# CHAPTER V

## *TRNSYS Simulation of Three-Season Systems*

### 5.1 Introduction

The thermal penalty maps previously presented give a general feel for the performance that can be expected from a three-season system. However, they are limited in part by the method used to create them. A number of hourly simulations were carried out using TRNSYS in order to both confirm and extend the conclusions drawn from the maps. Specifically, the benefit of recirculating storage tank water through the collector in order to gain an extra month at either end of the operating period was examined. The idea is that a place such as Madison, WI has a six-month down time (November through April) in which freezing may occur. During the two swing months, one at either end of the freezing period, the days may well be warm and sunny enough to collect a sizeable amount of solar energy while the nights are still freezing. Under the assumptions made in the previous chapter, these months are unacceptable for a three-season because of the nighttime freezing. Yet if substantially more energy can be collected during the daytime than is needed to keep the collector free of ice at night, then the performance would benefit from the more complex control strategy.

## 5.2 TRNSYS versus *f*-Chart

To this point, the *f*-Chart method of estimating thermal performance has been adequate. However, it is unable to model the effects of freeze protection by recirculating tank water. The *f*-Chart method was developed at a time when computers were of limited availability. Its strength lay in its ability to accurately estimate annual performance with only twelve calculations, one for each month. Because of this, however, there are limitations as to the systems that can be modeled. Because the *f*-Chart method is based on the correlation of a large amount of calculated thermal performance data, the type of system that generated the data is intrinsically embedded in any estimations that are made using the method. Thus there is an *f*-Chart correlation to be used for liquid systems, a correlation for air systems, and a correlation for space heating systems. Each system is set up to operate in some manner and none of the basic correlations include recirculated tank water as a method of freeze protection.

With the current power and availability of computers, it is no longer as necessary to look for estimation methods. TRNSYS software, for example, allows hourly simulation and can run a year of thermal performance in less than five minutes (Klein, S.A. et al., 1997). Such a program also allows greater flexibility in the type of system to be modeled. In this case, TRNSYS was used to model a system that can be turned on or off at any hour during the year. It both backed up the conclusions drawn from using the *f*-Chart method and allowed examination of systems controlled in a more complex manner than simply “on” during summer or “off” during winter.

## 5.3 The TRNSYS Deck

TRNSYS is an hourly simulation tool in which various existing FORTRAN subroutines are linked together in order to model a thermal system, in this case, an SDHW system (Klein, S.A. et al., 1997). Each subroutine is called from a block of code called a TYPE which includes a list of parameters (constants describing the piece of equipment), and a list of inputs to that equipment (which tend to be the outputs of another TYPE.) The entire list of subroutine calls is created in an interface program called TRNSHELL and makes up the input statements to TRNSYS. The list of input statements is referred to as a DECK. The deck used in this simulation consisted of a TYPE 1 Solar Collector, a TYPE 5 Heat Exchanger, a TYPE 60 Stratified Fluid Storage Tank, two TYPE 3 pumps, and a TYPE 2 controller (Figure 5.3.1).

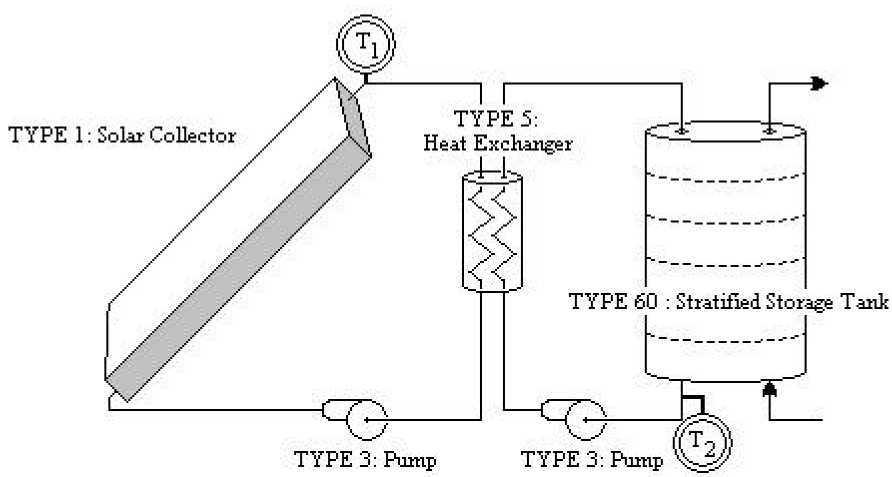


**Figure 5.3.1: TRNSYS System Model**

For clarity, the TYPE 2 controller is not shown in the figure but it compares the temperature at the outlet of the collector ($T_1$) with the temperature at the bottom of the storage tank ($T_2$) and turns on the TYPE 3 pumps if useful energy can be collected. In order to model the four season system, the heat exchanger was assumed to have a constant effectiveness of 0.2 (Buckles, 1983), and the $F_RU_L$ and $F_R(\tau\alpha)$ parameters of the collector were chosen to be 4.68 and 0.741 respectively, as in the case of the *f*-Chart model. Propylene glycol was circulated in the collector loop while water circulated in the tank loop (see Appendix C).

The three-season system was built on much the same model as the four-season system. The significant changes included: running water in the collector loop, removing the heat exchanger, changing the slope of the collector to the same three-season slope used in the *f*-Chart analysis, and adding a forcing function to the controller output that prevented the pumps from activating during the location's freezing season (see Appendix D).

The third deck, shown in appendix D, modeled a three-season system with recirculation. In this case, the down time was reduced by one month at either end over the nominal freeze period. Also, a second controller was added which looks at the outdoor ambient temperature and sends an "on" signal to the pumps if it falls below 5 °C. The TYPE 3 controller sends an output of 1 for "on" and an output of 0 for "off." The specifics of making this work were slightly different as the TYPE 3 controller is only able to compare two temperatures and send a single output signal. Thus, one controller is set up to output a 1 if the temperature of water exiting the collector is higher than the temperature of water at the bottom of the tank. The other controller compares ambient temperature to 5 $^{o}$C and outputs a 0 when the temperature falls below 5 $^{o}$C. The signal from the second controller is then inverted (made 0 if it was 1 and vice versa), and added to the signal of the first controller. The output is inverted because you want a temperature lower than 5 $^{o}$C to turn the pump on, not off. The output signal then carries a value of 0, 1, or 2. The pumps are designed to turn on if this signal is greater than or equal to 1, meaning that either a freezing condition, or above critical solar radiation is sufficient condition to turn on the pumps (Figure 5.3.2). There is a TRNSYS microprocessor controller type, which could have been used in this case, but it requires a complex set up and was discarded in favor of the simpler, two differential controller model.

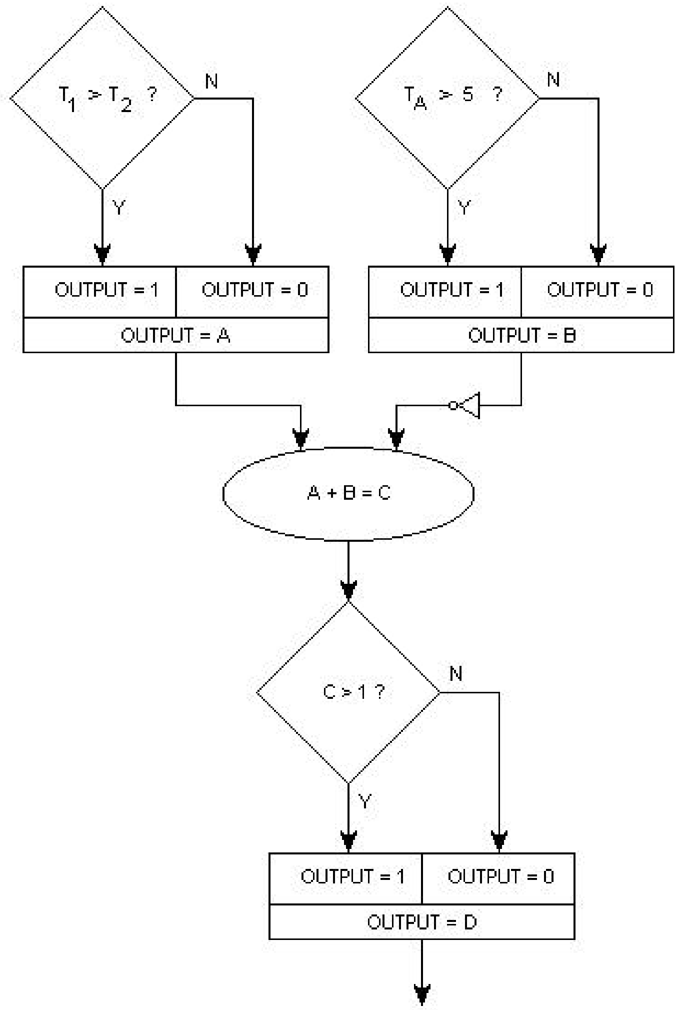


**Figure 5.3.2: Two Controller Decision Making Process**

## 5.4 Results

Simulation of the three and four-season systems using TRNSYS yielded a number of important results. Table 5.4.1 shows a comparison between *f*-Chart and TRNSYS results, indicating both that the *f*-Chart method used in producing the thermal penalty maps is valid and that the TRNSYS deck is properly modeling the desired system.

**Table 5.4.1: Comparison of TRNSYS and F-Chart Results for Madison, WI**

| | F-Chart Results | | TRNSYS Results | |
|---|---|---|---|---|
| | Four Season | Three Season | Four Season | Three Season |
| Load *[GJ/year]* | 24 | 24 | 23.92 | 23.92 |
| Auxiliary Energy *[GJ/year]* | 12 | 14.7 | 13.64 | 16.20 |
| Annual Solar Fraction *[-]* | 0.5 | 0.39 | 0.43 | 0.32 |
| Decrease *[points]* | 11 | | 11 | |

The second result of the TRNSYS simulation was an indication that recirculating tank water through the collector as a method of freeze protection in order to shorten the three season system's "off season" can have a number of different effects depending upon location (Table 5.4.2).

**Table 5.4.2: Benefits of Recirculation in Various Locations**

| Location | Four Season System Solar Fraction *[-]* | Three Season System Solar Fraction *[-]* | Three Season Recirculation System Solar Fraction *[-]* |
|---|---|---|---|
| Madison, WI | 0.43 | 0.32 | 0.40 |
| Caribou, ME | 0.48 | 0.24 | 0.36 |
| Sault Sainte Marie, MI | 0.49 | 0.27 | 0.24 |
| Denver, CO | 0.51 | 0.32 | 0.52 |

Finally, TRNSYS was able to show that further shortening the "off season" gives diminishing returns in terms of annual solar fraction (Table 5.4.3).

**Table 5.4.3: Effects of Increasing the Length of the Recirculation Period**

| System Type (Albuquerque, NM) | Annual Solar Fraction |
|---|---|
| Four Season System | 0.57 |
| Three Season System: June 1 – October 31 (no recirculation) | 0.32 |
| Three Season System: May 1 – November 30 (recirculation) | 0.41 |
| Tree Season System: April 1 – November 30 (recirculation) | 0.47 |
| Three Season System: March 1 – November 31 (recirculation) | 0.51 |

## 5.5 Discussion

One of the first difficulties encountered in corroborating and extending the conclusions drawn from using *f*-Chart lay in creating a TRNSYS model that yielded the same result as the *f*-Chart analysis. It must be kept in mind that *f*-Chart is a curve fit with a limited range of applicability while TRNSYS performs energy balances on each component at specified timesteps (usually one hour or less). Furthermore, the system configuration is built into the *f*-Chart model and cannot be changed without creating a different curve fit. However, it is important to compare the two results because they should be approximately equivalent. In table 5.4.1, it can be seen that for Madison *f*-Chart predicts a four-season annual solar fraction of 0.5 while TRNSYS gives a result of 0.43 for the same system. There are a number of possible reasons for such discrepancies.

The differences that arise between TRNSYS and *f*-Chart are numerous. First, there are some important differences in the two systems modeled. *F*-Chart assumes that there is a second storage tank (referred to as the solar preheat tank) and that the tank shown in figure 5.4.1 has no heating elements and simply feeds a standard water heater.

Such a system has additional losses from the piping between the tanks and from the second tank itself. Furthermore, *f*-Chart assumes that both tanks are fully mixed, having no thermal gradient along the vertical axis. The TRNSYS system, however, includes a stratified storage tank. It is possible to use a fully mixed tank in TRNSYS but the benefit of a stratified tank is that the hottest water is delivered to the load while the coldest water is returned to the collector. Such a strategy increases the efficiency of the collector and decreases the load on the auxiliary heaters.

Another difference between TRNSYS and *f*-Chart arises in the calculation of losses and loads. The governing equation for energy loss from a tank is shown below in equation 5.5.1. F-Chart conservatively calculates the temperature difference as the set point temperature of the heater minus the environmental temperature of the tank. TRNSYS, on the other hand, calculates the temperature difference as the average of the inlet and outlet temperatures minus the environmental temperature. TRNSYS allows that if the temperature of fluid near the top of the tank exceeds the set point, the losses will be greater while *f*-Chart assumes there to be an upper bound on losses. Since the heaters in the tank maintain the set point temperature, there is never a situation in which TRNSYS calculates a lower energy loss from the tank.

$$E = UADT \tag{5.5.1}$$

Furthermore, *f*-Chart allows the user to change the losses from only the water-heating tank. The losses from the solar preheat tank cannot be changed. Since the TRNSYS model only contained one tank, the losses for the two models are different.

Loads are also calculated with similar differences. In *f*-Chart, the load is defined as the difference between the temperature set point and the temperature of the mains water multiplied by the specific heat of the fluid (Equation 5.5.2). In TRNSYS however, the load is the difference in energy levels of the mains water and the water exiting to the load. If the fluid near the top of the tank is hotter than the set point temperature, then the load is increased, which makes sense as it represents the actual amount of energy delivered to the load. The hotter water may have to be mixed with cold water in order to avoid scalding in which case it appears to be thrown away. However, the hotter temperature means that the draw from the tank will be proportionally decreased.

$$L = C_p \Delta T \tag{5.5.2}$$

Creating the TRNSYS models had two benefits. First, it made sure that the *f*-Chart results were reasonable and obtainable through other, similar means. However, the true purpose of this exercise was to examine the effects of more complicated control strategies. The maps of thermal penalty can be loosely divided up into three categories. Locations in which a three-season system actually performs better than a four-season system, locations where the thermal penalty is very large, and locations where it could go either way depending on a number of externalities such as economics or clever control strategies. One such control strategy is tank water recirculation.

The reason for having to shut down the system during the winter is obviously that freezing can damage the collector or the piping. The downtime, as previously mentioned is highly dependent upon the length of the freezing season. However, the beginning and end of the freezing season do not occur all at once, meaning that the system does not go from a constantly positive temperature to a constantly negative temperature environment all at once. For a time, the nights may be cold and the system freeze prone while the days may still be warm and sunny. At these times shutting the system down because of nighttime freezing may waste a great deal of potentially collectable energy. One method of avoiding this problem is to circulate comparatively warm water from the bottom of the storage tank through the collector whenever the environmental temperature is lower than freezing plus some factor of safety (5 $^{o}$C in this case). The recirculation prevents ice from forming assuming that the freezing danger isn't so great that the warmer water is cooled down to zero. If the amount of solar energy collected by the system during the day significantly exceeds the amount lost at night, then the control strategy will recuperate some of the thermal penalty paid by removing the heat exchanger from the system and running for only three seasons.

A number of different situations can arise, as shown in Table 5.4.2. In most locations, running the three-season system for an extra two months will greatly improve the system's annual solar fraction. In some cases, it may even improve the three-season system performance beyond that of the corresponding four-season system. One might expect a place such as Denver, CO, which has a high winter clearness index but a long freeze period, to be a good example. TRNSYS indicates that a four-season system installed in Denver and meeting 51% of the annual load has a three-season solar fraction of 32%. Adding recirculation to the three-season system increases the annual three-season system solar fraction to 52%, slightly higher than that of the four-season system. In such a case, it may be worthwhile to add a second month on either end of the freeze period in the hopes of further increasing the solar fraction.

At some point, however, the ambient temperature will drop low enough for an extended period of time such that the losses would be greater than the benefit. While the recirculating system does not actually perform better than its four-season counterpart in Albuquerque, New Mexico, the diminishing return of decreasing the freeze period can be seen in Table 5.4.3. In March and April, the losses to the cold environment are increasingly large in comparison to the amount of energy that can be collected during the days.

The last situation occurs in locations that have cloudy, cold winters. In this case, the recirculation will further degrade the solar fraction. Such places tend to be extremely poor candidates for solar anyway and only extremely favorable economic incentives can make solar profitable. Table 5.4.2 indicates that in Sault Saint Marie, Michigan, adding extra months to the system's running time further degrade the annual performance. If solar is to be considered at all, a three-season system with a shorter on time might be considered.

## 5.6 Conclusions

A number of important results arise from analyzing the three-season system concept using an hourly simulation tool such as TRNSYS. First, it can be seen that the *f*-

Chart method is an acceptable tool to use in predicting the basic thermal performance of a three-season system. Since *f*-Chart predicts the annual performance of an SDHW system in a given location within a few seconds, it lends itself well to analysis of a large quantity of locations. TRNSYS, which takes on the order of minutes to complete an analysis, would be a much more cumbersome tool to use.

Second, TRNSYS allows the analysis of more complex control schemes than are included in *f*-Chart. Specifically it has been used to examine the effect of using storage tank water recirculated through the collector during freezing periods in order to extend the system's operating period. From the results it can be seen that this strategy has both benefits and drawbacks, depending primarily on location. In some cases, extending the operating time will reduce the penalty paid in annual solar fraction because enough energy is collected during daylight to more than offset the losses associated with cooling tank water by exposure to ambient during freeze periods. In a very few locations, collecting during two extra months adds enough energy to offset both the losses during the months and the losses associated with the four-season system's heat exchanger. In these cases, the three-season solar fraction is higher than that of the four-season system. There are also locations in which three-season systems do not benefit from recirculation and exhibit further penalty in annual solar fraction. In these locations, the operating period of the three-season system can be shortened in order to decrease the annual solar fraction penalty.