CHAPTER I

Introduction

1.1 The Current State of Solar Energy Technology

A great deal of research has been carried out on solar energy alternatives to heating by conventional means. The conclusion of a great part of this research is that solar energy is a viable, clean and sustainable source. Yet 17 years after the energy scare of the early 1970s, solar energy's market share remains disappointing. In fact, solar accounts for less than 1% of water heating systems in the United States (Fanney and Dougherty, 1996). In order to propose remedies that will increase the acceptance of solar energy technology, it is first necessary to understand the reason for the poor market penetration. A number of these reasons are illuminated in a Public Service Commission of Wisconsin market study carried out between August 1996 and March 1997. Primary among the obstacles that they noted are: lack of knowledge about solar, concerns about system reliability, concerns about the effect of Wisconsin weather on performance, concerns about dealer credibility and competence, high system cost and redundancy with other heating options (Peters, Robison, and Winch, 1997). Essentially it seems that a customer would be more willing to consider solar if it were less expensive and there were someone to whom they could turn for maintenance issues and to be assured that the system was operating properly.

One proposed solution to both of these problems is to encourage the involvement of electric utilities. If a utility were to buy a large quantity of solar systems and rent them to homeowners there would be a number of benefits to all involved. The utility could buy systems at a volume discount rate, recuperating their cost through a leasing program. Furthermore, there are business tax incentives for solar options that are available to corporations, such as utilities, but are unavailable to individual consumers. The other benefit to the utility is that of avoided generation cost. Most utilities are summer peaking meaning that the highest demand occurs during the summer when a large number of air conditioners are in operation. Because this is a problem for almost all utilities, simple rerouting of power from one utility district to another is not a sufficient solution. Many utilities maintain extra generating capacity year round so that they can meet their summertime load, a costly undertaking. If however, a large number of houses in the utility's service area heat water without creating an increased load on the utility, the utility's extra generating capacity could be reduced at great economic and environmental benefit. The benefit to the customer is that solar energy collection becomes much less expensive and that the utility would be in charge of maintenance. Furthermore, the customer would pay a fixed monthly lease on the collector, and would be charged a reduced electricity rate, hopefully decreasing the overall bill.

1.2 Solar Domestic Hot Water Systems

Solar thermal energy can, of course, be used for many purposes. The vast majority, however is used in heating water, especially for residential homes. The majority of solar domestic water hot water (SDHW) systems make use of thermal energy collectors that convert radiant solar energy into thermal energy in a fluid by exposing the collector to the sun. The working fluid is circulated from the bottom of a storage tank by means of a pump, through the collector, and is deposited at the top of the tank. The pumps are operated by means of a differential temperature controller. In the simplest case, the pumps circulate fluid when the fluid temperature at the collector outlet is greater than the fluid temperature at the bottom of the tank. In locations where freezing is an issue, a heat exchanger is placed between the tank and the collector, allowing propylene glycol (antifreeze) to be circulated in the collector, and potable water to be circulated in the tank, separate from the glycol. Figure 1.2.1 shows a typical SDHW system configuration.

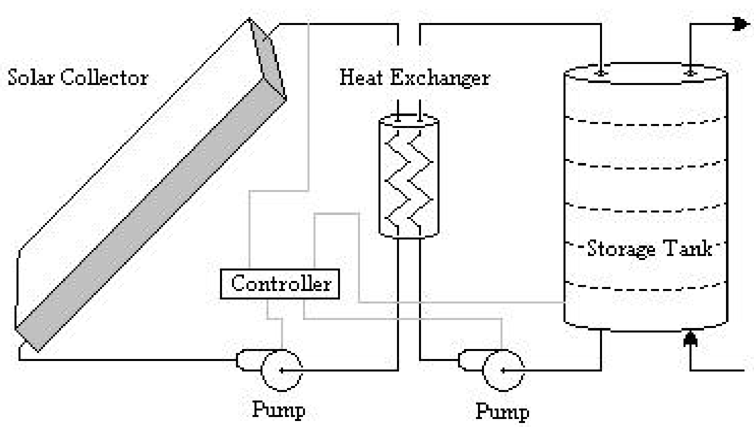

Figure 1.2.1 Typical Solar Domestic Hot Water System

There are numerous variations on the basic system in figure 1.2.1, including those that have a second storage tank, the first one being used as a solar preheat tank and the second being a standard water heater. Recently, systems have been integrated with photovoltaic (PV) panels that power the pumps (Jahnig, 1997) or that directly heat the water (Williams, 1996). The advantage of such systems is a reduction in parasitic energy cost. The PV panel also replaces the controller since the pumps circulate fluid only when the radiation input is above a certain critical level. Other systems are designed with a coil heat exchanger that wraps around the inside of the storage tank, and are sometimes designed without a heat exchanger at all. The heat exchanger is something of a double-edged sword, providing freeze protection but decreasing the overall performance of the system while increasing the system cost.

1.3 Promising Alternatives

One of the problems with solar collectors in northern climates is that of freezing. SDHW systems necessarily bring water outside through pipes to the collector where the water is heated before being returned indoors. The scheme works well as long as the sun is shining and the water temperature is never allowed to fall below freezing. However, if the water does freeze, then chances are that the collector, and possibly the structure supporting it, will be damaged or destroyed.

The most common solution to the freezing problem is to place a heat exchanger between the tank and the collector, and to run antifreeze through the collector loop. This, however, is a wasteful method of transferring heat from one fluid to the other. Because of comparatively low flow rates and small temperature differences, the heat exchanger effectiveness in a typical solar collector system will vary between 0.1 and 0.5, causing the solar collector to operate at a higher temperature and lower efficiency (Buckles, 1983). Figure 1.3.1 shows that the collector's efficiency decreases with higher operating temperatures. T_i is the inlet temperature to the collector, T_a is the ambient temperature and G_T is the incident radiation. Increasing T_i acts to shift the collector operating point to the right, decreasing the efficiency.

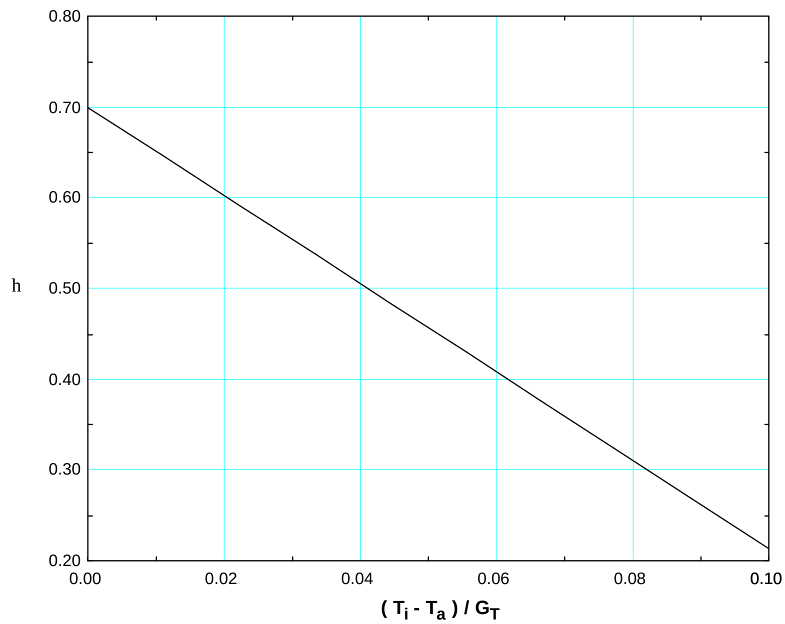

Figure 1.3.1: Collector Efficiency

It would be extremely beneficial to be able to provide freeze protection without paying the efficiency penalty associated with a heat exchanger. This thesis explores two such freeze protection possibilities.

1.3.1 Thermo-Elastic Collectors

The fluid in a standard collector is carried into a header where it is distributed throughout small diameter (typically about 0.75 cm) copper tubes. These tubes are separated by thin copper fins approximately 7 cm in width and 0.5 mm in thickness.

Solar energy incident on the fin is conducted towards the tubes (which are at a slightly lower temperature due to the internal fluid flow) and is delivered to the working fluid. Being a solid material that becomes more brittle when exposed to low temperatures, the header and copper tubes can crack with the expansion of freezing internal fluid.

In a thermo-elastic collector, the copper tubes and absorber plate are replaced with tubes made of some compliant material that does not deform permanently when water freezes inside them. Instead, they deform elastically, and regain their original shape once the water begins to flow again. Thermo-elastic materials provide built in freeze protection but have their own disadvantages since they tend to be good thermal insulators and do not conduct heat well. Is it possible, however, to design a collector plate geometry that overcomes the low thermal conductivity problem?

1.3.2 Three-Season SDHW Systems

Another option for freeze protection without resorting to a heat exchanger is to simply turn the system off and drain it during those months when freezing temperatures occur. Because the system would operate during a fraction of the year, its performance would be reduced, giving a lower annual solar fraction (the fraction of a heating load met by solar energy). However, removing the heat exchanger would increase the performance of the system during those times when it is in operation. Furthermore, the collector system would be optimized for summer collection, having a different slope and perhaps a different collector area. Would the benefit of removing the heat exchanger be great enough that the overall performance would not be degraded by leaving the system inoperational for some portion of the year? The answer depends upon the local weather conditions such as length of winter and the winter's relative cloudiness.

While the thermal benefits or penalties of a three-season system are easily quantified, there are also economic concerns that must be addressed. Even if there is a reduction in annual solar fraction associated with the three-season system, such a system also costs less to install and operate. Choosing a three-season system saves the customer the up-front cost of the heat exchanger, one of the pumps, and the antifreeze charge.

The idea of a three-season system also ties in to the utility ownership concept. Since the utility's greatest need for extra generating capacity occurs during the summer when the three-season system is operational, the economic benefit to the utility may be greater for a three-season system than for a four-season system that requires more maintenance.

1.4 Other Freeze Protection Alternatives

Inventing freeze protection methods requires a fair amount of imagination, but the technology often already exists. Consequently there are a great number of freeze protection methods available to SDHW system designers. While none of these methods were investigated within the scope of this project, they are worth mentioning.

One common freeze protection method is to attach a strip of electric resistance heating tape to the pipes that are in danger of freezing. To implement such a method, a controller would also be required to turn on the heater upon sensing a low fluid temperature. The main advantage of such a scheme lies in its simplicity. However, it is not appropriate for all situations. First, any SDHW system that relies upon electricity for freeze protection is in danger during periods of concurrent freezing and power failure. Second, electric resistance heating is not appropriate in all locations. In a climate where freezing temperatures are a rarity, such a method works well. However, in a place such as Colorado, the heater would need to be on during a significant portion of the year and the cost of running such a heater might outweigh any benefit that the SDHW system could have delivered. Table 1.4.1 shows a number of locations and the amount of energy required to power an electric resistance type freeze protection scheme (Barnaby and Wilcox, 1977). The second column in Table 1.4.1 reports degree hours. One degree-hour is added to the annual sum for each hour that the temperature is one degree less than an arbitrary base temperature. Two degree-hours would be added if the temperature were two degrees below the base temperature during a given hour.

Table 1.4.1 Power Requirements for Electric Resistance Freeze Protection in Various Locations

Location	Annual Degree Hours (base 1.7 ^{o}C) [^{o}C-hr]	Freeze Protection Energy [kWhr/m^2]	Percentage of 315 kW-hr/m^2 annual output [%]
Oakland, CA	33	0.23	0.07
Sacramento, CA	191	1.34	0.4
Portland, OR	1574	11.02	3.5
Denver, CO	12473	87.31	27.7

Another method of active freeze protection is to include a controller, which upon sensing a low ambient temperature, opens a valve and allows the fluid contained within the collector to drain into a small expansion tank. These so-called drainback systems suffer from the problem of simultaneous freezing and power failure. There are also the added equipment costs of a more complex controller and of the solenoids used to control the valves as well. One method used to prevent problems that arise from simultaneous freezing and power failure is to design the system such that power is used to hold the solenoid open. Upon interruption of power the system would drain, regardless of the outdoor temperature.

Passive freeze protection schemes also exist which do not suffer from the drawbacks of the electric resistance heater or the drainback system. A freeze protection scheme has been analyzed in which the water in a tube is allowed to freeze briefly. However, as the water freezes, it expands into a compliant region such as an air filled tube, preventing the water tube itself from being damaged (Bickle, 1975). The disadvantage of such a system is that ice may form which blocks further expansion into the compliant zone in which case, there is essentially no freeze protection. A further disadvantage is that the required pumping power of the collector system will be increased (leading to increased operating costs) by the inclusion of a rubber tube or foam core contained within the copper pipes. The rubber tube or foam core will increase the friction factor of the pipe significantly.

Evacuated tube collectors also provide passive freeze protection. In such a collector, water is passed through an inner glass tube containing a low emmitance absorber plate. A second tube surrounds the first and the gap between the two is evacuated. The vacuum provides excellent insulation and the major losses from the collector occur in the header. Experiments have shown that such a collector tube can remain surrounded by dry ice (a temperature of –78 ^{o}C) for 120 hours without damage (Craig and Harding, 1987). In these experiments, the water in the header (which is directly attached to the collector tubes) was not subjected to freezing temperatures and it is theorized that any ice forming in the collector tube floated up into the header and melted (Figure 1.4.1). Since the header of the collector was unrealistically protected from freezing conditions, the validity of the experiment's results is debatable. Certainly, however, an evacuated tube collector has only radiation losses from the tubes themselves, and some passive freeze protection is inherent in the design. The disadvantages to evacuated tubes are that they are expensive, fragile, and that most of them have a glass to metal seal at the header the integrity of which is difficult to maintain over a long period of time.

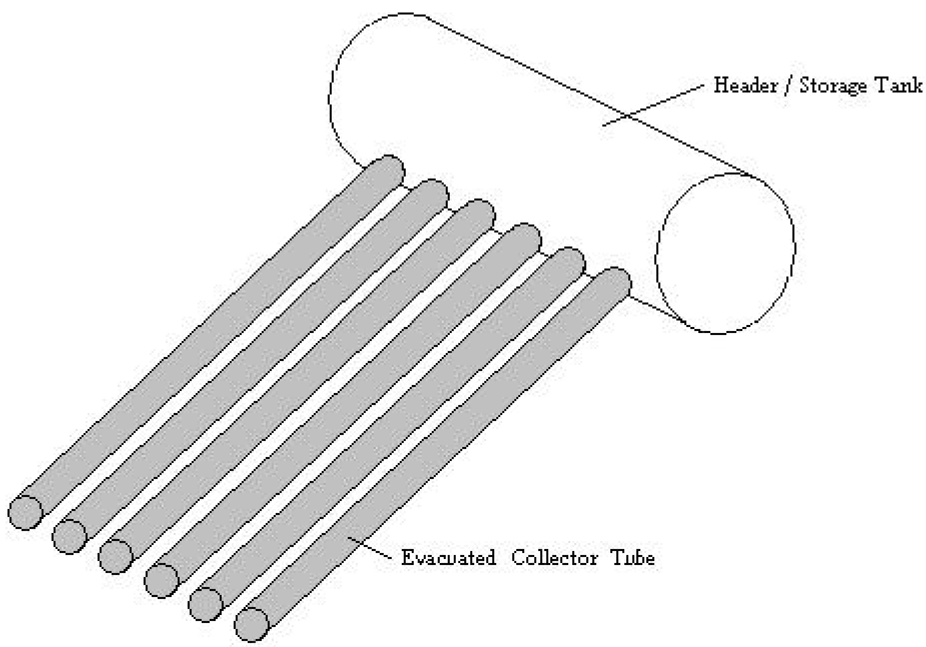

Figure 1.4.1: Evacuated Tube Collector

1.5 Objectives and Research Scope

The overall goal of this project was to assess the feasibility of two heat exchangerless SDHW system alternatives: the thermo-elastic collector and the three-season collector. The project included a number of tasks.

1. Create and validate a model for collector/plate geometries that make use of low thermal conductivity materials.
2. Design a thermo-elastic collector plate that gives similar performance to a standard collector.
3. Analyze the idea of an SDHW system that operates only when the outdoor temperature is above freezing.
4. Create guidelines for designing three-season systems, and for deciding whether a three-season or a four-season system is best suited to a given location.
5. Assess the impact of a three-season system ensemble on an electric utility as compared to that of a four-season system ensemble.