SOLAR WATER HEATING WITH BACKUP HEATING
A REVIEW

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ABSTRACT

Solar domestic hot water (DHW) equipment for the single-family residence has been available for over a century, but the market has been small and regional, and there has been little continuity in the industry. It is very easy to produce solar DHW. For decades this was done without any understanding of flat plate collector operation, and even today the effects of DHW consumption variability on equipment design or operation are not being considered. Virtually all the equipment still involves crude tank system designs, with primitive and inefficient ways of providing backup heating. Before the end of this decade there will be an enormous demand for solar DHW equipment, because the production peaks of oil (world-wide) and of natural gas (in North America) will become clear to the public (2-4). Neither the solar DHW devices nor the people in the solar energy field are ready for this challenge.

1. INTRODUCTION

The solar DHW field, just like all of the other solar energy technologies, is at a critical point in its history. For over 100 years it has involved a technology of little importance. Small manufacturers produced equipment for people who could not have hot running water otherwise, or who had a great moral urge to use solar energy. Much of the equipment had no backup heating. Where backup heating was possible, fossil fuel was generally priced low enough so that "solar energy could not compete" in the alleged "free market" (10). That is about to change radically in the next few years, as the depletion of oil and of natural gas (2-4) becomes obvious to humanity. The solar DHW market may very rapidly become huge, and this called for a paper on the status of the solar domestic water-heating field. The solar DHW tank system designs that have been offered on the market are very crude and ineffective, and the analytical techniques that have been used for equipment design and evaluation are quite inadequate. It will take a serious effort to get ready for the future.

2. SOLAR WATER HEATING TECHNOLOGY

The outer surface of the sun is at 6000^{o}K. We get a solar heat flux of 1,352 w.m^{-2} outside of the atmosphere, and of about 1,000 w.m^{-2} at ground level. To produce solar DHW for a residence, all one has to do is to use this ground level heat flux to heat water about 40-50^{o}K above ambient. This is so easy that only an imbecile cannot do it. We have all met someone who said: "The water from my garden hose lying in the sun is so hot it burns me." That was not an imbecile, but a successful solar DHW practitioner (1).

The above paragraph may seem brutal, but it describes a curse that solar DHW has had for over a century. Almost any well-meaning plumber or solar enthusiast can put together a solar DHW device that will provide comfortable showers often enough to satisfy the needs of customers who are not very demanding, or for whom the possession of a solar DHW device satisfies a moral urge even when the equipment is not very good. Whether backup heating is used or not, producing solar DHW is very easy.

The real problem in solar DHW is not in heating water with solar energy. It is in satisfying the real DHW needs of a customer with solar DHW equipment that is durable, reliable, and safe; that is unobtrusive or at least not ugly; that does not create problems in or to the building; that does not take up too much space; and that yields a very high solar fraction as cost effectively as possible. Hardly any of the residential solar DHW heaters to date have satisfied these objectives to any significant degree, since there has been little effort to optimize the solar DHW equipment designs to meet the real needs of the customers. The market for solar DHW has never been large and competitive enough to change this, but fossil fuel depletion (2-4) will create a huge and very competitive market in the very near future. We must get ready for this.

3. THE HISTORY OF SOLAR DHW

Just a few decades ago running water was a luxury, and hot running water an enormous luxury. By 1940, only 50% of the houses in the USA had running water, and there were probably few countries with a much higher percentage. In the late 1800s some wealthy people in the USA already had hot and cold running water with solar water heaters (5-7), but the designs were quite crude (8, 9) and expensive. Expensive electricity provided the incentive for solar water heating. Natural gas was not available.

Solar water heating became fairly widespread in 13 southern states of the USA (7-9), with 14 equipment manufacturers listed in 1942 (9), most of which were probably quite small. Some heater designs even had an antifreeze loop (8). Most of the early units had no backup heating, and those that did often used a “one-tank” design (see below) with the electrical (or other) backup either turned on or off. By the 1950s there were many solar water heaters (including 50,000 in Miami alone), but cheap natural gas drove them out (7). Natural gas could be sold at “throw-away” prices, for it was a waste product of the oil industry, generally burned (“flared”) at the wellhead, and it could only be sold if it was offered at prices lower than those possible for solar DHW (10), establishing a “free market” in which “solar energy was not competitive.” The energy crisis of the 1970s led to some solar water heater sales, but then sales decreased again. In South Africa, Australia, Israel, and a few other countries there is still a market.

De Saussure invented the flat plate solar heat collector in the late 1700s (5), but it was only in 1942 that a good understanding of flat plate collector operation was developed, and the foundations were laid for the Hottel-Whillier equations (11, 12). The collector designs of the 1930s (8) and the 1940s (9) were very crude, and the disadvantages of these crude designs are discussed in the Hottel and Woertz paper (11). A heat exchanger factor for a pumped double loop antifreeze system for heating water was later added to the Hottel-Whillier equations by de Winter (13), but the form of the equation always used for this factor (14, 15) is due to Klein (16). A heat exchanger factor for a single loop antifreeze system was developed later (17). For many years the flat plate collector analysis used the external convection heat transfer loss coefficients of Juerges (18), which were impossibly high - much higher than those predicted with (and allowed by) boundary layer theory (19). Virtually the whole solar energy literature (11, 12, 14-16, 20) was based on the Juerges numbers. Current values are about 4 times lower than those of Juerges (21, see chapter of Lior; see also 22). These values make unglazed swimming pool heaters and Thomason collectors much more effective than was thought earlier, but should be used for glazed collectors also.

Certified and effective solar collectors, pumps, and controllers are now available, but the overall solar water heater systems are still crude. Most of the customers only had a choice between cold water and erratic solar hot water, and there has never been a large enough market of demanding customers to allow the good solar DHW units to eliminate the poor ones. Most of the units with full time backup still use traditional "one-tank" or "two-tank" designs. In one-tank units the backup heater is at the top of the tank, and in two-tank units the second tank is the backup heater. The standard one-tank system has the disadvantage of downward heat flow, which uses backup heat for heating some water that should be solar-heated. The standard two-tank system only transfers solar heat to the backup tank when DHW is being used. During times of no DHW consumption (e.g. during a vacation) backup heating must be used to keep the backup tank warm, and solar heating is of no help. The “one-tank” and “two-tank” units are very poor designs.

For many years it has been assumed that the typical US family uses an average of about 246 liters (65 gal) of hot water at 60ºC per day (14-16), but the current value (23) seems to be about 413 liters (109 gal). Hot water usage in the single-family home varies wildly from day-to-day, between 3 times as high and only 1/3 as high as the average value (24). This does not affect gas or electric water heaters much, since these can rapidly produce large amounts of hot water, but the fluctuations have a great impact on solar DHW equipment design and performance (25). Solar DHW practitioners have however insisted on using a daily water consumption profile that never changes (14-16). The F-Chart method can only be used with such an invariant consumption (14, 16, 24). This unrealistic design method, coupled with the crude "one-tank" and "two-tank" units, and the poor backup heater designs that have been used, has condemned solar water heaters for the single-family home to have a solar fraction that is rarely above 60% or 70%.

4. PRODUCTIVE DESIGN FEATURES

DHW consumption variability is such that the maximum daily consumption is about three times as much as the average, and the minimum (when people are at home) about one third as much as the average. It is simply impractical to get any DHW supply that will always supply the needed hot water. Unless one is willing to spend an enormous amount of money, one will occasionally have a lukewarm (or even cold) shower, and one may have to wait a short while for the backup heater to catch up. A good heater choice is one that is large enough so that this rarely happens. If it happens too often, a larger heater is needed.

In solar DHW systems "optimized" for an invariant (i.e. an imaginary) daily DHW usage the solar tank is too small. It is however unproductive and unnecessary to use an invariant daily DHW usage or to use the "one-tank" or the "two-tank" solar DHW heater designs. A modified, heavily insulated "two-tank" design, in which the backup tank is mounted above the solar tank, in which the tanks are coupled with a natural convection thermal diode, in which the solar tank is about 30% larger than the average daily hot water usage, in which an efficient backup heater is used, and in which the temperatures are controlled properly, can get solar fractions of above 90% (26-28), as shown by lab tests, a field test, and computer runs. This design does not require costly features; it just requires useful design and control ideas.

With the superposed, diode-coupled design, the backup tank can become part of solar storage. The solar fraction can be increased by controlling the temperatures of the two tanks. The backup tank thermostat can be set at 45ºC, the minimum temperature for a comfortable shower. The solar tank might be heated with solar energy until it gets up to 80ºC, with a tempering valve to ensure that the water is never delivered at a temperature above 60ºC. This increases the effective storage size, and ensures that the backup heater will never turn on unless the storage is really depleted.

One of the costs to be considered in a solar (and any other) water heating system is the cost of the floor area involved. In the USA, it costs about US$1,000 to 2,000 for each square meter of building, and garage or storage shed area might cost half as much. The cost of the area that is used for a water heating system should be counted as a water heating cost. The design with the superposed tanks uses about half the area. In Australia water heaters are currently installed outdoors, but that is hard to do in a cold climate.

5. SOLAR WATER HEATING NEEDS OF THE FUTURE

In the past, both oil and gas have been sold at what can only be considered "throw-away-prices" (10), and it was no accident that "solar energy was not competitive." With both oil and gas at or past their production peaks (2-4), "throw-away-prices" are no longer likely, since humanity can no longer allow people to throw our fossil fuel resources away. Improved living standards have made DHW a necessity, and solar DHW without backup heating is no longer an option. Until now solar DHW has only been used by a very small fraction of the population: those who lived off the grid and had no other choice, and those for whom solar energy was a moral choice. Now however solar DHW offers an almost irresistible means of saving very large amounts of natural gas, especially if high solar fractions are achieved. Massive changes (29) are ahead, and things will happen rapidly (30). In the USA over 5 million gas and over 4 million electric DHW heaters are sold per year (31), mostly to replace heaters that wear out. The solar DHW market may very rapidly become absolutely enormous.

Solar water heating can help to reduce the natural gas (and other fossil fuel) consumption markedly, but only if the equipment is designed to meet the real hot water needs of the customers (and not some imaginary and invariant daily consumption profile), and only if there is a serious attempt to use optimized equipment designs (and not the primitive "one-tank" or "two-tank" configurations inherited from antiquity and now accepted worldwide as engineering dogma). Max Planck used to say that: "Only death can separate physicists from their pet theories." Planck may have reached that conclusion since many of his contemporaries refused to accept the Planck quantum theory. His saying may however apply to solar water heating as well, for it seems that some may spend the rest of their lives examining only the traditional "one-tank" and "two-tank" solar DHW devices, subjecting these devices to tests and to computer runs in which a family of robots uses the same amount of DHW each day with a consumption profile that never varies, and refusing to see or to admit that this is a totally unproductive garbage-in-garbage-out ("GIGO") approach.

Achieving effective thermal stratification in the solar water tank(s) is essential to ensure efficient solar collection. We found that downward heat transfer in a metal water tank is about 3 to 4 times higher than one might expect from stagnant conduction in the water alone. Hence we used separate tanks for solar and backup heating. Arata et al (32) used multiple tanks for solar storage in commercial solar DHW systems, and this might also be useful in small solar-alone systems. Stratification baffles were used years ago (8), and Tabor (33) and many others studied stratification effects. Such studies must use good fluid dynamics computer programs or very careful tests, and must be based on realistic DHW consumption behavior. The stratification effectiveness can be determined with methods such as those of Rosen (34).

Large-scale (e.g. commercial) solar water heating is somewhat more straightforward, although there are also design approaches that have not been used widely enough (32). Solar swimming pool heating is already widely used, good heaters are available, and people can also build their own heater (35-37).

6. CONCLUSIONS AND RECOMMENDATIONS

Solar domestic hot water technology has been around for more than a century, addressing residential markets that were always trivially small with equipment and design techniques that can only be considered as amateurish. Because of natural gas and petroleum depletion (2-4), a huge market is about to open up for cost effective residential solar DHW equipment with reliable backup provisions and a very high solar fraction. It is time for the solar hot water field to become serious: to begin using productive equipment designs, and to begin using realistic hot water consumption behavior of the DHW consumers, for system R&D, design and evaluation. For those who are interested in the future market, that will be easy.

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