+IV Conferencia Latino Americana de Energía Solar (IV ISES CLA) y XVII Simposio Peruano de Energía Solar (XVII-SPES), Cusco, 1-5, 11, 2010

Optimum Designs for Solar Water Heating Equipment for the Single Family Home

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Abstract. *The standard solar domestic hot water (DHW) heaters for the single family home have a solar fraction of no more than about 65% because of curious and serious design limitations. A solar water heater with a different tank design has been developed, with the backup tank mounted above the solar tank, and the two tanks coupled with a thermal diode. A new gas-fired backup heater was developed, which is very efficient by acting as a thermal diode to minimize the backup tank heat losses. This water heater, when sized properly for the customer's hot water consumption, and when controlled with the right temperature control strategy, can obtain a solar fraction of above 80% and even above 90%.*

Key Words: Solar water heating, Solar water heating optimum designs.

1. INTRODUCTION

In the Roman Empire many people already had running water in their villas. Hot and cold running water was already available in many houses of rich people in the 19th century. However in 1940 only about half of the houses in the USA had any running water, and very few had hot and cold running water. Perhaps hot running water existed long before the 19th century, for even in Rome there was nothing to stop a technically minded and rich aristocrat from building and operating a simple water heater and including it in a hot and cold water plumbing system in his villa. In some of the 19th century houses the hot water was already provided with solar domestic hot water (DHW) heaters (Butti and Perlin, 1980).

Solar water heating became quite popular in the 20th century, and by 1950 there were over 50,000 solar DHW heaters in Miami, Florida (Butti and Perlin, 1980). Natural gas pipelines put an end to the solar water heaters in much of the USA, for fossil fuels were on purpose always sold cheaply enough so that "solar energy was not competitive in the free market." For decades (and still in many places now) natural gas was considered a useless byproduct of petroleum wells and it was burned ("flared") at the well. It could be sold very cheaply and still be profitable. In Australia, South Africa, Israel and some other parts of the world solar water heating does not have the competition of fossil fuels, and it continues being popular. Now the threat of global warming and the effects of the Hubbert peak of petroleum are likely to revive interest in solar water heating everywhere, for it is unlikely that fossil fuels can be sold very cheaply much longer. This will be especially likely if humanity eliminates the large subsidies enjoyed by the fossil fuels, and imposes carbon taxes. This seems inevitable. An enormous and very competitive solar water heating market is likely to develop in the next few years (de Winter, 2006).

People are becoming ever more educated and demanding, and currently almost all the solar water heaters will be expected to have backup heating, with the backup heating provided perhaps with electric resistance heaters, or perhaps by burning natural gas or LPG or biogas. Without backup heating one would often have to wait for the sun to come up again to heat the water, but with backup heating one does not have to wait that long, perhaps no longer than an hour, and perhaps even less.

The last few decades have seen great improvements in solar heat collectors, heat exchangers, pumps and controllers, but not in the design concepts and the configurations of the solar water heating storage tank systems. That is the topic of this paper.

2. THE RATIONALE FOR SOLAR WATER HEATER DESIGN IMPROVEMENTS

Solar water heaters with backup heating should provide a reliable hot water supply with a minimum total cost. This requires minimizing the equipment purchase cost plus the operating expenses. It requires a large "solar fraction" to have a minimum cost of the backup heating energy, and it requires a reasonably low cost for the whole installation. A large solar fraction clearly requires careful and intelligent equipment design, but curiously enough solar water heaters have almost never involved any careful and intelligent equipment design whatsoever. Solar water heating is so incredibly easy that one can get very hot water out of a garden hose lying in the sun, and for over a century that incredible easiness has provided a temptation to almost everybody for using very simple equipment designs, that may well work better than a garden hose, but that have a solar fraction of no greater than at most 60% to 70%. In much of the equipment there has indeed been little need for an intelligent design, for the customers were often not very demanding, and there was little competition in the market. For some, solar DHW provided the only way to have hot water, and any hot water was better than none. For others, solar DHW satisfied their environmental interests, and the equipment performance was not very important, so long as it was a solar water heater. In the near future, the solar DHW market will however become very competitive and very large (de Winter, 2006), and that will change things.

The flat plate solar water heating collectors provided an example for far more than a century of pathetically poor design. De Saussure built the first flat plate solar heat collector well over two centuries ago (Ackermann, 1915), but even in the early 1930s nobody bothered to try to understand how the flat plate collectors really worked, and to try to use that understanding to produce a reasonably cost-optimized design. Hottel and Woertz finally did this in the late 1930s and early 1940s (Hottel and Woertz, 1942). The technology spread rapidly (Veltford, 1942), and the final "Hottel-Whillier" collector equations were developed in the 1950s (Whillier, 1953 and Hottel and Whillier, 1955). Currently virtually any solar thermal textbook (Duffie and Beckman, 1980) carries an adequate set of equations and criteria for the dependable design and evaluation of cost-effective flat plate solar heat collectors, and for many years it has been easy to find the good papers on the technology (de Winter, 1975a; de Winter, 1990). To anybody who understands the Hottel-Whillier equations and the heat transfer mechanisms these equations describe, virtually all the flat plate collectors built and sold before 1940 seem almost comically crude and primitive and inefficient (see, for example Brooks, 1936).

The tank systems for solar water heating with backup heating in the single family home however continue being almost comically crude and primitive and inefficient. They have nearly always involved the "two-tank" configuration, in which the solar heated water and the backup heated water are not coupled at all; or the "one-tank" configuration, in which the solar heated water and the backup heated water are coupled far too intimately. These design features can only be considered serious design problems, for they lead to unnecessarily low values of the solar fraction.

In the one-tank configuration the backup heater heats a section of the tank directly above the solar heated section, but the backup heat migrates surprisingly rapidly downwards into the solar heated section: about 3 or 4 times as fast as one might expect based on the thermal conductivity of stagnant water (Souproun and Nielsen, 1993, and Grunes et al, 1982), probably because the water is not really stagnant. As a result the next day when the sun comes up the solar section is already heated in part by backup heating, one cannot collect quite as much solar heating, and the solar fraction is reduced. One cannot get solar fractions of more than perhaps 60% or 65% with a "one-tank" system.

In the standard two-tank configuration the solar heating can only get to the backup tank if hot water is being used. If one is away or goes on a vacation one might as well not have a solar water heater during the time one is away, for all the heat losses from the backup tank must be provided by backup heating. This reduces the solar fraction unnecessarily, and one cannot get solar fractions of more than perhaps 60% or 65% with a "two-tank" system.

The most incredible feature of the use of solar water heating for the single family home however involves the crude calculations that are used almost universally to establish equipment design, and to evaluate equipment performance. Many pride themselves on using intricate computer programs like TRNSYS (Klein, 1976 and Klein et al, 1976) or F-CHART (Beckman et al, 1977) to do the calculations, and make sure that they have modeled the local climate correctly (for the collector performance) by using the local "TMY" (Typical Meteorological Year) files to describe the detailed characteristics that one can expect for the local weather. They would not dream of doing the calculations with crude computer programs or crude weather models, or with weather models for another and totally inappropriate location. The next step is however almost incredible, for they assume that the hot water consumption in the single family home is exactly the same each and every day; as if they are dealing with a family of rigidly programmed robots with a fixed daily schedule. That is of course not true. On some days there might be many showers, dishwasher loads, and washing machine loads, and on other days there might be few or none. That shows. In the USA and in Canada, the hot water consumption per day in the single family home typically jumps randomly up and down, from about 3 times as high as the average hot water consumption, down to about one third as high (Laue, 1982), and when people are away from home it goes to zero. It was clearly shown by Buckles in his MS thesis work at the University of Wisconsin at Madison, that the variability of hot water consumption has an enormous effect on solar DHW equipment design and performance, and that only the area of the collector has a greater effect. This was reported in the literature by Buckles and his main thesis professor (Buckles and Klein, 1980) 30 years ago. Nevertheless, for 30 years thereafter the professors of Buckles have continued to recommend that the equipment design and performance calculations be based on the rigidly programmed robot model of hot water consumption, a simple and invariant 24 hour history of hot water consumption which was established by ASHRAE for gas-fired or electric water heaters, but which is totally inappropriate for solar DHW systems (see the current editions of Duffie and Beckman, 1980; Klein et al, 1976; and Beckman et al, 1977). This of course gives the wrong answers, but perhaps the professors of Buckles never read their own papers (like Buckles and Klein, 1980). The solar DHW establishment seems to have adopted the invariantly programmed robot family approach everywhere.

3. DETAILS ON THE IMPROVED DESIGN

For over 30 years I have worked with my coworkers to develop solar DHW storage tank equipment designs for the single family home that could be properly optimized (de Winter, 1975b; de Winter and Horel, 1978; de Winter, 1978; de Winter, 1980; de Winter and Grunes, 1982; de Winter et al, 1985; de Winter et al, 1987; de Winter et al, 1991; de Winter, 1994; de Winter; 1996a; de Winter, 1996b; de Winter, 2005; de Winter, 2006; Morrison et al, 1980; Grunes et al, 1982; Grunes and Morrison, 1983; Arata and de Winter, 1991). The current model (Grunes et al, 1982) has involved a superposed system of tanks as shown in Figure 1, with the backup heater tank above the solar heated tank (de Winter, 1978), and the two tanks connected with a thermal diode based on natural convection in a double-chimney device (de Winter, 1980; de Winter, 1994; de Winter, 1996). The inter-tank thermal diode is very effective. In the water heaters we built on our GRI-funded program (Grunes et al, 1982) the upward heat transfer between the two tanks was seven times as high as if the neck between the two tanks had been made of solid copper, and there was only a temperature difference of about 3 ºC between the two tanks when there was full insolation on the collectors. Downward heat transfer in the diode is almost zero. In effect the backup tank becomes an integral part of solar storage, and when one is on vacation no backup heating is ever needed. The water heater involved a gas-fired backup heater that is a Two Phase ThermoSyphon (TPTS), a patented (Grunes and Morrison, 1983) thermal diode. With such a TPTS unit using an atmospheric gas burner one can have a firing efficiency, based on the natural gas upper heat value of about 83% to 84%, and the backup tank has very low heat losses, about the same heat losses as one gets from an electrically heated water tank (Grunes et al, 1982). Typical standby losses from a 150 liter TPTS heated tank are 0.6% of the stored heating per hour, equivalent to an exponential time constant of 167 hours – almost a full week. This TPTS patent and the equivalent patents in 10 other countries have all expired.

Our early engineering prototype model built on our US DOE program has a solar tank with a coil heat exchanger thermally coupled to the tank wall for the collector loop (Morrson et al, 1980). The two pre-production prototype units we built on our Gas Research Institute (GRI) program have a drain-back annular jacket heat exchanger for the collector loop (Grunes et al, 1982). One can also use a double loop system with the associated heat exchanger factor (de Winter, 1975), or one can use a single loop system (as in the DOE unit of Morrison et al, 1980) with a coil fastened to the tank wall or with an internal heat exchanger coil (de Winter and Horel, 1978). Any of these heat exchanger options can involve a hermetic loop with a drain-back tank, as is used in the GRI units (Grunes et al, 1982). This makes it possible to use water instead of a possibly toxic antifreeze fluid in the collection loop, and one does not need to use a double wall heat exchanger.

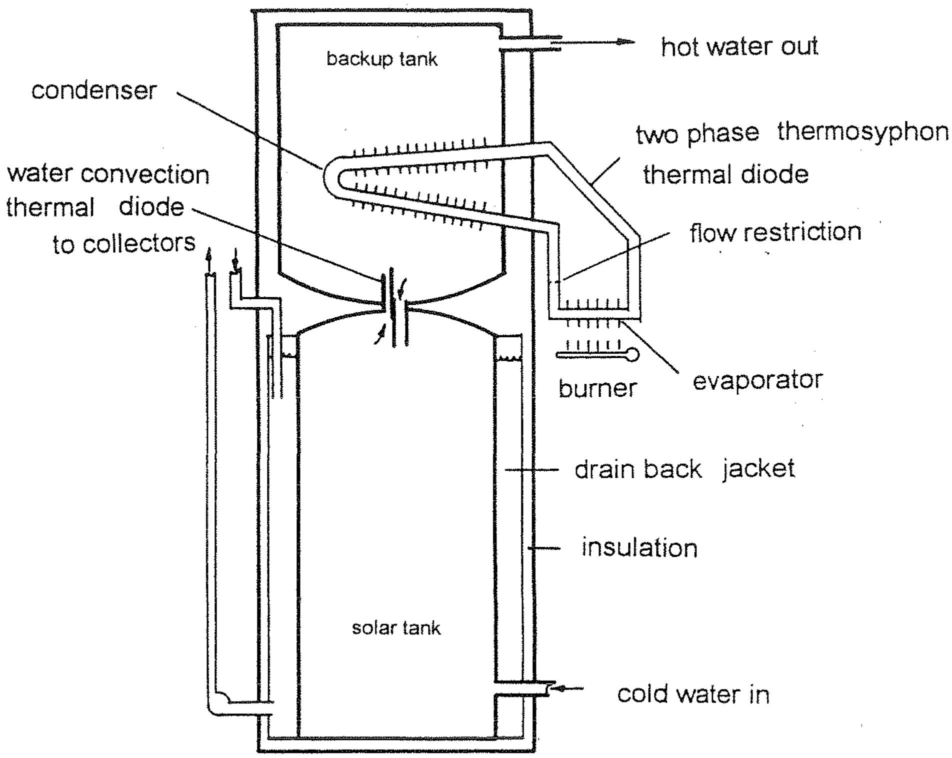

Figure 1. Cross Section of Our Current (Grunes et al, 1982) Solar-Augmented Gas-Fired Water Heater

Professor Adolfo Arata of the Universidad Técnica Federico Santa María of Valparaiso in Chile has proposed a total of 7 different system design configurations involving the solar storage tank (or tanks) and the backup heater, with the most effective ones being the Arata systems number 5 and 7. The units we have developed and built involve the Arata system number 5, with the solar storage tank coupled to the backup tank with a thermal diode, allowing heat transfer to go from the solar tank to the backup tank but not in the opposite direction. The Arata system number 7 involves two solar storage tanks, followed by a backup tank, with all three tanks coupled with thermal diodes, or with thermostatically controlled solenoid valves and a circulation pump to achieve the same function as these thermal diodes. I have worked with Prof. Arata to perform and publish three studies on solar water heater systems (de Winter et al, 1986; de Winter et al, 1991; and Arata and de Winter, 1991), and I plan to work with him again in the near future.

3. CONCLUSIONS AND RECOMMENDATIONS

There are a number of advantages of the design we have developed, but these have still not been very precisely evaluated. Virtually all the funded development has been done under very tight funding with ambitious objectives: to develop intricate equipment that was close in design to commercial hardware and that worked properly. We always managed to be successful in this, but we never had enough funding to do exhaustive tests or to do very thorough modeling. The funding was also often interrupted for long periods of time, for starting in 1980 with US President Reagan solar energy has had almost no priority (and almost no budgets) in the USA. Much of the work was done under very limited in-house funding.

Some comments follow on what we do know. Having the backup tank mounted on top of the solar tank makes more floor area available in the house or the garage, and this can involve a saving of perhaps US$250 to US$1,000 per square meter. In our GRI contract (Grunes et al, 1982) it was determined that the inter-tank thermal diode added about 3% to the solar fraction if we used the same day-to-day variability as was used by Buckles (Buckles and Klein, 1980), but did not change the sizes of the tanks to adjust for the variability, and made no changes in the temperature control strategy. Cromer (Cromer, 1987) found a 10% to 14% improvement in performance with a superposed tank system coupled with a thermal diode. Simple simulations found that an optimum tank system operating with the daily hot water consumption variability described in the Laue, Perlman, and Baker papers (Laue, 1982) should have a total volume (solar tank plus backup tank) of about 30% to 40% larger than the average daily hot water consumption (de Winter, 1994). Finally, one can also use a custom temperature control strategy. The best control strategy seems to be one in which solar energy is collected until the tanks are at a very high temperature (say 80 ºC if the water is fairly soft, instead of hard), and that the thermostat of the backup heater is set at the lowest temperature that will provide comfortable showers, perhaps just over 40 ºC . Under these conditions a lot of solar heating will be collected on sunny days with low hot water consumption, and a minimum of backup energy will be used when the solar heated water runs out. In our 9 year field test in Hawaii (de Winter et al, 1987), it was found that with a tank system generously larger than the average hot water consumption one could achieve a solar fraction of almost 100% by using such a temperature control strategy. The collectors do not need to be significantly larger, and extra-large tanks do not cost much.

Solar water heating designs that have a solar fraction of 65% or so may be acceptable for a vacation cabin or for an environmental enthusiast, but they do not really help much as humanity strives to change from fossil fuels to a sustainable energy system. With a solar fraction close to 100% it becomes attractive to use renewable energy for the backup function, and this could involve biogas or even solar or wind generated electric power.

Most solar DHW systems in the USA to date have used tanks pressurized at line pressure, and this imposes a cost that can be greatly reduced by using tanks at atmospheric pressure. The pressurized tanks must not only withstand the typical line pressure of about 7 bar (7 atmospheres), but must be able to survive the 20 bar (20 atmospheres) pressure one can get frequently in water hammer incidents. One can get inexpensive and corrosion-proof tanks of fiberglass reinforced plastic material that will withstand temperatures of 82 ºC and even of 99 ºC (Anon, 2010), and solar DHW systems built with such tanks can provide an adequate distribution line pressure by being mounted on the roof of a home or building, or by using a small pump, with a pressure control and a tank with a pressure bladder. In the USA many are accustomed to having the water pressure at 7 bar (7 atmospheres) in their homes, but in Latin America low pressure water supply system are widespread, and roof-mounted hot water tanks could be very useful and popular. Plastic tanks might also provide a better thermal stratification behavior (Souproun and Nielsen, 1993; Grunes et al, 1982). Much of our future work will involve such plastic tanks.

Our next step, in conjunction with the Gas Technology Institute (GTI) and probably with the San José State University and with the Universidad Técnica Federico Santa María, will be to prepare a detailed and validated TRNSYS model of the heater, and to determine the optimum design parameters as a function of equipment costs and of hot water consumption. This would involve the ratio between the volumes of the two tanks, the total volume of the tanks, the firing rate of the backup burner, and possibly some other numbers. All the results and the software packages would be posted and made public on the internet.

It is really curious that for over 30 years we have slowly and very openly worked on these ideas with almost no effect on the solar DHW field, except for the heat exchanger factor papers (de Winter, 1975, and de Winter and Horel, 1978) that have become accepted worldwide. Prof. Page Smith may have an explanation (Smith, 1990), for he concluded that in academic R&D circles many people have become quite timid, afraid to look at things that are not already widely accepted. Thus many may have said or thought that "Everybody looks at one-tank systems or at two-tank systems, and everybody uses an invariant daily hot water consumption profile. How could I ever dare to be different?" I hope to be able to count on more open and more adventurous people in the future.

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temperature capability of up to 99 ºC and with no corrosion problems, at a cost ranging from US$0.46 per liter to US$1.50 per liter. The solar DHW market would be large enough so that one would get much lower prices (and a wider range of models) directly from the manufacturer.
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