
CHAPTER VII

Conclusions

7.1 Summary

Since the inclusion of a heat exchanger in a solar domestic water heating system incurs a thermal penalty and increases the cost of the system, there would be obvious benefits to its removal. However, the heat exchanger provides important freeze protection to the system, a function which must be carried out by another component if the exchanger is to be removed. While many freeze protection schemes exist, they have been shown to be inappropriate in certain locations. Two alternate freeze protection schemes have been proposed in this thesis; that of designing a collector plate that is not damaged by freezing, and that of running the heat exchangerless system only when the ambient temperature is above 0 °C.

Designing a collector plate from a thermo-elastic material that does not deform plastically on freezing poses interesting problems due to its low thermal conductivity. A model was developed that assumed that heat transfer occurs only in one dimension along the length of the fin. The model was used to predict the amount of energy delivered to the collector fluid. The results were then validated by comparison with a finite element analysis that considered two-dimensional effects caused by low thermal conductivity and thick fins. A thermo-elastic collector plate was designed using the one-dimensional

model in a range for which two-dimensional effects were shown to be unimportant. Its performance was then matched to a standard copper collector by increasing the collector area. Tools useful for graphically designing thermo-elastic collector plates were developed. Furthermore, the one-dimensional model was shown to model standard copper plate collectors extremely well, making it an extremely versatile model while validating the assumptions used in developing the standard copper collector design equations.

The second freeze protection scheme involves shutting down the SDHW system during the winter months resulting in a changed performance and in different optimum system set points. At first, economics were used in an effort to design three-season systems that would have a life cycle savings equal to that of an optimum four-season system in the same location. The first step in designing three-season systems involved learning about the system's sensitivity to various variable changes. Three-season systems were then designed for four locations whose weather patterns are representative of the United States as a whole using life cycle savings. Next, three-season systems were designed for the same locations using simple payback period as the indicator. Various system dynamics were identified.

A thermal analysis was then carried out in an effort to divorce the three-season system economic performance results from the thermal penalty incurred by shutting the system down for a number of months. All economic factors were discarded and the thermal penalty of a three-season system was determined for 230 locations across the

United States. In each location, three three-season systems were analyzed. The first had the same area as a four-season system meeting 25% of the annual heating load. The second had an area equal to that of the four-season system meeting 50% of the load, and the third was based upon a four-season system meeting 75% of the load.

Because the initial method used in determining the three-season thermal penalty was limited to analyzing standard system configurations, an hourly simulation tool was used to investigate alterations to the basic three-season concept. Specifically, the result of recirculating warm storage tank water through the collector during freezing periods in the swing months at either end of the system's down time was investigated. Such a scheme would increase the amount of energy collected but would also add an energy loss to the system.

Lastly, an investigation of the impact on an electric utility of a large-scale three-season system implementation was carried out. The idea is that a large number of SDHW systems in the utility's service area will cut the peak electricity demand seen by the utility. In so doing, the utility is able to delay building further generation capacity and gets credits for reduced emissions. The electric customers benefit by paying a monthly lease rate for the collector and very little for their electricity thus receiving a lower monthly bill. Furthermore, customers are able to install SDHW systems without having to lay out a lot of money and have an authority to whom to turn for maintenance issues. The impact of a three-season system ensemble upon a Milwaukee utility was assessed and compared to the impact of four-season systems.

7.2 Conclusions

Both the thermo-elastic collector and the three-season system have been proven to be viable freeze protection alternatives. Of course both alternatives also have important disadvantages which must be understood when designing solar domestic hot water systems that make use of them.

The tubes in the thermo-elastic provide freeze protection by expanding to accommodate any freezing water. Once the ambient temperature rises above freezing, the ice in the tubes melts and the tubes return to their original size and shape. The results of the Chapter 2 analysis show that such a collector can be designed that has comparable performance to a standard copper collector. Such a collector would need to be approximately 1.5 times as large as a standard flat plate collector is in order to maintain the desired annual solar fraction. An increase in area is undesirable in that it puts further limitations on where the collectors can be mounted. Perhaps more important than the actual design, however is that equations were developed which are more generally useful in designing collectors of all designs. The current collector design equations and plots are created using the assumption that the temperature around the circumference of the collector tube is constant. While this is a valid assumption for collector geometries that involve thin walled tubes and high thermal conductivity materials, it breaks down with thick walled tubes and low thermal conductivities.

Breaking the fin and tube into a three fin problem and allowing the temperature to vary around the tube circumference generated collector design equations that are valid for

a wider range of collector plate materials. However, these equations are valid somewhat out of luck and only for configurations similar to those studied in this thesis. The upper “fin” has a temperature distribution running parallel to its length which means that heat flows directly through its width and not along its length. Because of this, it is incorrect to assume that the upper portion of the tube is a fin. It should be instead analyzed as a wall. Moreover, the one-dimensional model is of limited use as the problem is truly two-dimensional. Anyone wishing to actually design thermo-elastic plate collectors would want to use a two-dimensional model.

The other freeze protection alternative investigated was that of an SDHW system that is shut down during the winter and so does not need to include a heat exchanger. A number of important conclusions can be drawn from the investigation. Obviously, the three-season alternative reduces the annual solar fraction in most locations. There are some locations however, where the freezing season is extremely short or extremely cloudy in which the four-season system barely collects any more total energy than the three-season system. In these locations, the thermal penalty paid with a heat exchanger throughout the year is greater than the energy collected by operating during the winter months. A three-season system is the obvious choice in these locations as it yields a higher annual solar fraction than the corresponding four-season system.

As previously mentioned, the majority of locations suffer some decrease in thermal performance due to shutting down the system. Various areas of the country are affected differently but in general, for a small system, the thermal penalty is not

debilitating unless the system is located high in the mountains or in Alaska. As the system is designed to meet more of the annual load, however, the penalty becomes much more significant.

An economic analysis of three-season systems indicated that such a system is no more sensitive to parameter changes than a four-season system. Such a result is valuable because it means that three-season system design is no more complicated than four-season system design. The main lesson learned in the economic analysis was that economics are fickle and great care should be taken when using them to make three-season SDHW design decisions. A standard economic indicator, life cycle savings, indicated that a three-season system would never be profitable and that a customer would have to be paid to install one if the same life cycle savings as a four-season system are desired. In retrospect, it is obvious that a four-season system with a larger optimum area would save the customer more money than the smaller system operating for only a fraction of the year. The proper indicator is instead the return on investment as a smaller capital outlay is required for the three-season system.

Designing three-season SDHW systems using return on investment as the indicator is possible. However, the geographic dependence of economic variables and the subjectivity involved with choosing their values makes it a poor method for assessing the viability of three-season systems across the United States.

There are a great number of modifications that can be made to a three-season system which can help it to perform almost as well as a four-season system thermally while still costing less. Recirculating warm storage tank water through the collector at night during the first and last month of the freeze period was shown to greatly increase the three-season system's thermal performance. There are two extremes in results however. In some locations such as Denver, CO, recirculation can increase the three-season solar fraction beyond that of the four-season system. At the opposite end of the spectrum, recirculation in Saulte Saint Marie, MI further degrades the three-season solar fraction. Again, the majority of locations across the United States fall into a middle category in which the three-season system performance is increased, but not so much that it overtakes that of the four-season system.

The final step in the analysis of three-season systems involved an examination of their impact on a Wisconsin electric utility. It was found that because of a lower installation cost, a theoretically lower maintenance cost, and the same lease rate as a four-season system, the three-season system ensemble benefited the utility more from an economic point of view. The four-season system ensemble, on the other hand, reduced annual energy demand on the utility by a greater amount. If, however, only the peak demand periods are examined, the three-season system ensemble is more beneficial, annually reducing peak demand by 90 kW more than the four-season system ensemble. Evidently, the three-season system ensemble is better suited to meeting the utility's demand. In fact the four-season system ensemble operating during the winter may be producing energy at a higher cost than the utility's marginal plant. At such a time, the

utility would normally want to shut down the higher cost SDHW electricity generator.

Unfortunately, the ensemble is impossible to shut down all at once. The three-season system ensemble, which only operates when the marginal plant generates electricity at a high cost, may have an added benefit to the utility that was not accounted for in the EUSESIA analysis.

7.3 Recommendations for Further Research

At the outset of this project, a utility in Green Bay, WI had an *f*-Chart model of an SDHW system that would have provided them with acceptable returns to make the project profitable. They were, at the end of 1996 prepared to begin performance experiments of two systems and hoped to begin offering a solar alternative to their customers by the end of 1997. Because of various setbacks the project was discarded before experimentation began.

Previous work has shown that such programs can be profitable to utilities (Trzesniewski, 1995) and (Williams, 1996). The best use of this thesis would be to redesign the SDHW system so that it could be used in Green Bay. It may turn out that while the four-season system did not seem profitable that the three-season system with its reduced operating costs would. Such research would make use of the EUSESIA software in order to model system alternatives.

Perhaps the most enlightening further research into three-season systems would involve an analysis of the cost at which three and four-season systems produce energy throughout the year. If, because of maintenance costs, the four-season system ensemble heats water very expensively during winter when there are plenty power plants which can be run inexpensively, then it has an adverse economic effect upon the utility that the three-season system does not share.

The next step in investigating the thermo-elastic collector is to begin choosing a material for the plate. This task is not easy, as there are many requirements of stiffness, resistance to high temperatures and low cost. Building and testing a prototype thermo-elastic collector would also lend immeasurable credence to the presented model.

Experimentation would also validate the results of the three-season system thermal penalty analysis. A number of SDHW systems across the country could be outfitted for data collection and run in both three and four-season modes. After collecting data the annual solar fractions could be easily calculated and compared with the predicted results.

One of the major shortcomings of the three-season system analysis is the definition of the freezing season. An investigation of the time required for a collector to freeze up under various conditions would lead to a much more accurate estimation of the start up and shut down times in each location analyzed.

Lastly, in all the analyses thus far the flow rates of fluid on the tank side and on the collector side of the four-season system has been kept equal. Previous work has shown that significant benefits can be met using lower flow rates (Dayan, 1997). It could be that the four-season system is not operating at its optimum in terms of flow rate and it therefore being unfairly penalized.