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DEVELOPMENTS IN SOLAR WATER HEATING

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Abstract
Solar water heating system technology is described and the scale of the International solar water heater market is surveyed. New product developments for both direct solar water heating and solar boosted heat pump water heating are outlined. Procedures adopted by the International Standards Organisation for assessing solar water heater performance and quality are discussed.

1. Introduction

The world market for solar water heaters expanded significantly during the 1990's and as a result there has been a substantial increase in range and quality of products now available. Solar water heater production is now a major industry in China, Australia, Greece, Israel and the USA. The "self-build" industry has also expanded significantly in Europe. The primary exporters of Solar water heaters are Australia, Greece, Israel and the USA, most other countries only supply domestic demand. solar water heater technology has recently expanded to include a range of vacuum insulated collectors in both flat plate and tubular form, solar boosted heat pumps and a range of concepts to reduce the cost and improve product performance of pumped circulation systems.

The most common forms of solar water heaters are integrated solar pre-heaters and thermosyphon systems with a mantle heat exchanger around a horizontal storage tank. In areas where freezing is not a problem solar water heaters are based on direct potable water circulation between the tank and collector, with protection against the occasional frost provided by drain valves or an electric heater in the collector. For markets requiring a temperature regulated hot water supply, auxiliary boosting of solar water heaters is generally integrated into the solar tank, two tank systems are not commonly used outside of Europe and North America. The principle types of solar water heaters are outlined in the following sections.

1.1 Passive systems

The majority of domestic solar water heaters use thermosyphon circulation of water between the solar collectors and the storage tank. This requires the storage tank to be mounted above the collector to produce thermally driven circulation between the collector and the tank. The advantage of these systems is that they do not require an electrical connection and have very low maintenance. The collector-tank configurations used include:

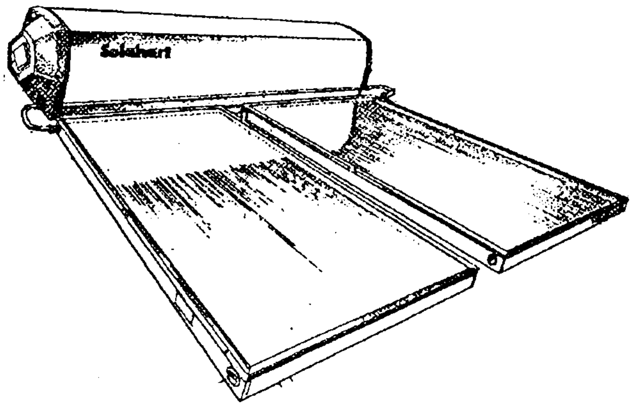

Figure 1. Thermosyphon solar water heater with externally mounted horizontal tank.

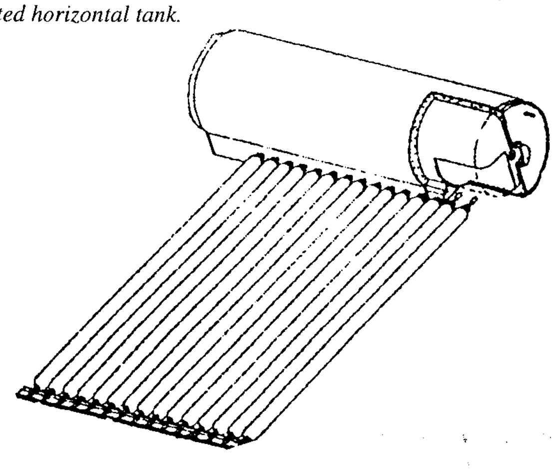

Figure 2. Evacuated tube collector with direct connection to tank.

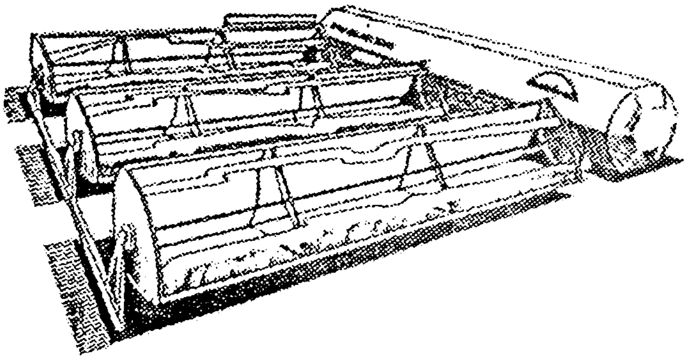

Figure 3. Concentrating collector with heat pipe connection to the tank and water pressure driven tracking.

- Thermosyphon flat plate collectors with direct connection to a horizontal tank or connection through a heat exchanger for freeze protection, Figure 1.
- Thermosyphon evacuated tubular collectors with direct connection to a horizontal tank, Figure 2.
- Heat pipe energy transfer from parabolic trough concentrating collectors with the heat pipe condenser inserted directly into the base of a horizontal water tank, Figure 3.

1.2 Integral tank-collector systems

Integral systems combine the tank and collector into one unit, Figures 4, 5. These systems are simple and effective however, due to high heat loss at night they only provide hot water during the day and early evening. The products range from simple glazed low-pressure plastic tanks to high quality steel tank systems with selective surface coatings to minimise

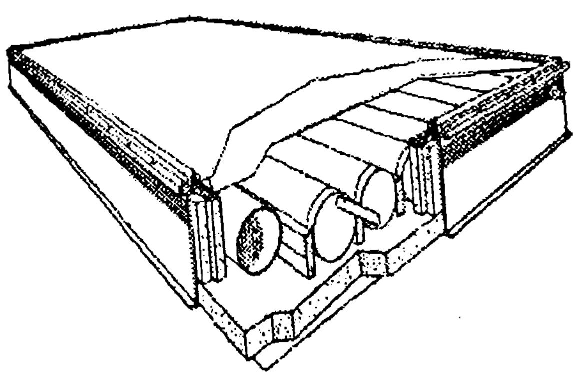

Figure 4. Integral collector-tank solar pre-heater with flat plate collector.

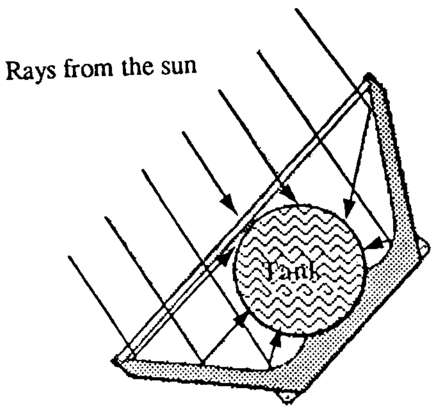

Figure 5. Integral collector-tank solar pre-heater with concentrating collector

heat loss. These systems make up the major portion of the large market in Japan. The main limitation with this system concept is that it is only a pre-heater and hence must be connected in series with a conventional water heater if a 24hr hot water supply is required.

1.3 Pumped circulation systems

Pumped circulation solar collector arrays connected to conventional enamelled steel hot water tanks have been widely used for domestic solar water heating in North America and Europe. The development of this

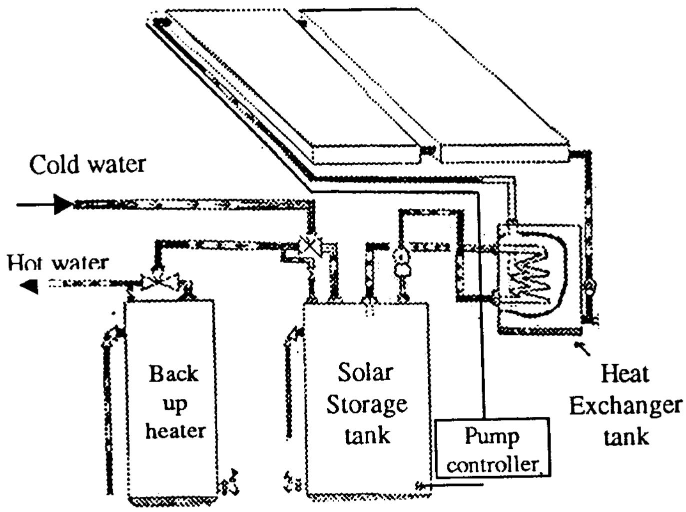

Figure 6. Pumped circulation system with drain down freeze protection.

design concept was driven by the need to provide freeze protection in these climates. The market share of such systems dropped significantly during the 1990's due to the lower cost of externally mounted thermosyphon systems. However production of pumped systems has started to increase in recent years, due to an increasing number of consumers who are not willing to accept the visual impact of an external roof-

mounted tank, even though such systems are cheaper and have better performance. New design concepts for pumped systems may result in increased use of this configuration however, it is primarily suited to larger commercial systems.

2. MARKET SCALE

The solar water heater market in many parts of the world was recently surveyed by IT Power for the CEC Directorate General for Energy [1], the IEA CADDET Renewable Energy review [2] in 1994-1995 and the APEC Compendium of renewable energy programs in 1995 [3]. The findings of these studies are summarised in table 1.

Comparison of markets in different countries is difficult due to the wide range of designs used for different climates and different demand requirements. In Scandinavia and Germany a solar heating system will typically be a combined water heating and space heating system with 10 to 20 m^2 collector area. In Japan the number of solar domestic water heating systems being installed is large however, most installations are simple integral preheating systems. The market in Israel is large due to a favourable climate and to regulations mandating installation of solar water heaters. The largest market is in China where there is widespread adoption of advanced evacuate tubular solar collectors.

Table 1
Major solar water heater markets

Country	Number of SDHW systems in use.	Number of SDHW systems produced in 1994	Total glazed collector area installed m^2	Glazed solar collector area produced in 1994 m^2
Australia	350,000*	30,000*	1,400,000*	140,000*
Austria			400,000+	100,000^
Canada	12,000#			
China				500,000#
Cyprus			600,000+	30,000+
Denmark	14,000*	2,000*		8,000°
France				18,000+
Germany				40,000+
Greece				170,000+
Israel			2,400,000+	300,000+
Japan	3,800,000*	150,000*	7,000,000*	
Korea	>8660#			50,000+
Netherlands	10,000*	3,000*		9,000°
New Zealand	10,000*	750*		3,000*
Norway	100*	20*		200°
Portugal				13,000+
Spain				12,000+
Sweden		2,000*		20,000°
Switzerland	9,300*	1,300*		6,000°
Thailand		>740#		
Taiwan			200,000#	
UK	45,000*	1,821*		7200°
USA	1,200,000*		4,000,000*	70,000**

+ CEC survey [1], * CADDET survey [2], # APEC Compendium [3],
** DOE USA [4], ° estimated, ^ primarily "self-build" products.

The largest exporters of solar water heaters are Australia, Greece and the USA. The majority of exports from Greece are to Cyprus and the near Mediterranean area. France also exports a substantial number of systems to its ôverseas territories. The majority of US exports are to the Caribbean area, Australian companies export approximately 50% of production (mainly thermosyphon systems with external horizontal tanks) to most areas of the world that do not have hard freeze conditions.

2.1 *Impact on Utility*

The adoption of solar water heating is not wide spread however these renewable energy products make a significant contribution to the energy supply systems in countries such as Australia, China, Greece, Israel and the USA. The magnitude of the energy supply from 100,000 m^2 of flat plate domestic water heater collector area is of the order of 50 MW during the middle of the day (assuming 1000 W/m2 and 50% collector efficiency). Thus the peak power capacity of solar water heaters in a number of countries already exceeds 1000 MW. The wide scale adoption of solar water heaters can have benefits for electricity supply utilities as solar water heaters displace a significant part of the expensive peak electricity demand generated by domestic water heating [5].

2.2 *Financing and Economics*

In countries with large coal or gas based electricity grids solar water heating is not generally cost competitive. The current low price of coal and gas makes competition very difficult however, when external factors such as environment benefits, are included the economics of solar waters are very favourable. As countries accept the new greenhouse gas emission targets the low cost of pollution reduction through the expansion of a local solar water heater industry can substantially change the economic value of these products.

However consumers are discouraged from purchasing solar water heaters due to the high initial cost, even though the life cycle return of the investment may be very good provided the consumer remains in the dwelling for more than six years. When utilities are required to meet lower pollution targets the benefit of pollution reduction through solar water heating can be a profitable way for the industry to maintain business volume while implementing energy conservation and pollution reduction. A number of utilities have determined that there is a better return from investing capital to promote solar water heating then investing in new low pollution and costly generating equipment.

3. NEW CONCEPTS

A wide range of concepts for solar water heating have been proposed in the literature, some of the designs that have reached prototype status or recent commercial availability are outlined below:

3.1 *Pumped circulation systems*

Innovative pumped circulation system designs, based on the low flow concepts, have recently been developed that achieve reductions of capital cost and improved performance. a significant contribution to this development was an International Energy Agency program to develop and test new system configurations. The eight countries participating in the IEA program each developed a system configuration that was considered the "Dream System" for their market, accounting for local climate and technology. Some of the "Dream Systems" were successfully commercialised before the IEA report [6] was published. The concepts incorporated in the "Dream Systems" include

Low flow rate circulation of the working fluid in the collector loop resulting in lower capital cost, lower parasitic energy use and improved performance due to increases thermal stratification in the storage tank.

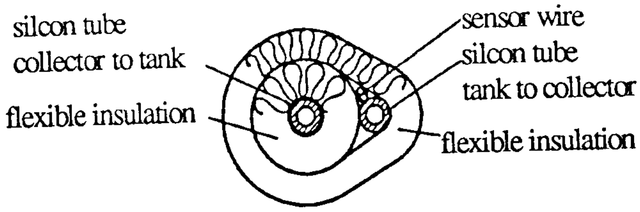

Figure 7. Cross section of flexible integrated collector-tank interconnection for pumped circulation.

- Integration of supply and return working fluid lines and the collector temperature sensor lead in one flexible bundled connector between the tank and the collector as shown in Figure 7. This greatly simplifies installation.
- Efficient natural circulation heat exchangers to remove the need for two pumps in pumped circulation freeze protected systems.
- Evacuated tube collector systems

The low collector flow rate concept adopted has been demonstrated to be an important design principle that gives scope for system cost reductions at the same time as the system performance is improved. A low flow rate system

incorporating the integrated collector/tank connection system developed as part of the IEA program in Switzerland is shown in Figure 8.

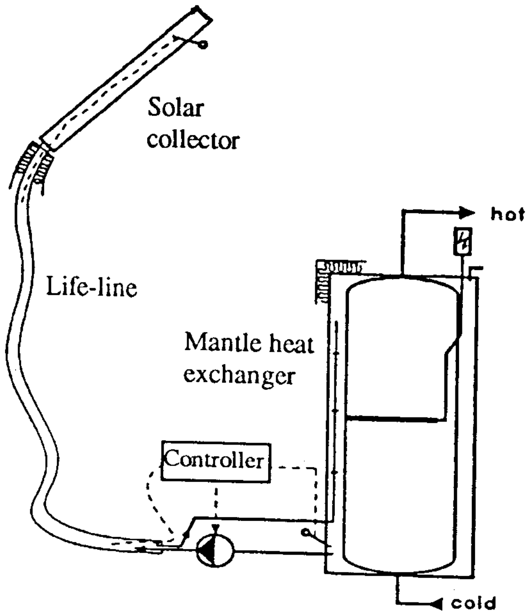

Figure 8. Swiss "Dream system" developed during the IEA program

The features of this system are reduced installation costs due to improved tank design and reduced installation costs achieved by the use of the flexible "life-line" between the collector and the tank. The single run low flow rate "life-line" connector replaces two hard pipes and the controller sensor wire used in standard pumped circulation system designs. The low flow rate design enhances performance as a result of improved thermal stratification in the storage tank and reduced parasitic energy use. The system shown in Figure 8 uses a vertical tank with a manifold heat exchanger around the bottom of the tank. This tank configuration has been adopted by a number of European manufacturers.

Another outcome of the IEA program was the commercialisation of a cheap and compact heat exchanger, designed for low collector flow rate (pumped) in one stream and thermosyphon flow between the other side of the heat exchanger and the tank. This heat exchanger is based on a small diameter spiral tube construction and is now manufactured in Germany and Canada.

A combination of low flow rate collector circulation with a compact heat exchanger fitted to a low cost standard water heater tank has been developed in Canada. This system has the benefit of easy installation and low shipping cost as the solar components can be fitted to any locally available hot water tank.

3.2 *Single tank gas boosted systems*

For markets that require 24-hour availability of regulated temperature hot water it is necessary to have an auxiliary heating system. In North America solar water heaters are primarily used as pre-heaters to conventional gas or electric water heaters. In most other markets electric auxiliary heating is incorporated into the primary solar system storage tank. Recently a number of integrated single tank gas boosted solar water heaters have been developed. These systems integrate a low cost thermosyphon solar water heater with a high efficiency gas booster in one integrated package. Such water heating systems have the lowest pollution rating possible, as a result of the combination of a zero pollution natural circulation solar pre-heater and a high efficiency gas burner with piezoelectric ignition. Although these systems are more expensive than electrically boosted systems they are ideally suited to off-grid applications where bottled gas or liquid fuels are the only alternative for water heating.

3.3 *Solar boosted heat pumps*

The heat pump water heater concept has been extended to incorporate solar boosting of the heat pump evaporator performance. Solar boosted heat pumps are now manufactured in a number of countries. The original system concept proposed by Charters [7] was for a system with direct evaporation of the heat pump working fluid in the solar collector. This was a significant simplification over earlier designs based on a solar pre-heater in series with a heat pump. To minimise system costs and parasitic energy requirements this system incorporates the heat pump condenser directly in the water storage tank. The integration of the condenser into the tank eliminated the parasitic energy of the pump used to transport heat

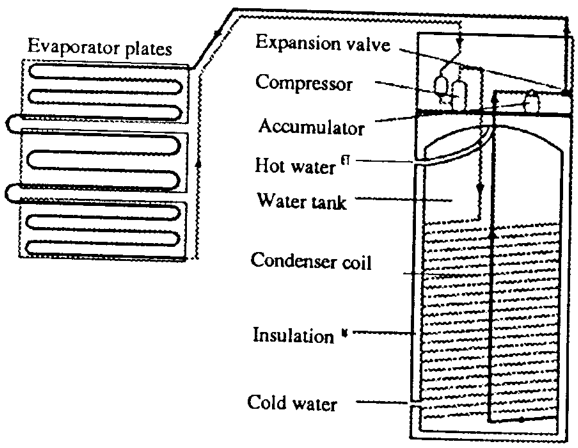

Figure 9. Solar boosted heat pump water heater.

from the heat pump condenser to the water storage tank in more conventional solar heat pump configurations. The solution for an effective condenser was to use an external wrap-around heat exchanger covering the bottom two thirds of the tank as shown in Figure 9. The disadvantage of this system is that the condenser heat transfer is limited by free convection over the tank wall however, this penalty can be minimised by using a large heat transfer area in the tank. Systems incorporating the wrap-around condenser on the outside of the storage tank are now manufactured in Australia, New Zealand and Korea.

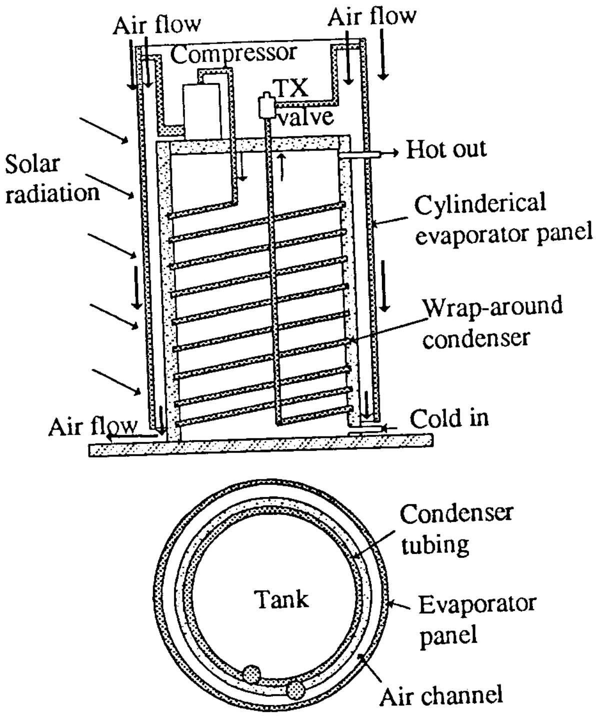

Figure 10. Compact "solar boosted" heat pump water heater.

Although this system has achieved significant acceptance it has the disadvantage that the heat pump refrigeration circuit must be evacuated and charged at the installation site.

A compact heat pump system has also been developed to reduce installation costs due to the need for on-site refrigeration component installation. This system incorporates an evaporator mounted round the outside of the water tank with natural convection air circulation over the evaporator as shown in Figure 10.

This system can be installed outdoors in order to gain solar boosting however, a significant part of its operation may be in the conventional air to water heat pump mode [8]. This system is being extensively used in commercial plant rooms where there is a high ambient temperature due to heat generated by other equipment. It can also be installed near or inside air conditioner exhaust outlets to benefit from the warm humid exhaust air passing over the evaporator. The advantage of this system over a conventional air to water heat pump is that it does not have the significant parasitic energy of a conventional fan coil unit. The packaged system also has the advantage that all the components are assembled in the factory and the installation is simpler than a conventional electric water heater since the unit does not require a high current electrical connection, as the compressor motor power is typically only 500 W.

3.4 *Evacuated tubular absorbers*

Extensive development of evacuated tubular solar collectors in Australia and China has led to the development of a range of selective surfaces for use in all-glass evacuated tubes. The Australian designed tubes are manufactured under licence in Japan and have been adopted in China where they are now produced in very large quantities for wet tube domestic water heaters. The wet tube concept in which water is in contact with the glass tube can only be used for low-pressure water heating systems, as the tubes cannot withstand more than a few metres water pressure. Systems incorporating pressure tubing inside the evacuated tubes have been developed in Australia and are manufactured in Japan.

Overheating of solar water heaters in summer is a problem in many parts of the world particularly with pressurised water tanks attached to evacuated tubular solar collectors, due to their high efficiency at temperatures above 100° C. Introduction of a high temperature switch in the heat loss from evacuated tubes by the use of temperature dependent gas desorption materials has been investigated however, these devices have not gained commercial acceptance.

An unusual evacuated tube system using air in the tubes rather than water was developed to overcome the two extreme problems of overheating in summer and freezing in winter.

This system uses a fan to circulate air through the tubes and a concentric heat exchanger around a horizontal tank. Using air as the working fluid overcomes freezing problems in the collector and the fan controller can be used to avoid tank overheating. The tube outlet is mounted above the tank so that thermosyphoning is restricted between the collector and the tank when the fan is off. The tubes can operate safely under stagnation conditions in the non-concentrating configuration that was adopted for this system as shown in Figure 11. Commercialisation of this system has not proceeded due to the high cost of evacuated tubes manufactured under licence in Japan,

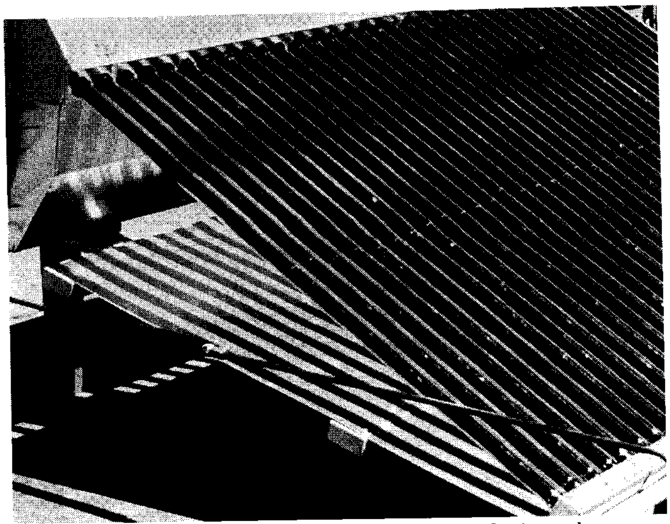

Figure 11. Evacuated tube solar water heater with air as the working fluid.

Figure 12. Evacuated tube solar water heater with seasonally biased concentrating collector.

however, with low cost tubes now available from China this system and other evacuated tube configurations may be commercialised in the near future.

3.5 *Seasonally biased collectors*

For locations outside the tropics a major operational problem with domestic solar water heaters is over heating in summer and insufficient capacity in winter. The summer over temperature problem is often due to the practice of mounting collectors flush with low inclination roofs to minimise the installation cost. The over temperature problem can be easily overcome by using a dump valve to control the tank temperature however, consumers think water discharge is an indication of system failure and water supply authorities often do not allow water dumping as an operational feature. Manufacturers go to considerable trouble to incorporate over temperature control without excessive water dumping which requires considerable ingenuity in thermosyphon systems design.

An alternative approach to over temperature control and improved winter performance is to use a collector design that can be mounted on a standard 20° to 25° roof pitch and yet give a winter biased performance. Such a collector was originally developed for a solar cooking system and then adapted to solar water heating [9]. The collector employs a series of low profile reflectors that give a winter bias to the system performance, Figure 12. These collectors have been used on a number of demonstration projects and elements of this technology are being adopted for commercial production.

3.6 *Low cost tanks*

The high cost of specially designed tanks for solar water heating systems is one of the major barriers to the development of cost effective systems [10]. In the standard thermosyphon design the weight of the tank is also a significant contributor to high installation costs, as the tank is mounted on top of the roof. A new low weight tank has been developed in Australia for solar water heaters. This system is based on a plastic bag welded to rigid plastic end flanges with the pressure load taken by a thin steel cylinder that clips onto the plastic end flanges. This tank has low weight, excellent corrosion resistance and needs relatively low capital investment for production.

4. TEST PROCEDURES

A wide variety of solar domestic hot water systems are marketed throughout the world. Hence there is a need for standardised test methods to evaluate, predict, and compare the performance of competing systems. International trade in solar water heaters could be greatly facilitated if the performance evaluation and certification procedures were the same in all countries. However a generalised performance model, which is applicable to all systems, has not yet been developed and it has not been possible to obtain an international consensus for one test method, and one standard set of test conditions for all countries. Work is continuing internationally on the development of universal system test procedures through the International Standards Organisation (ISO), Technical Committee ISO/TC 180, Solar Energy, Subcommittee SC 4, Systems – Thermal Performance, Reliability and Durability. Until such methods are available simple measurement and data correlation methods have been promulgated by ISO while the more general procedures are being finalised.

The five thermal performance test procedures selected for development as international standards and the stage of development of each procedure are described below:

4.1 *Indoor test methods*

The test method defined in ISO 9459-1 [11] defines procedures for indoor testing of solar water heaters under specified benchmark conditions. The procedures are based on testing with a solar irradiance simulator or non-irradiated thermal simulation.

Specification of solar simulator requirements includes duplication of air mass 1.5 spectrum defined in ISO9845-1, with a total irradiance of 952 W/m^2 and a spatial irradiance uniformity of ± 10% in the collector aperture plane and variation of average irradiance during a test less than ± 2%. A test sequence is repeated each day until the daily system solar energy contribution for solar-only and solar-preheat systems or the daily system supplemental energy required for solar-plus-supplementary systems, is within 3% of the value on the previous test day. The entire test sequence usually takes 3-5 days and is a rather expensive procedure due to the complex equipment required.

4.2 *Outdoor test for solar only systems*

This test ISO 9459-2 [12] evaluates the daily energy gain in solar pre-heat systems. The system is charged to a required temperature at the start of the day and then left to operate during the day without any loads applied. At the end of the day the contents of the tank are drawn off and the useful accumulated energy evaluated.

The useful energy collected in the tank is correlated with the daily radiation level and a temperature difference factor (T_a-T_c).

$$Q_u = a H + b(T_a-T_c) + c$$

where

Q_u	=	useful delivered energy
T_c	=	tank temperature at start of day
T_a	=	ambient temperature
H	=	daily total irradiation
a,b,c	=	correlation coefficients

The daily energy gain is determined for at least four days, with a range of daily irradiation from 8 to 25 MJ/day, with approximately the same value of (T_a-T_c) each day. The tests are repeated for a range of T_a-T_c *values.*

A calculation procedure is used to evaluate the effects of night-time heat loss and energy carry over from day to day, on the long-term system performance. The long-term system performance is determined by a day by day calculation procedure accounting for climatic conditions, load volume and energy carry over from day to day. The Commission of European Communities, Ispra Research Centre, developed this procedure [13].

4.3 *Outdoor test for solar plus auxiliary systems*

This procedure ISO 9459-3 [14] uses a model of solar water heater performance to correlate data collected while the system is operating under typical load cycle conditions. The parameters monitored are daily thermal energy delivery (load), bulk mean delivery temperature, auxiliary energy use, daily irradiation on the collectors and ambient temperature. Monitoring is limited to input/output factors so the system can be treated as a "black box." The correlation model is then used to compute the annual performance for the test site or for other locations, and for a range of loads. The correlation model given by equation (2) has been found to correlate outdoor test data and solar simulator data, for both passive and active SDHW systems [15].

$$f = (a + b(T_o-T_a)/L)H/L + c(T_o-T_a)/L$$

where

T_o	=	delivery temperature
T_a	=	ambient temperature
L	=	load energy
a,b,c	=	correlation coefficients

In this procedure the effect of internal energy change in the tank is minimised by averaging the performance over 5 to 15 number of days, so that the change of tank energy is small compared to the total load energy for the period.

4.4 *Computer simulation*

This method ISO 9459-4 [16] combines test results from individual components with computer simulation models for the balance of system. For example, test data are used to determine performance correlations for the collector and heat exchanger and computer simulation models are used to provide performance equations for the store, pump, controller, etc. The result is a computer simulation program that thas great flexibility, which can be used to predict system performance under a wide range of solar meteorological conditions, loads, load profiles, and operating set points.

The USA Solar Rating & Certification Corporation [17] and the Australian Standards Association [18], use this technique to determine ratings of solar domestic water heating systems. Thermal performance ratings are determined using mathematical models and empirical correlations in conjunction with the computer simulation program TRNSYS [19].

4.5 *Outdoor system test and parameter identification*

This procedure ISO 9459-5 [20] is based on a numerical model of the solar water heater and parameter identification software [21]. The

parameters in the numerical model are determined by comparison of measured and predicted performance results. This method has the advantage over direct simulation methods in that the performance prediction is based directly on system measurements and not component measurements or performance models. The prediction will therefore reflect any differences between actual system operation and the system operation deduced from design information and direct simulation models. Performance data for the water heater are collected at one to two minute intervals, with more frequent monitoring during load draw-off periods. An identification process is then used to compute the system parameters that produce the closest match between the simulation model predictions and the observed performance. Measured inputs and outputs are entered into the identification procedure as a function of time, rather than as daily averages used in the correlation methods. Thus load pattern effects are accounted for in the parameter identification process. The process is based on matching the simulation model prediction with short time step experimental data, and is referred to as the Dynamic Test Method. Typically fifteen to twenty days of monitoring are required.

The dynamic parameter identification procedure can be interpreted as the inverse of dynamic simulation. Conventional simulation models predict the system output on the basis of measured or design values of parameters for individual components. The dynamic parameter identification procedure computes the parameters from system performance measurements and then uses these parameters to simulate the annual performance in the usual simulation process.

4.6 Comparison of test procedures

The SDWH test procedures being developed as international standards range from simple, low cost procedures for assessing solar pre-heaters, to complex procedures that require extensive equipment and highly trained staff for assessing complex systems under any climatic an load conditions. In terms of outcomes, the primary differences between the methods is that the procedures in Part 1 only produce a rating for a standard day, while the other Parts predict annual performance for a range of climatic and load conditions. The results of tests performed under Parts 4 & 5 are directly comparable. These two procedures both permit performance predictions for a range of locations and system loads.

The procedure that requires the least investment in equipment and operator skills is Part 2 however, it is limited to solar preheat systems.

In this procedure the system is pre-conditioned at the start of each day and then left to operate without the need for data acquisition other than radiation and embient temperature monitoring. Energy monitoring is performed during a single load draw-off at the end of the day. This can be achieved with simple temperature and flow rate recorders or with an on-line data acquisition system.

The procedures required for Part 3 closely mirror actual operating conditions of a typical system installation. The main equipment required is a controller than can apply typical domestic draw off patterns throughout each day. The main difficulty with this procedure is that the test is very long, typically six to ten weeks and an unbroken sequence of steady daily loads is required over periods of five days or longer. This test is close to the ideal in-situ procedure. However, the results are limited to the particular daily load draw off pattern used during the tests.

The simulation procedure being developed as Part 4 is the most flexible. However, it is limited by the availability of verified numerical models for the types of systems to be assessed. The problem with simulation results is that the actual system may not be as good as the ideal design case that the simulation model usually represents. An approach to allow for practical imperfections in a particular product is to require a comparison between the simulation model predictions and observed performance over a period of a few days. Any difference between the model results and the observed performance can be allowed for by introducing a scaling factor in the simulation results. The Solar Rating and Certification Corporation in the USA [17], have adopted this type of approach.

The procedure defined in Part 5 of the standard over comes the difficulty of obtaining a match betweent he simulation model and the actual system performance. This is achieved by using a parameter identification procedure to evaluate the important parameters from a series of system tests, rather than from component tests or manufacturers specifications as in the case of conventional simulation modelling. Part 5 also requires a validated simulation model of the system being assessed, however, it automatically matches the model to the observed operation of the particular SDWH system being assessed. A feature of the matching procedure in Part 5 is that stationary measuring conditions are not required. This means that the experimental effort is minimised as a wide variety of measurement sequences can be used in the parameter identification process.

The ISO development provides measurement procedures that can be used for applications in

developing and advanced markets. Due to the wide range of product designs and quality it is essential that countries planning to incorporate solar water heating as a core energy supply element should implement a certification program to guarantee satisfactory product life for a positive economic and pollution return.

5. CONCLUSIONS

The solar water heater industry has developed into a significant industry in a number of countries. The peak power output already exceeds 1000MW during the peak solar periods in at least four countries and power levels above 500MW are achieved in many other countries. The significance of the contribution of solar water heaters to energy self efficiency, pollution reduction and local manufacturing capacity should see this industry expand significantly in the coming years.

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