.
- Most systems operate on mains pressure. This ensures a good water flow to each hot tap.
- Usually all the components required for the installation are supplied.
- Selling a close coupled unit is easier than a remote storage system. Most people are familiar with close coupled systems.
- Giving a quotation is reasonably straightforward.
- A leak should not result in water running through the ceiling.
- Replacement of the storage tank does not mean having to open up the roof.
- No spill tray is required under the storage tank.
- The systems still operate during power outages.

Disadvantages of close coupled systems

- The wide, low storage tank has poor stratification and heat is conducted down from the hot water to the cold water beneath it.
- The roof has to be strong enough to support the weight of the water in the storage tank. Sometimes it is not and additional strengthening is sometimes not possible.
- Some people find the tank on the roof aesthetically unattractive.
- The steel storage tank, and particularly the double jacket heat exchange unit, is heavy. Getting it onto a roof, especially a steep one, can be very difficult without lifting equipment.
- Safety equipment is now required by legislation, adding to installation cost.
- If the roof on which the close coupled unit is to be mounted does not face the sun (north in the southern hemisphere), a support frame is required. This can often be aesthetically most unattractive and is usually expensive. The support frame, in turn, requires significant support through the roof to the building frame.
- Connection to a combustion cooker or heater as a boost source is possible but is not straightforward. Vitreous enamel-lined steel cylinders should not have water in them in excess of about 75ºC as this can shorten their life. The higher the average water temperature, the more adverse the effect.

Key points

- The typical components of a close coupled system include:
  - storage tank (direct heating or integral heat exchanger types)
  - collectors
  - supplementary heating or booster element
  - sacrificial anode (vitreous enamel tanks only)
  - hot water pressure/temperature relief valve
  - cold water valves.
- The standard size system uses about a 300 litre storage tank and $4m^2$ of collector area.
- Tanks and collectors come in a range of sizes to meet varying demands although most collectors are about $2m^2$ in area.
- A typical system has the following:
  - inlet valves isolated to prevent back-flow, reduce pressure and relieve pressure from the storage tank
  - a pressure/temperature relief valve on the hot outlet
  - a sacrificial anode to protect vitreous enamel-lined tanks – not used in stainless steel or plastic tanks
  - an electric or gas booster either in the storage tank or mounted in-line after the storage tank
  - heat exchanger tanks if the system is used in frost prone areas or those with very poor water quality.

Section 3.4 questions

In the 1980s the close coupled hot water system became the ‘standard’ solar water heating system. It was easily recognised. It was easily marketed. It was reasonably easily installed. All the customer had to decide was, ‘Do I buy one or not?’

1. What are the features, dimensions, etc. of a standard close coupled solar hot water system?

2. What fittings are normally included?

3. What are the positive features of a horizontal close coupled tank?

4. In what situations can a close coupled solar hot water system be installed when other types of systems can’t be installed?

5. Close coupled solar hot water systems can use direct or indirect heating. What is the difference?

6. Starting at the isolating valve, list the fittings and valves that get the cold water to the hot water storage tank.

7. What is the purpose of the diffusers on the cold supply into a horizontal hot water storage tank?

8. Why is a heat dissipater unit included in some solar water heaters? What type of storage tanks might have a heat dissipater?

9. Why is there such an enormous difference between the 13MJ/hour gas rate for the boosting unit in the close coupled system and the instantaneous gas heater, which may have a gas rate of 200MJ/hour?

10. Why is the all plastic Solco solar hot water system not available as a mains pressure unit?

3.5 Pump-circulated (or split) systems

What this section is about

Pump-circulated systems have become popular in recent years due to their cleaner appearance with only collectors roof-mounted. They are known by various names, including '**pumped storage**' and '**split**' **systems**. Both flat plate and evacuated tube collectors are used for these systems.

This section aims to provide an understanding of:

- the principles of a pumped circulated system
- the important components of the system
- the requirements for the pump
- the operation of the pump controller
- methods of connection to a storage cylinder.

Reasons for split system use

The ideal solar water heating system operates on the thermosiphon flow principle as it is simpler, cheaper and often more efficient. However, this is not always possible for the following reasons:

- It may not be possible to get the hot water tank high enough above the collectors because the roof pitch is low and the customer does not wish to use a mounting frame.
- The customer may not wish to have the tank on the external roof for aesthetic reasons.

In these situations we need to consider a forced circulation system where a pump is used to circulate the water from the tank at a lower position, up through the collector panels and back down to the tank. This allows us to locate the tank at ground level and possibly some distance from the collectors. It also allows us to use smaller pipe sizes and to operate multi-collector installations.

Principles of operation

This type of system consists typically of a ground-mounted tank and roof collector panels. A small circulation pump is used to pump water through the collectors. A differential temperature controller with two or more temperature sensors is used to control the pump operation. This is described in detail below.

Components

A typical system configuration and components are shown in Figures 3.5.1, 3.5.2 and 3.5.3. It consists of:

- storage tank (direct heating or heat exchanger types available)
- collectors
- auxiliary heating or booster element
- sacrificial anode (vitreous enamel tanks only)
- hot water pressure/temperature relief valve
- cold water valves
- circulation pump
- pump controller.

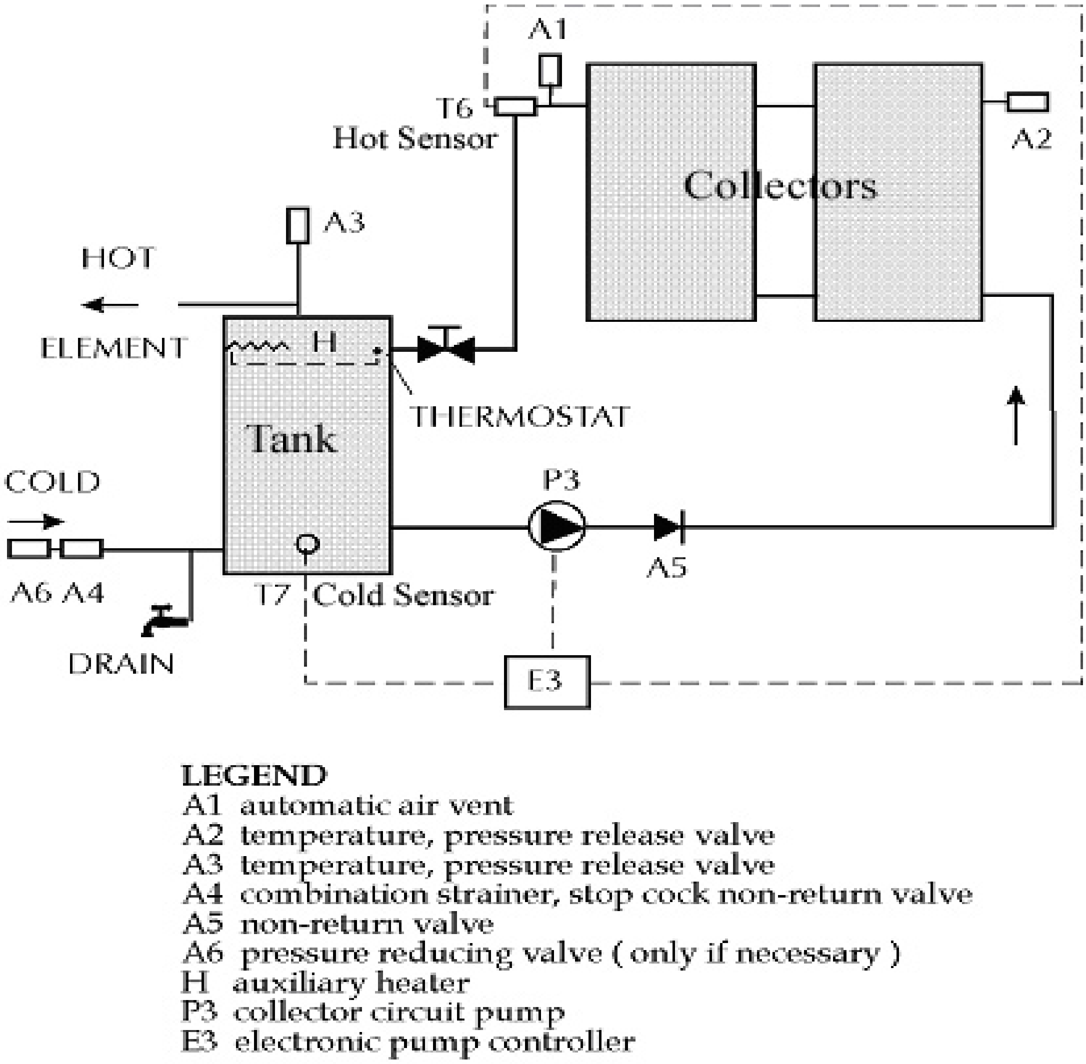


Figure 3.5.1 – Pump-circulated system

Storage tanks

Typical storage volume is about 300 litres. Tanks sizes vary from 160 to 420 litres. A significant difference between close coupled thermosiphon system and split systems is that split systems use vertical tanks that more easily maintain temperature stratification.

Tanks may use:

- direct heating of the potable (drinking) water (softer water supplies and mild climates)
- indirect heating of potable water via a internal coil heat exchanger or a jacketed shell heat exchanger (i.e. a thin tank surrounding the large inner tank with potable water)
- indirect heating of potable water via a heat exchanger external to the tank and collectors.

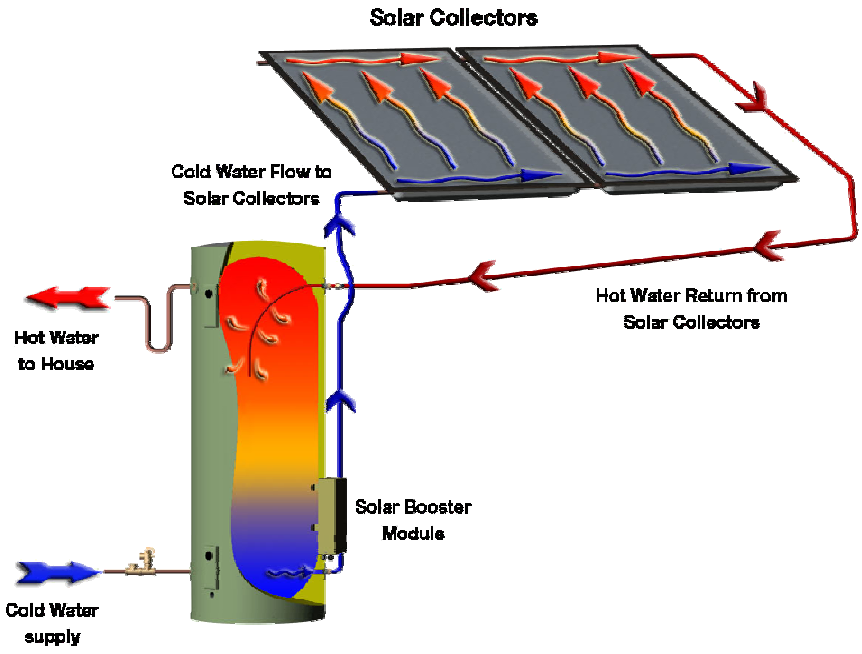


Image: Courtesy of Conergy.

Figure 3.5.2 – Direct (open circuit) pump-circulated system

Heat exchange systems are used to overcome problems of corrosion and freezing in hard water areas and cold climates respectively.

The tank may be supplied with cold water at:

- full mains pressure
- reduced pressure via a pressure reducing valve.

Depending on the operating pressure, the tank may be made from:

- vitreous enamel-lined mild steel (high-pressure systems)
- stainless steel (high-pressure systems).

Tanks are reasonably well insulated with about 50mm thickness of high density polyurethane foam insulation. Government regulation via Minimum Energy Performance Standards (MEPS) is gradually improving insulation levels to decrease heat losses.

Photo: Courtesy Rinnai.

Figure 3.5.3 – Forced circulation (pumped) system

Collectors

Both flat plate and evacuated tube collectors are used. For domestic applications, one, two or three flat plate collectors of approximately $2m^2$ area each are used, depending on storage tank size. A rule of thumb is $2m^2$ of flat plate collector per 150 litres of storage. For evacuated tube collectors, the number or tubes in a bank can be varied. Typically, they come in lots of about 10 tubes (for collector construction details, see Section 3.2 – Collector types and operating principles).

Rule of Thumb 3.1 – For flat plate collectors, use $2m^2$ of collector area per 150 litres of storage

Absorber

Flat plate absorbers are enclosed in a glass-covered metal box made from zinc-alume or aluminium sheeting, insulated at the back and sides. The absorber surface may be painted matte black or finished with a selective surface (e.g. AMCRO or Black Chrome). The glass cover may be toughened low-iron, anti-reflective (higher transmittance) or plain window glass (cheaper models).

Flat plate absorbers are made from:

- copper pipe attached to copper or aluminium sheeting (fin and tube design)
- mild steel (flooded plate design – heat exchange systems only).

Evacuated tube absorbers are made as cylindrical glass tubes from:

- Double-layered glass tube – a tube within a tube
- Single-layered glass tube with a copper U-tube and attached cylindrical or flat aluminium fin inside
- Single-layered glass tube with a copper heat pipe and attached flat aluminium fin inside.

With both types of collectors, the number of collectors (or tubes) and the storage tank size can be changed to meet the demand for hot water.

Cold water entry and hot water exit valves

These are similar to those explained in Section 3.4 – Close coupled solar water heater systems. The main difference is the use of:

- a non-return valve after the pump to prevent reverse thermosiphon at night
- a pressure/temperature relief (PTR) valve at the top of the collectors to protect against damage from excessive pressure or temperature or both
- an air eliminator valve at the highest point in the circuit to bleed air out of the circuit to prevent air locks restricting the flow (see Chapter 5 for details).

Pumps

Time and experience have helped to determine the most suitable pumps for this application. Most importantly, they must be able to operate for long periods with temperatures of the pumped fluid reaching 100ºC. The most commonly used pumps are the Grundfos UP 15-14B or 20-60B, which draw around 20 to 40 watts of electrical power. This is a brass pump with a brass impellor and has three speed settings. It can be fitted with small isolating valves on the connections, which enable the pump to be removed from the circuit without emptying the lines. Other pump brands/models include Wilo and Salmson NSB 04-15. Generally the annual energy used by the pump is less than 5% of the total solar energy harvested and the cost of running the pump is less than $15 per year.

Pump controllers

Two types are now available: simple controllers that switch the pump only on and off, and smart controllers that control both the pump and booster switching.

Simple controllers for pump only

The pump must be controlled so that it does not run continuously and thereby cause the water to be cooled down at night. Several methods have been used to ensure the pump only runs when solar energy is available.

These are:

- A 24-hour timer or a photoelectric cell–operated switch to turn the pump on and off. The 24-hour timer can be set to operate the pump between say 9am and 4pm. It does not have an automatic sensing system to tell it to turn on when a frost is imminent. Also, if the flow rate through the collector is too high or the flow persists for too long under poor solar conditions, then the water may in fact be cooled rather than heated. The alternative is a photoelectric cell operated switch that senses the light level and turns the pump on during daylight hours. Again, similar problems exist.
- An appropriately sized photovoltaic (PV) module to provide power to a DC pump. In this case, no differential controller is required as the PV output and hence the pump flow rate will increase and decrease in proportion to the solar

energy available. However, a maximum power point electronic controller will be required between the PV module and the DC pump.

- Differential temperature controllers. These units rely on temperature information received from thermistors placed at various points on the hot water circuit. Some controllers use two sensors while others use three or more. With two sensors, one sensor is placed at the outlet from the collectors and one at the bottom of the tank. They measure the temperatures at each location and send that back to the temperature controller. When the controller sees a difference of 7º to 10º between the sensors (it varies a little from controller to controller), then it will turn the pump on. As the water is pumped through the collectors this difference in temperature will be gradually lost until the controller turns the pump off at about 2º difference. Under this situation the pump will be turning on and off all day. Similar units are used by solar pool heating manufacturers.

Other controller functions

The controller will also turn the pump on **if the water temperature drops to 3ºC to 5ºC as an anti-freeze function**. In some cases, there is a third sensor, mounted at the bottom of the collectors, which is used to switch the pump on when freezing conditions occur. Remember water starts to expand at 4ºC and continues expanding until freezing is completed at 0ºC. This expansion will burst the tubes in the collectors or pipe work. The pump switches off when the water in the bottom of the collector reaches about 7ºC. This method is, of course, wasting heat energy stored in the tank by passing hot water through the collectors and heating them a little.

Some manufacturers advise that the use of anti-freeze dump valves should be combined with the pump circulation freeze protection, as a power failure will prevent the pumps and controller from working.

The controller can also turn the **pump off to prevent overheating of the water in summer** for safety reasons or to prevent damage to vitreous enamel linings in mild steel tanks. Over heating might occur if the system is unused during holidays. Some controllers would then switch the pump off when the bottom tank sensor reaches 65ºC.

The thermistors are best fitted in a sealed tube which protrudes *into* the water flow. The sealing is important as water can greatly affect the accuracy and operation of the thermistor. For this reason it is inadvisable to simply tape the sensors to the side of the pipe. If that is the only option, the thermistors should be set in heat-conducting paste and then covered with sealing tape.

Smarter controllers for pump and booster

More intelligent controllers are now available that aim to optimise the solar contribution while minimising booster use and meeting user hot water demands in all weather conditions. For example, the Solarit controller uses three sensors, the third one being at the centre of the tank. The collector outlet and tank bottom sensors do the usual pump control for solar heating, freeze and over-temperature control. This third sensor allows monitoring of the amount of hot water in the tank and control of the boosting. By following an adjustable two-hourly temperature profile over the day, the third sensor will limit boosting to a preset (but user adjustable) temperature for each two-hour period of the day. This allows the user to boost sufficiently to meet their patterns of hot water demand, but avoid excessive heating during daylight hours when you want the collectors to do most of the work (see Chapter 4 – Boost Heating for more details).

Calibration of controllers

It is important to check the calibration of the controller and sensors to ensure the correct temperature settings are used to turn the pump on and off for the most efficient operation.

Auxiliary heater or booster types

The booster element can be either electric or gas. Electric boosters are usually located either at the bottom of the tank or towards the top of the tank. A thermostat switches the element off when the water reaches the desired temperature – typically about 60ºC, but it may be set higher. The electric elements are generally rated at 2.4 or 3.6 kilowatts of power, with 4.8kW elements also available.

Gas boosters can either be tank mounted on the side of the tank to heat the tank water directly or a separate in-line instantaneous gas booster after the storage tank. Gas boosters are generally rated at between 13 (tank mounted) and 200 Megajoules per hour (in-line instantaneous type), providing fast recovery time. Electronic ignition systems are used to avoid wasting gas with a pilot light. Electricity is required to operate the electronic control, which turns on the gas when the water temperature drops and a spark ignites the gas. A big advantage of the electronic ignition is the ability to control it from a remote location and disable the burner during daylight hours. Boosting is shown diagrammatically in Figure 3.5.4 (below).

Details of booster operation and control are given in Chapter 4 – Boost Heating.

Other system types

Figures 3.5.4 and 3.5.5 show schematic diagrams of evacuated tube collector, pumped systems.

The system configuration is very similar to conventional, flat plate collector pumped systems. The main difference with this particular system is that the collectors are a bank of evacuated tubes connected to a manifold. Cold water from the tank is pumped through the manifold at the top of the tubes. Each tube contains a heat pipe inside the evacuated tube that conducts its heat via a heat exchange condenser to the pump-circulated water in the manifold (see Section 3.2 – Collector types and operating principles for more details). The pump is controlled in a similar way to that outlined above.

Evacuated tube collectors are generally more efficient than flat plate collectors for higher temperature applications or in colder climates due to their lower conduction and convection losses. Therefore, a smaller collector area should be able to be used for the same application. However, their efficiency for lower temperature applications may be little different to selectively coated flat plate collectors. The only way to assess this is to compare the collector efficiency data for Australian Standards testing requirements.

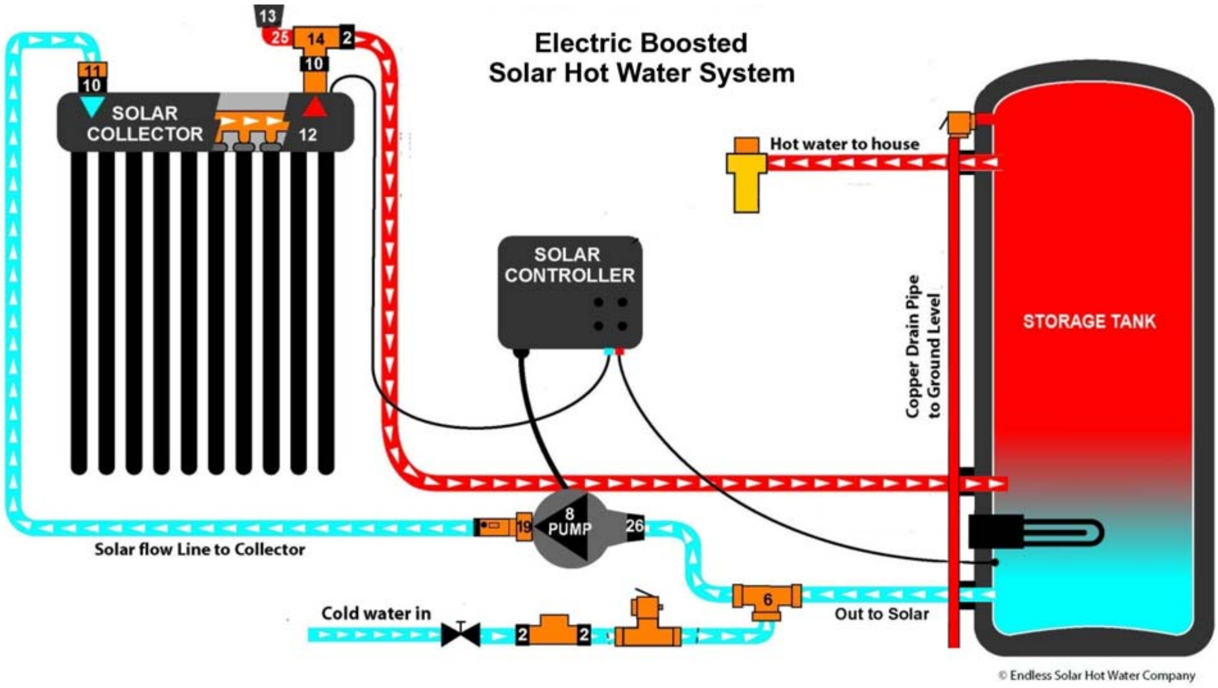
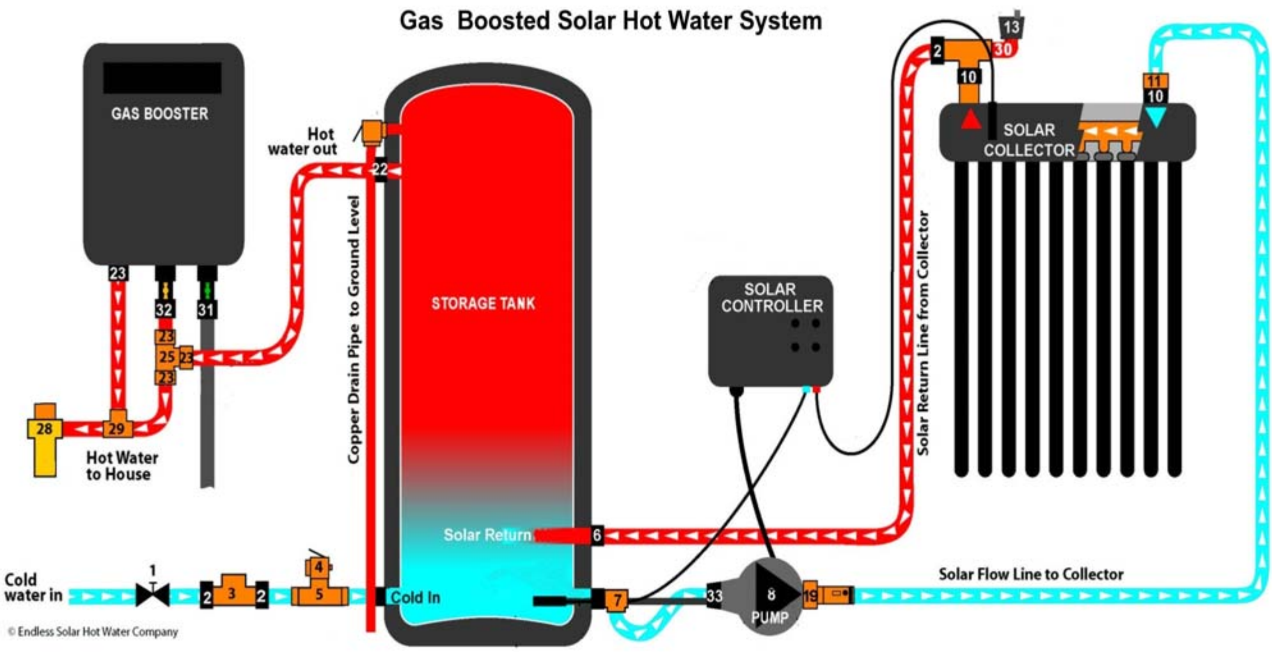


Figure 3.5.4 – Evacuated tube split system with electric boosting



Diagrams: Courtesy of Endless Solar.

Figure 3.5.5 – Evacuated tube split system with in-line gas boosting

Finally, both flat plate and evacuated tube systems can be retrofitted to existing vertical storage tanks via either:

- additional fittings already in the storage tank to accept the collector circuit
- A five-way connector fitted into the cold inlet at the tank bottom (see Section 3.3 – Storage tanks for details).

Alternatively, a complete split system could be added as a pre-heater to an existing electric or gas storage tank or instantaneous heater.

Advantages and disadvantages of split systems

Compared with close coupled or remote thermosiphon systems, split systems have the following advantages and disadvantages:

Advantages:

- no 'unsightly' tank on the roof
- can sometimes be retrofitted to use existing storage tanks
- less roof work
- tank or collectors can be located in more accessible or appropriate locations.

Disadvantages:

- more expensive than thermosiphon systems due to the pump and controller costs
- they require power to run the pump and temperature differential controller – this can be done with a photovoltaic module to drive the pump; the pump will then run faster when it is sunnier so a controller is not required.

Key points

- Pump-circulated or split systems have been around a long time but have become more popular due primarily to aesthetic reasons; i.e. no ‘ugly’ tank on the roof.
- As the tank is located below the collectors, the water must be pumped up through the collectors and back to the tank. This requires a very small pump (20 to 40 watts power) that uses less than $15 of electricity per year.
- A significant difference between close coupled thermosiphon system and split systems is that split systems use a vertical tank that more easily maintains temperature stratification. This helps keep the hottest water at the top of the tank ready to be drawn off.
- Collectors can be either flat plate or evacuated tube type. The latter should perform better for higher temperature loads or in colder regions due to reduced heat loss.
- Split systems require a couple of extra valves. These include:
    - a non-return value after the pump to prevent reverse flow
    - an air eliminator at the highest point in the circuit to vent trapped air
    - a PTR valve at the top of the collectors to release excess pressure.
- The pump operation is controlled by a:
    - timer, photo-cell-controlled switch
    - PV module and DC pump
    - differential electronic controller
    - smart controller.
- Differential electronic controllers use two or more sensors located at the top of the collectors and the bottom of the tank to:
    - switch the pump on and off so it operates only when there is adequate solar energy to heat the water
    - protect the system against the extremes of freezing and overheating.
- Smart controllers are available that use more sensors and can control both the pump operation and boost heating to optimise solar collector contribution.
- Split systems can be retrofitted to existing tanks via a five-way valve at the cold inlet to the tank or as a pre-heater to an existing storage or instantaneous heater.

Section 3.5 questions

1. What types of collectors are suitable for use with pump circulation systems?

2. Is there any difference between the collectors used in a pump circulation system and a close coupled system or a remote (in-ceiling tank) system?

3. Suppose a family of six people has a 400 litre hot water storage tank. How many $2m^2$ collectors would you recommend be used in conjunction with that tank?

4. Why is a circulating pump required in some solar systems?

5. What does the circulating pump do? How is the pump controlled?

6. The circulating pump is often called a ‘circulator’. Why is it not just called a pump? Is there any difference to any other pump?

7. An electric storage tank is used as the hot water store for many pump circulation systems, whether the electric boost element is used or not. Some systems adapt other tanks for use as the hot water storage tank. List the characteristics of the following mains pressure storage tanks:

    a. stainless steel

    b. vitreous enamel-lined mild steel.

8. The valves on the cold water supply to a pump circulation solar system are the same as for a close coupled solar hot water system. There are, however, two other valves not normally part of a close coupled system:

    a. The air eliminator valve. Where is this located and what is its function?

    b. The non return valve associated with the circulating pump. Why is it installed?

9. Other fittings that are required to go with the circulating pump controller are the pockets (tubes sealed at one end) for the sensor probes. The sensor pockets are often made on site from small diameter copper tube (often 10mm outside diameter). Where are these positioned, and what is their function?

10. The differential temperature sensors are not the only temperature sensors in the system. What other temperature sensors are there?

11. What advantages do pump circulation systems have to offer?

3.6 Thermosiphon remote storage systems

What this section is about

Thermosiphon systems with remote storage are low-pressure, open-vented, solar water heaters that have been used for many years in southern parts of Australia and in homes not serviced by reticulated water. They are largely being replaced by mains pressure feed, close coupled thermosiphon systems and split (pumped) storage systems. This is unfortunate because lower water pressure usually means less water is wasted. However, they still have a role to play as the lower pressure gives long life and allows back-up heating from combustion heaters. In well-designed systems, they provide more than adequate low-pressure hot water supply and can improve the overall energy and water efficiency of any water supply system by reducing the need for inefficient pressure pumps.

This section gives a summary of their features. It covers:

- typical system configuration
- factors that affect system performance
- reverse thermosiphon.

Principles of operation

These systems operate by thermosiphon flow. The water is heated in the collectors and rises naturally up to the storage tank. The heavier, cold water from the bottom of the storage tank flows to the bottom of the collectors. Hence, there is no need for a pump to circulate the water.

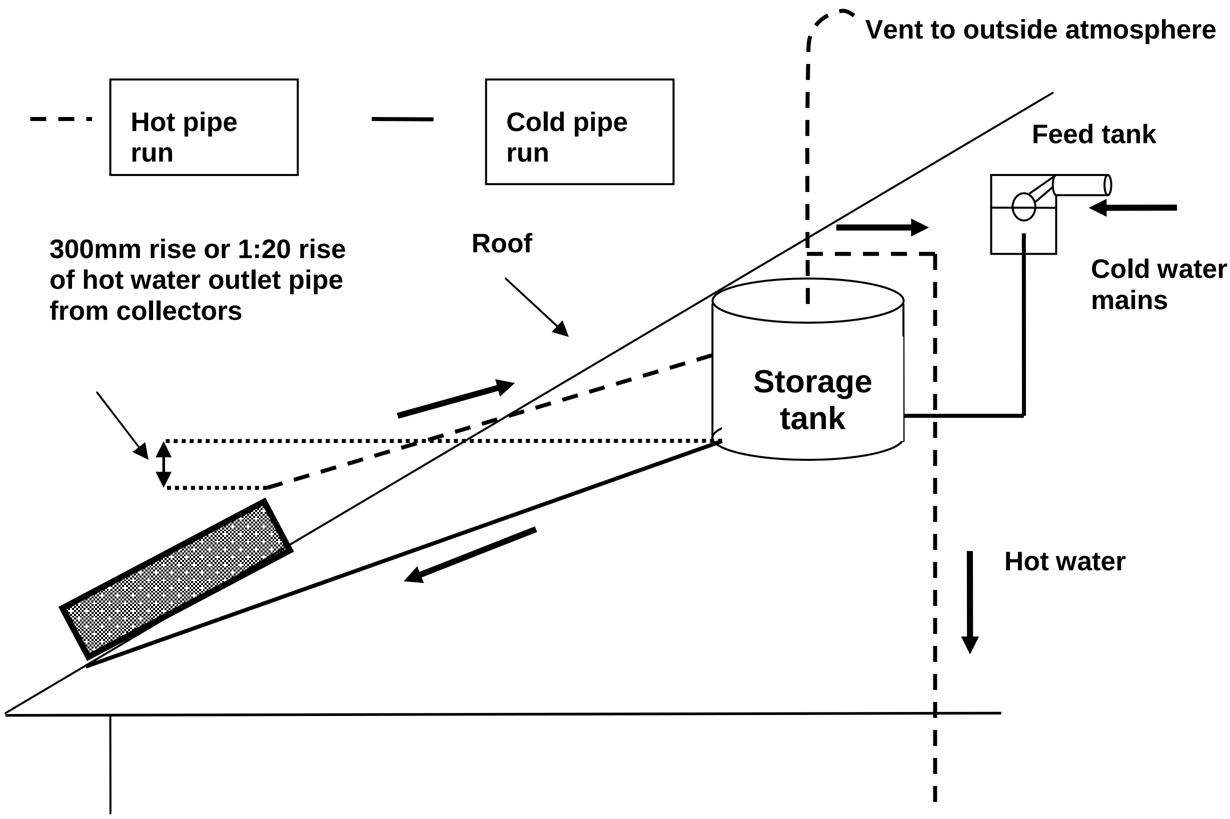


Figure 3.6.1 – Typical thermosiphon remote storage system configuration

Figure 3.6.1 shows a typical system configuration. The storage tank is usually located in the roof space and is kept full with a feed tank and float valve control.

This is similar to a toilet cistern valve in operation. This reduces the pressure at the feed tank to one atmosphere. The feed tank is usually attached to the side of the storage tank. The storage tank is vented, usually constructed of thin copper sheet and hence is not designed for high pressure. A **safety tray** is required under the tanks with a drain to the outside. The collectors are usually roof-mounted at least 300mm below the bottom of the tank as shown. The location of collectors and tanks can be quite flexible depending on roof space and distance. For example, the collectors could be ground mounted, with the tank in a roof space. Alternatively, the whole system could be ground mounted.

A thermosiphon system has a cost advantage over a pump-circulated system. A pump system requires a pump and a pump controller as well as a power supply to run the pump. Pumps and controllers can fail – therefore a thermosiphon system is more reliable.

Factors affecting system performance

Important factors that affect the performance of thermosiphon remote storage systems are as follows:

- The bottom of the tank should be at least 300mm above the top of the collectors unless special piping arrangements, tanks or valves are used to prevent reverse thermosiphon flow.
- Thermosiphon flow is driven by a relatively weak force due to a small density and pressure difference between the hot and cold water. Therefore, the pipes between the collector and the storage tank should rise continuously upwards at a minimum slope of about 1:20 to avoid air locks that would prevent or slow thermosiphon flow. The steeper the slope, the easier it is for thermosiphon flow to circulate.
- The connecting pipes between the collector and tank should be adequately sized to prevent friction slowing the thermosiphon flow. A 25mm diameter copper pipe is a common size.
- The distance between the collector and tank should be minimised to reduce the need for larger pipes to, in turn, reduce friction that would restrict the thermosiphon flow. This also helps to reduce pipe heat losses.
- The connecting pipes should be well insulated because the heat loss increases with surface area and pipe length. Bigger diameter pipes have a much larger surface area; e.g. a 25mm diameter pipe has roughly four times the surface area and so four times the heat loss rate per metre of pipe compared with a 13mm diameter pipe.

The installation requirements to account for these factors are explained in Chapter 6 – System Design and Installation.

Reverse thermosiphon flow

Reverse thermosiphon flow is a process whereby hot water cools when exposed to cold air temperature conditions, becomes denser and sinks to the lowest part of a plumbing circuit. It can occur at night, particularly when clear sky conditions exist causing the air temperature to be generally lower. It can occur with:

- split (or pumped) systems because the collectors are mounted above the storage tank. In this case, cold water in the external pipes connecting the collector and tank can cool and sink down to the storage tank, pushing hot water into the outside pipes towards the collector. This is the case with most split systems. Non-return valves must be used to prevent this happening in split systems.

- thermosiphon systems where the collector is only just below the tank as with close coupled systems. Reverse thermosiphon occurs when the water in the connecting pipe supplying water to the bottom of the solar collector from a storage tank becomes colder than the water inside the bottom of the collector. A small pressure difference will then be created by the heavier, colder water. The water in this supply pipe can potentially sink down to the bottom of the collector. In doing so, it would displace some water from the collector back to the tank, and push some warm water from the bottom of the storage tank into the collector supply pipe. As a result, warm water from the tank would be cooled as it comes into contact with the outside air temperature. This can happen on cold clear nights when uninsulated external connecting pipes are used between the collector and tank.
- thermosiphon systems where the collector is at the same height as the tank. The same process as in the previous case occurs, but to a greater extent.

Reverse thermosiphon flow is prevented by:

- insulating external piping
- mounting the tank base at least 300mm above the top of the collectors (see Figure 3.6.1)
- using a special non-return valve that can operate at very low flow rates and pressure (see Section 6.2.4.2 – Solutions to the problem of collectors being too high); a normal non-return valve of either the spring or flap type is not suitable
- arranging the connecting pipes so that the supply pipe from the tank to the collectors exits the storage tank at about the same height as the hot return pipe from the collectors (see Figure 3.6.2 below).

The following diagram shows the external plumbing to prevent reverse thermosiphon flow. The cold supply pipe exits the tank at the same height as the hot return pipe.

Inside the tank, the cold supply pipe is extended to the bottom of the tank to draw water from this level. Note that this type of tank is called a squat tank and is especially designed to fit in lower pitch roofs where roof space is limited. Figure 6.2.14 shows the internal pipe connections of this type of tank.

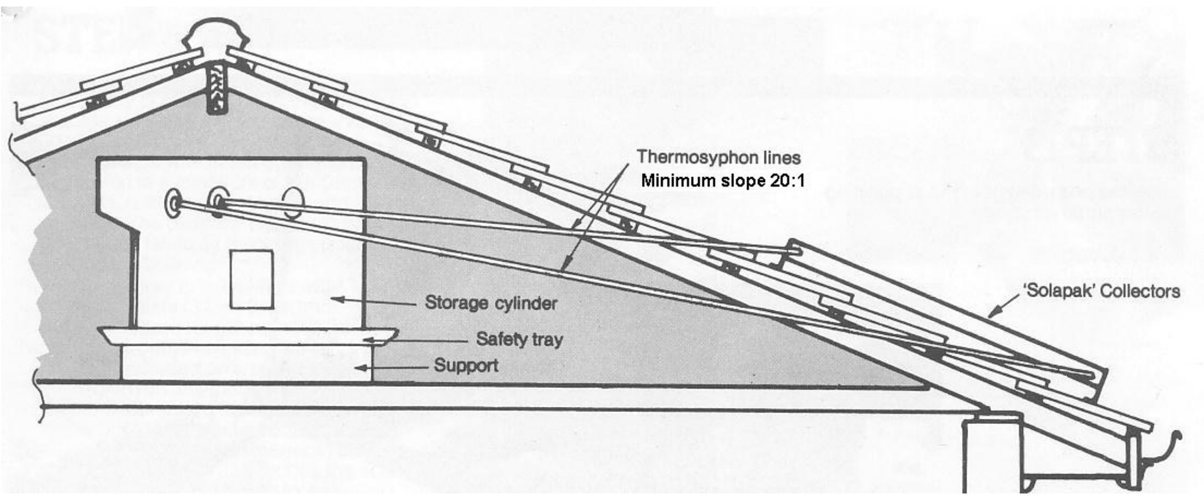


Diagram: Courtesy of Rinnai.

Figure 3.6.2 – Plumbing connections that prevent reverse thermosiphon flow

Advantages and disadvantages

The advantages and disadvantages of thermosiphon remote storage systems are:

Advantages:

- simple with no moving parts
- flexibility to design to suit customer needs
- usually cheaper than other system configurations
- longer life than mains pressure systems due to all-copper tanks, and lower pressure and stress on tank and collectors
- no 'unsightly' tank on the roof
- the tank is more upright and so promotes temperature stratification, improving system efficiency
- tank is more protected from the weather and therefore has lower heat losses
- less weight on the roof and therefore no need to reinforce the roof
- can be connected to another uncontrolled heat source such as a wood heater or slow combustion stove
- can provide hot water without external power
- can be more energy efficient if header tanks are used to supply water pressure instead of pressure pumps.

Disadvantages:

- more complex installation compared with the close coupled type, especially if the system has to be installed in an existing house
- requires space in the ceiling
- low water pressure and if pipes are undersized, flow to taps will be restricted
- access to replace or service the tank is more difficult.

Key points

- Thermosiphon remote storage systems are low-pressure solar water heating systems with longer life than mains pressure systems. They continue to be used in non-reticulated water supply or remote areas with combustion stoves or wood heaters as back-up. Their use on reticulated mains pressure water supply systems is reducing due to their lower water pressure and more difficult installation. This is unfortunate because lower water pressure usually means less water is wasted.
- Care needs to be taken during installation to prevent restriction on thermosiphon flow through correct pipe sizes, minimising pipe lengths and optimising pipe slope from collector to tank.
- Reverse thermosiphon flow can occur in poorly installed systems. Take appropriate measures such as installing the collectors below the tank, insulating external connecting pipes or using purpose-made tanks and non-return valves.
- They offer a range of advantages including lower cost, longer life and flexibility in installation arrangements.

Section 3.6 questions

1. Describe the features of an in-ceiling gravity feed hot water system, without solar collectors attached.

2. How would you convert such a hot water system to a solar system?

3. Supposing the bottom of the storage tank was not 300mm or more above the top of the collectors. How would it be possible to use the tank?

4. If you were selecting a tank especially for the job it might be possible to have a tank with both the cold and hot solar connections (flow and return) near the top of the tank. Such a tank is made by Rinnai Beasley. Why is it so important to have the solar collectors lower than the connections on the storage tank?

5. It is most important that the pipe slopes uphill (however slightly) from the collectors to the storage tank. Why?

3.7 Heat pump water heating systems

What this section is about

A heat pump system is a form of solar water heating system. It may use the standard refrigeration cycle to transfer heat from the ambient air outside the house into the water in the storage tank or it may rely on solar radiation to directly heat a refrigerant fluid in a collector.

This section outlines the types and operation of heat pump water heaters. It covers:

- the refrigeration cycle used by heat pumps
- the difference between split solar, split air and compact systems
- the advantages and disadvantages of heat pumps compared to other solar water heaters.

Principle of operation

The heat pump operates like a refrigerator or an air conditioner. It pumps heat from one place to another. In a refrigerator the heat is pumped out of the food and into the grille at the back of the refrigerator, where it is dissipated as waste heat to the air. Air conditioners pump heat out of houses in summer (and into houses in winter if they have the reverse-cycle capability). They all work on the refrigeration cycle.

In a typical refrigerator, there are four main components:-

- **Evaporator** – a heat exchanger consisting of either a flat plate with tubes attached or a set of fins attached to a network of tubes. In a refrigerator, it is the plate inside the cabinet at the back that gets cold. It absorbs heat from the food in the refrigerator.
- **Condenser** – a heat exchanger consisting of either a flat plate with tubes attached or 'grille' (like fins and tubes) at the back of the refrigerator that becomes hot and dumps heat collected from the food to the air.
- **Compressor** – this pumps the refrigerant around the system.
- **Expansion device** – this controls the rate of refrigerant flow through the evaporator.

For water heating, the condenser has to be on the inside, wrapped around or immersed in the hot water storage tank. The evaporator has to be on the outside to extract heat from the surrounding air. This is the reverse of a refrigerator. Figure 3.7.1 (below) shows the components of two types of heat pump water heater available on the market today: split and compact types.

For water heating, the heat pumps work as follows:

- When the system is turned on the compressor pressurises the refrigerant so that its pressure and temperature are raised. The refrigerant is then pumped through the condenser as a hot gas. The condenser is a long coil of tube or a mantle-like array of channels in contact with the inner shell of the storage tank, or a coiled arrangement inside the tank. The water in the tank is at a lower temperature than the refrigerant in the condenser and as a result, heat flows to the water and raises its temperature.
- After going through the condenser, the refrigerant has cooled and is then pumped through the expansion valve. This has a small orifice that lowers the temperature and pressure of the refrigerant as it enters the evaporator. By now this refrigerant is cooler than ambient and so it absorbs heat energy through the evaporator from the surrounding air.

- The refrigerant then returns to the suction side of the compressor where the cycle starts again. In essence, the heat pumped from the hail, rain or sun is dumped into the water tank.

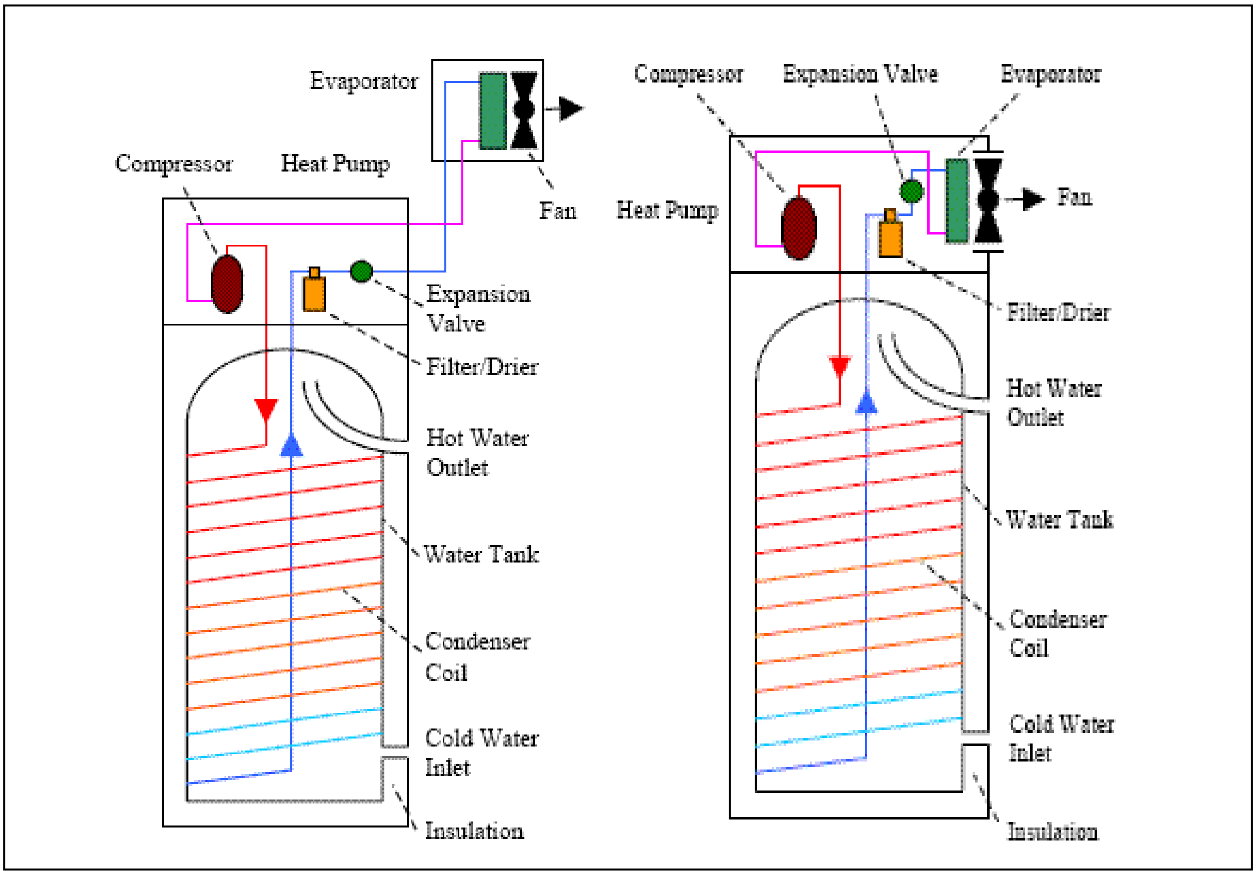


Image: Courtesy of Quantum.

Figure 3.7.1 – Components of a split (left) and compact (right) heat pump water heater

In the heat pump water heater, the evaporator is usually:

- a fan-cooled fin and tube or flat plate heat exchanger in a self-standing fan-coil box mounted beside the storage tank (split air system)
- a fan-cooled fin and tube or flat plate heat exchanger mounted on the top of the storage tank (compact system).

In all cases for heating, system performance will be improved if the whole system is located in a sunny, warmer, wind protected location.

Photos: Courtesy Quantum & Rheem.

Figure 3.7.2 – Split and compact heat pumps

The first commercial heat pump water heaters had the evaporator as a set of unglazed bare black aluminium plates. These collectors (evaporators) did not suffer from frost damage like normal water-filled solar collectors. These evaporators were usually roof-mounted and absorbed heat from the sun, wind and rain, operating at temperatures as low as -10ºC. However, the installation of the solar evaporator panel and connection of the refrigeration system required people trained in refrigeration techniques, which limited the number of people who could install the systems.

After development of the air-source heat pump, again working down to as low as -10ºC, split solar systems have become uncommon. More recently these compact air-source heat pumps have been available from most major hot water manufacturers and all have a compact fin coil as the evaporator.

Atmospheric air provides the heat and the condenser is either a coil wrapped around a water storage tank or a flat plate heat exchanger. The heat is transferred to the water in the tank either through the wall of the tank or as it is pumped through the heat exchanger. Installers for these compact systems do not have to be trained in refrigeration.

The storage tank is insulated on the outside to reduce heat loss. Figure 3.7.2 shows some examples from the real world and their location.

Advantages and disadvantages

Advantages:

- A relatively small amount of energy is required to heat the water when compared with a conventional system using an electrical element. The only energy used is by the compressor to pump the refrigerant around the system. The result is that for each kilowatt hour of energy used by the compressor, 2.0 to up to 5.0 kilowatt hours of useful hot water is produced.

- The compressors in heat pump systems use around 0.4 to 1.3 kilowatts of power, whereas the equivalent standard electrical water heater uses 2.4kW or 3.6 kW to produce the same result. This means that some heat pumps can operate from a standard 10 amp power outlet. Bigger units may require a 15 amp circuit with separate circuit breaker.
- A thermostat controls the temperature to a maximum of 60ºC, just like the refrigerator, so it turns the compressor on and off as required.
- Systems can be expected to operate for three to 12 hours per day depending upon water usage, air and water temperatures, and the size of the storage tank.
- While the system works best in sunny conditions, it also operates in cold, cloudy and wet conditions and even at night. This makes it particularly attractive for situations where shading from the sun is hard to avoid and a conventional solar water heater with collectors is not suitable.
- Siting is flexible and systems are generally ground mounted.

Disadvantages:

- Systems are expensive and may use more energy to run than the boosting energy for a conventional solar water heater.
- Depending on the solar fraction for a solar water heater, a heat pump may produce more greenhouse gas emissions and pollutants, unless it uses ‘green power’. For high-efficiency units this may happen when the solar fraction is above 75%, but it also depends on the environmental conditions such as air and water temperatures.
- It is not recommended to connect compact heat pumps to off-peak electricity tariffs in cooler regions due to the limited time for the compressor to run and hence the likelihood of running out of hot water. In addition, operating at night when the ambient air is cooler reduces the overall efficiency of the heat pump system. Intermediate tariffs that offer up to 18 hours per day of available power may be suitable.
- Current refrigerants can still damage the ozone layer, but to a much lesser extent than previous refrigerants. Alternative, truly environmentally friendly refrigerants are not yet available in Australia.

Heat pump rate of heating

The rate of heating water is determined by the ambient (air) temperature. The table (right) shows the hot water produced per hour at different ambient temperatures (water heated from 20ºC to 60ºC) by the Quantum 270L system. It also shows that with high temperatures more hot water can be generated per hour or conversely it takes less time to heat a given volume of water.

These figures came from the Quantum Energy website but do not indicate relative humidity, which also has an influence on how long it takes to heat the water.

Table 3.1 - Litres of hot water per hour by ambient temperature

Ambient temperature °C	Litres of hot water in one hour
35	112
30	100
25	88
20	75
15	59
10	48
5	38
0	31
-5	26
-10	24

Co-efficient of performance

As the ambient temperature increases, the quantity of water heated increases. The amount of electricity being used by the heat pump remains more or less fixed, so with an increase in ambient temperature the efficiency of the heat pump increases. For every kilowatt hour of electricity used, more kilowatt hours of energy go into the water. This ratio is called the co-efficient of performance (COP).

This heat pump water heater draws air in from the grille on the left-hand side and passes the air across the compressor and out through the grille on the right. The heat from the air is drawn into the evaporator before cold air is discharged out of the unit.

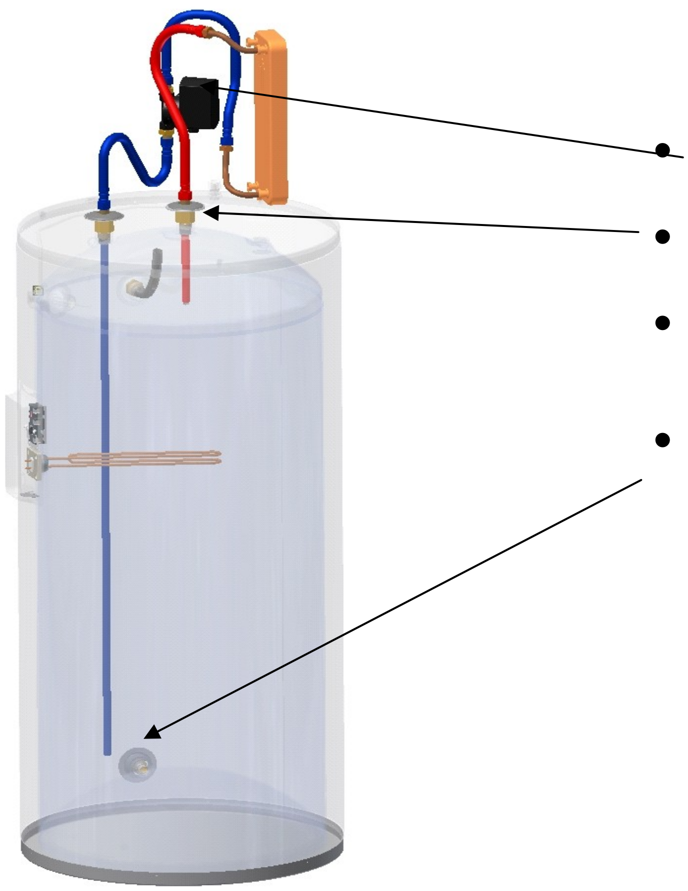
Placing the unit in the hottest location possible will increase the efficiency of the unit.

Photo: Andrew Blair

Figure 3.7.3 – Rheem heat pump

One manufacturer, Rheem, has produced a heat pump using a compact heat exchanger. The heat exchanger is not around the outside of the storage tank, but in a unit at the top of the tank. The two parts (refrigeration unit and storage tank) of the unit are assembled during installation. This can make transport and installation easier.

Figure 3.7.4 – Separate sections of compact heat pump



- Water is circulated by the pump
- through the heat exchanger
- Hot water is returned to the top of the storage cylinder.
- Cold water is drawn from the bottom of the cylinder.

Figure 3.7.5 – Cutaway view of Rheem heat pump

Water is drawn from the hot water storage tank, passed through a heat exchanger where it is heated to 60ºC and then discharged into the top of the storage tank. The water is circulated at a variable speed to ensure that it is heated to 60ºC in a single pass, regardless of the atmospheric conditions. It then enters the top of the storage tank at 60ºC.

An advantage of this arrangement is that hot water is available very soon after the unit starts running. The whole tank of water does not need to be heated before hot water is available.

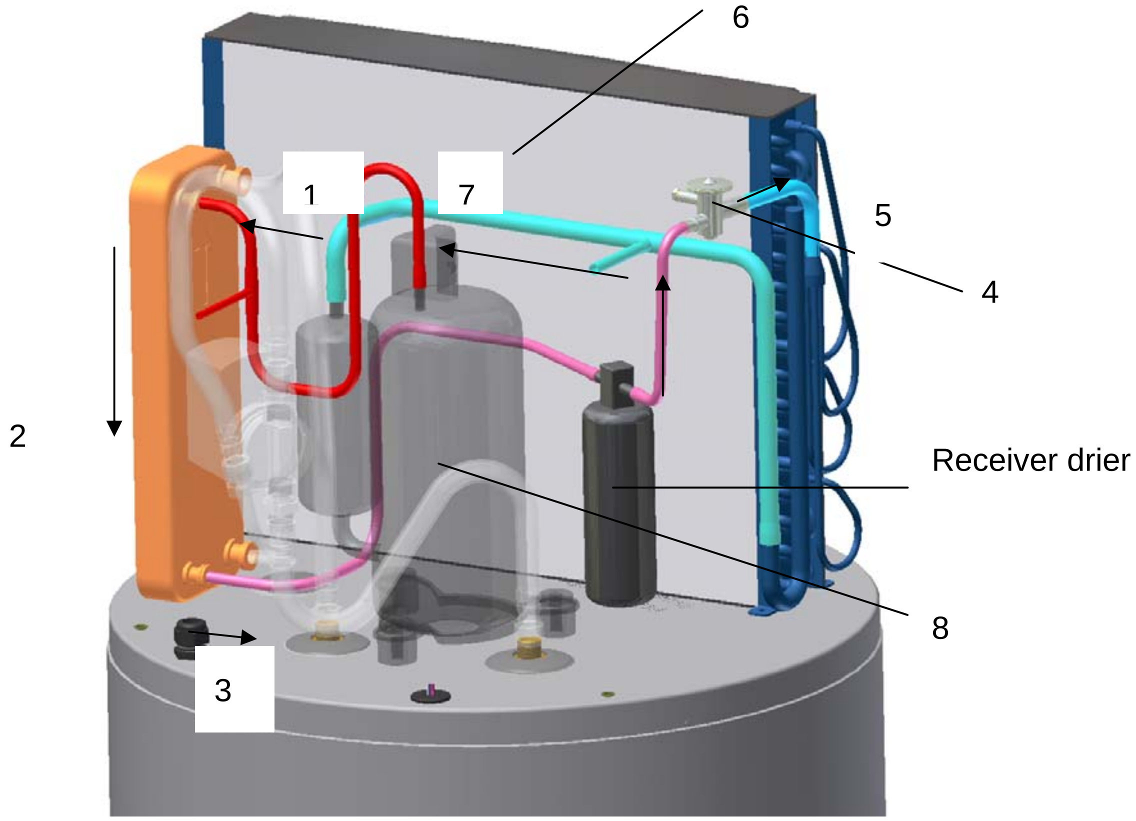


Diagram and information: Courtesy Rheem Australia.

Figure 3.7.6 – Rheem heat pump refrigerant flow diagram

1. Hot, high-pressure refrigerant vapour leaves the compressor and is passed to the heat exchanger.
2. The refrigerant condenses as heat transfers from it to the water passing through the heat exchanger.
3. High-pressure, liquid refrigerant leaves the heat exchanger and passes to the TX valve.
4. High-pressure liquid refrigerant expands through the TX valve to low-pressure liquid refrigerant.
5. Low-pressure, low-temperature liquid refrigerant is passed to the evaporator.
6. The low-temperature liquid refrigerant evaporates as it gains energy from the warmer air passing over the evaporator.
7. Warm, low-pressure refrigerant vapour is passed to the compressor.
8. Low-pressure refrigerant vapour is compressed to hot high-pressure refrigerant vapour by the compressor.

Key points

- Heat pumps use the refrigeration cycle to transfer heat from the surrounding environment into a storage tank.
- The main components are:
    - evaporator – absorbs heat from the air
    - condenser – dumps heat collected from the air into the water
    - compressor – pumps the refrigerant around the system
    - expansion valve – controls the rate of refrigerant flow through the evaporator.
- There are two types of system:
    - Split systems – where the evaporator is located remote from the storage tank and compressor. This allows the evaporator to be located in a sunny location to benefit from solar energy absorption.
    - Compact systems – where the evaporator is fan cooled and located integral to the top of the storage tank. This is a more flexible design that can be more easily located.
- Systems cost about the same as a solar water heater and are most suitable in locations where shading excludes the use of conventional solar water heaters due to lack of sunshine.
- Warm locations will always improve the performance of heat pumps for water heating.
- The main outstanding feature of the heat pump system is the small amount of energy required to heat the water when compared with a conventional system using an electrical element. The only energy used is by the compressor to pump the refrigerant around the system. The result is that for each kilowatt hour of energy used by the compressor, two to four kilowatt hours of useful hot water is produced.
- The compressor in heat pump systems uses around 1100W, whereas the equivalent standard electrical heater uses 3.6kW or 4.8 kW to produce the same result. This means that most heat pumps can operate from a standard 10 amp power outlet. An electrician is required to install the power point, but once in place the unit simply needs to be plugged in which can be done by anyone, including the installing plumber.
- Because the system can operate 24 hours a day, a smaller hot water storage tank is required than for a normal solar hot water system. It is logical to install a timer so that water heating occurs only during the day when the air temperature is warmer than during the night.
- The thermostat controls the temperature to 60ºC. Like a refrigerator, it turns itself on and off as required and can be expected to be in operation for three to eight hours per day depending upon water usage, and, very importantly, the temperature of the air from which the heat is extracted. In frosty districts if hot water is used in the late evening the unit can run all night attempting to reheat the water.

Section 3.7 questions

1. A heat pump hot water system has been described as being like a normal household refrigerator in reverse. What is meant by this?

2. Where does the heat that heats the water in the storage tank come from?

3. Is there any difference in the plumbing for a heat pump system than for an electric storage hot water system?

4. Is there any difference in the electrical connection between the heat pump system unit and the electrical or peak storage system?

5. Why would someone consider installation of a heat pump instead of:

   a. a mains pressure electric storage hot water system?

   b. a solar hot water system?

6. Why do manufacturers speak about the ‘co-efficient of performance’ in relation to heat pump water heaters? What does it mean?