

Feasibility Analysis of Two Indirect Heat Pump Assisted Solar Domestic Hot Water Systems

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

This thesis is an analysis of the simulated performance of two indirect heat pump assisted solar domestic hot water (i-HPASDHW) systems compared to two base systems: an electric domestic hot water (DHW) system and a traditional solar domestic hot water (SDHW) system. In this study, the four systems of interest were modeled in the TRNSYS software and simulated for a year in order to compare their performances. All of the systems had the same load profile and aimed to deliver domestic hot water at a constant temperature. This insured that each system delivered approximately the same amount of energy for the simulated period, thereby creating a common basis for comparison.

The heat pump was introduced into the system configuration in an attempt to further improve the performance. Theoretically, the heat pump should send colder fluid to the collector which will extend the solar collection periods, both daily and seasonally when compared to the traditional SDHW system, as well as increase the efficiency of the collector. This will help to reduce the reliance on the electric auxiliary heaters and thus decrease the total electricity consumption.

Both i-HPASDHW systems considered for this thesis collected more solar energy over the course of the simulated year compared to the base traditional SDHW system. They also consumed less electricity than the two base systems, which directly correlated to lower annual operating costs.

It was concluded that the two i-HPASDHW systems analyzed in this study proved to be feasible configurations that performed more efficiently than the two base systems under the simulation conditions. However, it is important to understand that the results presented apply to the specific configurations. While the potential has been shown, prototypes must be built and tested with properly sized equipment for specific applications to get an accurate idea of the potential benefits. Also, equipment costs must be considered to determine payback periods for each system.

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Table of Contents

Author’s Declaration	ii
Abstract	iii
Acknowledgements	iv
List of Figures.....	vii
List of Tables	x
Nomenclature	xi
Chapter 1 Background Information.....	1
1.1 Energy and Environmental Issues	1
1.2 Domestic Water Heating	3
1.2.1 Storage Tank Water Heaters	4
1.2.2 Tankless Water Heaters	5
1.3 Solar Energy	6
1.3.1 Solar Domestic Hot Water (SDHW) Heating	8
1.3.2 Introducing a Heat Pump to Improve Performance	9
1.4 Outline of Thesis	10
Chapter 2 Literature Review.....	12
2.1 Solar Domestic Hot Water (SDHW) Systems.....	12
2.2 Heat Pump Assisted Solar Water heating Systems	14
2.2.1 Direct Expansion Systems (DX-SAHPDHW)	15
2.2.2 Indirect Systems (i-HPASDHW).....	15
Chapter 3 System Descriptions and Models	21
3.1 Base Systems Introduction.....	21
3.1.1 Electric Domestic Hot Water (DHW) System.....	21
3.1.2 Traditional SDHW System	22
3.2 Heat Pump Assisted Solar Systems Introduction	23
3.2.1 Dual Tank i-HPASDHW System	23
3.2.2 Solar-side i-HPASDHW System	25
3.3 Tempering Valve	26
3.4 TRNSYS Software.....	27
3.4.1 TRNSYS Components.....	28

3.5	TRNSYS Models.....	42
3.5.1	Electric DHW System	43
3.5.2	Traditional SDHW System	44
3.5.3	Dual Tank i-HPASDHW System	46
3.5.4	Solar-side i-HPASDHW System	49
Chapter 4	Results and Discussion.....	60
4.1	Simulation Results and Performance Justification.....	62
4.1.1	Electric DHW System	62
4.1.2	Traditional SDHW System	65
4.1.3	Dual Tank i-HPASDHW System	69
4.1.4	Solar-side i-HPASDHW System	74
4.2	Comparison of i-HPASDHW Systems with the two Base Systems	77
4.2.1	Dual Tank i-HPASDHW vs. Electric DHW.....	77
4.2.2	Dual Tank i-HPASDHW vs. Traditional SDHW.....	80
4.2.3	Solar-side i-HPASDHW vs. Electric DHW.....	90
4.2.4	Solar-side i-HPASDHW vs. Traditional SDHW	92
4.3	Dual Tank vs. Solar-side i-HPASDHW.....	100
4.4	Overall Energy Consumption and Cost Comparison	108
Chapter 5	Conclusions and Recommendations	112
5.1	Conclusions	112
5.2	Recommendations	113
Appendix A	External Heat Pump Files	114
A.1	Dual Tank i-HPASDHW System	114
A.2	Solar-Side i-HPASDHW System.....	115
Appendix B	TRNSYS COMPONENTS (TRNSYS, 2006).....	116
References.....		159

LIST OF FIGURES

Figure 1.1 - Primary Energy Supply 2007 (IEA, 2009).....	2
Figure 1.2 - Energy Sources for Heating Water in Canada, by region, 2007 (NRC, 2007)	4
Figure 1.3 - Typical Electric and Gas Storage Tank Water Heater (HSW, 2000)	5
Figure 1.4 - Electric Tankless Water Heater (U.S. Department of Energy, 2009)	6
Figure 1.5 - Solar Radiation Breakdown (Smil, 2008)	7
Figure 1.6 - Typical Solar Assisted Domestic Hot Water Heater (BudgetSolarStore.com)	8
Figure 1.7 – Typical Flat Plate Collector Efficiency Plots	9
Figure 2.1 - Schematic of common configurations of SDHW systems. (a) A natural circulation system. (b) One-tank forced-circulation system. (c) System with antifreeze loop and internal heat exchanger. (d) System with antifreeze loop and external heat exchanger. (Beckman and Duffie, 1991).....	13
Figure 2.2 - An Example of a DX-SAHP (Huang et al., 2003).....	15
Figure 2.3 - i-HPASDHW System Analyzed by Freeman et al. (1997) and Bridgeman et al. (2008).....	16
Figure 2.4 - Air Based (SYS 4) and Liquid Based (SYS 5) Dual Source System (Chandrashekar et al., 1982)	18
Figure 2.5 - i-HPASDHW System Analyzed by Nuntaphan et al. (2009).....	20
Figure 3.1 - Electric DWH Schematic (SEL, 2006).....	22
Figure 3.2 - Traditional SDHW Schematic.....	23
Figure 3.3 - Dual Tank i-HPASDHW Schematic.....	24
Figure 3.4 - Solar-side i-HPASDHW Schematic	25
Figure 3.5 - Tempering Valve Schematic	27
Figure 3.6 - TRNSYS Stratified Tank Model (TRNSYS, 2006).....	29
Figure 3.7 - Daily Water Draw Profile	31
Figure 3.8 - TRNSYS Tempering Valve Model.....	31
Figure 3.9 - TRNSYS Heat Exchanger Model	36
Figure 3.10 - TRNSYS Controlled Flow Diverter Model.....	38
Figure 3.11 - TRNSYS Differential Controller Function	39
Figure 3.12 - Electric DHW System Layout in TRNSYS	44
Figure 3.13 - Traditional SDHW System Layout in TRNSYS	45

Figure 3.14 - Dual Tank i-HPASDHW System Layout in TRNSYS	46
Figure 3.15 - Dual Tank i-HPASDHW System Heat Pump Characteristics (For Inlet Load Temperature of 10°C).....	48
Figure 3.16 - Solar-side i-HPASDHW System Layout in TRNSYS.....	50
Figure 3.17 - Solar-side i-HPASDHW System Heat Pump Characteristics (For Inlet Load Temperature of 10°C).....	51
Figure 4.1 - Solar Irradiation and Ambient Temperature for a Typical February Day.....	60
Figure 4.2 - Solar Irradiation and Ambient Temperature for a Cloudy March Day.....	61
Figure 4.3 - Solar Irradiation and Ambient Temperature for a Typical July Day	61
Figure 4.4 - Solar Irradiation and Ambient Temperature for a Typical December Day.....	62
Figure 4.5 - Electric DHW System Operation on March 1st (Top) and August 1st (Bottom)	64
Figure 4.6 - Traditional SDHW System Operation on a Typical February Day (Top) and a Typical July Day (Bottom)	66
Figure 4.7 - Dual Tank i-HPASDHW System Operation on a Typical February Day (Top) and a Typical July Day (Bottom).....	70
Figure 4.8 - Heat Exchanger By-Pass and Heat Pump Switch-Over Example on August 1st	72
Figure 4.9 - Solar-side i-HPASDHW System Operation on a Typical December Day (top) and a Typical July Day (Bottom)	75
Figure 4.10 – Domestic Tank Operation of Electric DHW (Top) and Dual Tank i-HPASDHW (Bottom) Systems on a Typical February Day.....	79
Figure 4.11 - Dual Tank i-HPASDHW System Typical Daily Domestic Tank Operation	82
Figure 4.12 - Operation of Traditional SDHW (Top) and Dual Tank i-HPASDHW (Bottom) Systems on a Typical July Day	83
Figure 4.13 - Operation of Traditional SDHW (Top) and Dual Tank i-HPASDHW (Bottom) Systems on a Typical February Day	86
Figure 4.14 - Operation of Traditional SDHW (Top) and Dual Tank i-HPASDHW (Bottom) Systems on a Cloudy March Day	89
Figure 4.15 - Operation of Electric DHW (Top) and Solar-side i-HPASDHW (Bottom) Systems on a Typical July Day	91
Figure 4.16 - Operation of Traditional SDHW (TOP) and Solar-side i-HPASDHW (Bottom) Systems on a Typical July Day	94

Figure 4.17 - Operation of Traditional SDHW (Top) and Solar-side i-HPASDHW (Bottom) Systems on a Typical December Day	97
Figure 4.18 - Operation of Traditional SDHW (Top) and Solar-side i-HPASDHW (Bottom) Systems on a Cloudy March Day	99
Figure 4.19 - Operation of Dual Tank (Top) and Solar-side (Bottom) i-HPASDHW Systems on a Typical July Day	102
Figure 4.20 - Operation of Dual Tank (Top) and Solar-side (Bottom) i-HPASDHW Systems on a Typical December Day.....	104
Figure 4.21 - Operation of Dual Tank (Top) and Solar-side (Bottom) i-HPASDHW Systems on a Cloudy March Day.....	107
Figure 4.22 - Normalized Energy Into and Out of Each System.....	109
Figure 4.23 - Annual Operating Costs.....	110

LIST OF TABLES

Table 3.1 - TRNSYS Flat Plat Collector Parameters.....	34
Table 3.2 - Excel Controller Inputs	52
Table 3.3 - Excel Controller Question 4 Decision Matrix.....	57
Table 4.1 - Electric DHW System Overall Simulation Results	65
Table 4.2 - Traditional SDHW System Overall Simulation Results	68
Table 4.3 - Dual Tank i-HPASDHW System Overall Simulation Results.....	73
Table 4.4 - Solar-side i-HPASDHW System Overall Simulation Results.....	77
Table 4.5 - Electric DHW and Dual Tank i-HPASDHW Systems Comparison	78
Table 4.6 - Traditional SDHW and Dual Tank i-HPASDHW Systems Comparison	80
Table 4.7 - Electric DHW and Solar-side i-HPASDHW Systems Comparison	90
Table 4.8 - Traditional SDHW and Solar-side i-HPASDHW Systems Comparison	92
Table 4.9 - Dual Tank and Solar-side i-HPASDHW Systems Comparison	100
Table 4.10 - System Performance Comparisons	109
Table 4.11 - Annual Operating Costs	110

NOMENCLATURE

A_C	total collector area
C_P	specific heat
CS	control signal (also used as a subscript)
D	space heating demand
E_T	total electric consumption
HE	heat exchanger
HP	heat pump
m_{dot}	mass flow rate
N	number of nodes in stratified tank model
Q_S	solar flux on collector surface
S	thermal storage
SF	solar fraction
T^*	theoretical temperature
Td	temperature in domestic tank
Tf	temperature in float tank
T_L	temperature to load (for tempering valve) and lower input temperature (for differential controller)
X_i	value of variable at time step 'i'
Y_i	total integrated value at time step 'i'
ΔT_H	upper dead-band temperature
ΔT_L	lower dead-band temperature

Greek symbols:

θ	incidence angle on collector surface
$\tau\alpha$	product of the cover transmittance and the absorber absorptance
γ	control function (0 = OFF, 1 = ON, for some components $0 \leq \gamma \leq 1$)
γ_i	input control function
γ_o	output control function

Subscripts:

aux	auxiliary
b	beam
bot	bottom
c	cold
c,i	collector inlet
c,o	collector outlet
coll	collector
DB	dead-band
DIV	diverter
env	environment
h	heat source
i	in
L	load
mid	middle
n	normal
o	out
s	source
t,b	tank bottom

Chapter 1

BACKGROUND INFORMATION

1.1 ENERGY AND ENVIRONMENTAL ISSUES

The threat of global warming has become a very important international issue. With today's world still relying heavily on burning fossil fuels as a primary energy source, we are adding excessive amounts of greenhouse gases to the atmosphere (West, 2010). Although greenhouse gases naturally exist in the environment, it is believed by most climate scientists that the excess amount generated from burning fossil fuels is trapping more heat than the atmosphere normally would trap, and this has caused steady "increases in global average air and ocean temperatures" (IPCC, 2007). If these adverse climate trends are not reduced, then in the long term it would "be likely to exceed the capacity of natural, managed and human systems to adapt" (IPCC, 2007). Therefore, actions must be taken to reduce the greenhouse gas emissions from burning fossil fuels. This can be achieved by using less energy and by using renewable energy sources, such as solar and wind, to assist in meeting energy demands.

According to the report titled "Key World Energy Statistics 2009" by the International Energy Agency (IEA), fossil fuel sources (oil, coal, and gas) accounted for over 80 percent of the world's total primary energy supply in 2007 (IEA, 2009). The breakdown is shown in Figure 1.1.

Fossil fuel resources may seem abundant, but the usage compared to the available supply must be considered. The reason that fossil fuel sources are still the front runners for the world's energy supply is because of the low cost. The technology to convert these fossil fuels into usable energy is well established and the resources are plentiful right now. However, fossil fuels are a non-renewably energy source that take millions of years to form and the supply available is being used much faster than new ones are being produced.

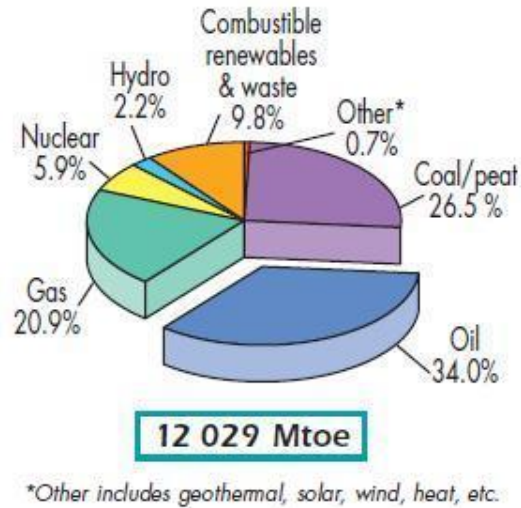


FIGURE 1.1 - PRIMARY ENERGY SUPPLY 2007 (IEA, 2009)

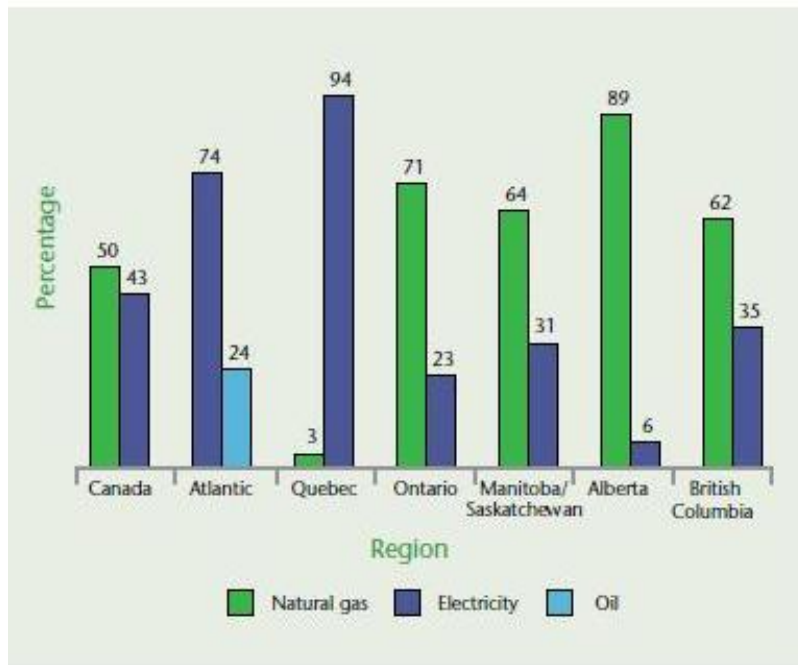
Due to the environmental concerns and the rapid depletion of fossil fuel reservoirs, there is a global push towards developing and implementing renewable alternative energy sources such as solar, wind, and geothermal. In fact, it was stated by the *Renewable Policy Network for the 21st Century* that climate change and energy security are the two main drivers of the renewable energy sector (REN21, 2009). Approximately \$120 billion was invested into renewable energy technology worldwide in 2008, which is roughly double the amount invested in 2006 and six times more than in 2004 (REN21, 2009). Also, many energy policies, tax credits and subsidies have been implemented worldwide to help increase the appeal of these energy sources to the general public and to promote the development of the new technologies (REN21, 2009). Although the initial start-up costs of the renewable energy systems are generally higher than fossil fuel systems, there are many benefits associated with these green alternatives. Not only are the renewable energy systems environmentally friendly, but the resources are abundant and very cheap, if not free. For example, once a solar system is installed and operating, it does not cost money to use energy from the sun. Therefore, long term environmental benefits and payback periods must be considered in order to see that renewable energies are a viable option to help reduce society's reliance on fossil fuels.

1.2 DOMESTIC WATER HEATING

For a typical Canadian household, “water heating is the second biggest energy user, after space heating” according to a 2007 survey conducted by Natural Resources Canada (NRCan, 2007). Water heating alone was responsible for 18 percent of the total residential use in 2007, which is substantial (NRC, 2007). In 2007, Canadian households in total used just under 1.4 million terajoules ($1 \times 10^{12} \text{ J} = 1 \text{ TJ}$) of energy, with an average of 106 gigajoules ($1 \times 10^9 \text{ J} = 1 \text{ GJ}$) per household (Stats Canada, 2007). Therefore, roughly a quarter of a million terajoules of energy in total was used for water heating in 2007 by Canadian homes, with an average of about 19 gigajoules per household. To put this into perspective, the average Canadian home would have spent approximately \$320 on water heating alone in 2007 if an electric domestic hot water system was used (Hydro One, 2007).

A domestic hot water (DHW) system is used to heat the household’s cold supply water, either municipal main water or well water, and deliver it to various appliances in the home such as showers, sinks, and dishwasher. In the 2007 survey by NRCan it was also revealed that almost all Canadian homes used either natural gas or electricity to heat their water. It was discovered that 50 percent of the Canadian households used natural gas and 43 percent used electricity (NRC, 2007). The spread was not consistent across the country, but rather depended on the resources at hand in each region. Figure 1.2 below shows a breakdown of the different energy types used for water heating in Canada as a whole, as well as in various regions across the country.

There are 2 main types of water heating systems. They are: storage tank water heaters, and tankless water heaters.



²⁴Natural Resources Canada, Energy Use Data Handbook Tables, 1990 and 2001 to 2007, oee.nrcan.gc.ca/corporate/statistics/neud/dpa/tablesandbook2/res_00_1_e_3.cfm?attr=0.

FIGURE 1.2 - ENERGY SOURCES FOR HEATING WATER IN CANADA, BY REGION, 2007 (NRC, 2007)

1.2.1 STORAGE TANK WATER HEATERS

Storage tank water heaters are the most common type of system used in Canadian homes today (NRC, 2009). They heat a relatively large volume of water, generally using electricity, gas, or oil, and store it in a tank until it is needed. The storage tank has a thermostat and controller that activates each heater to maintain the water near a specific set-point temperature. This ensures that the storage tank is charged in order to meet the hot water demands.

Most domestic water storage tanks are stratified with multiple temperature layers due to the density differences of the water at various temperatures. The hot water rises to the top of the tank because it is less dense than the colder fluid, which remains at the bottom. Therefore, hot water is drawn from the top of the tank and the cold replacement water enters at the bottom of the tank where it will be heated

and eventually rise to the top to be used. A schematic of a typical electric and gas storage tank water heater are shown in Figure 1.3.

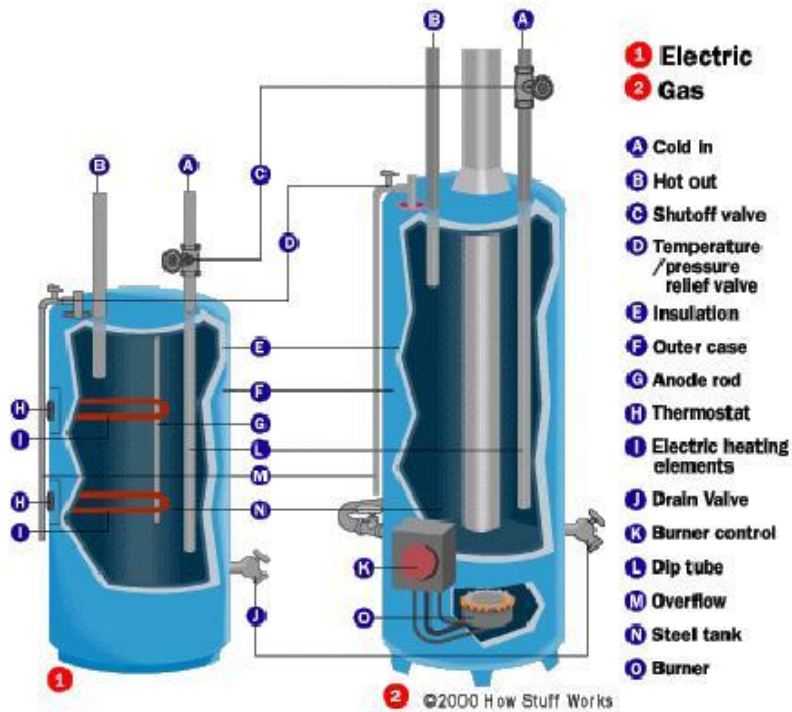


FIGURE 1.3 - TYPICAL ELECTRIC AND GAS STORAGE TANK WATER HEATER (HSW, 2000)

With hot water being stored inside of the tank, there will be losses to the environment. This will require additional energy from the heater to compensate for these standby losses. Therefore, insulation is used to increase the R-value of the tank and minimize these losses.

1.2.2 TANKLESS WATER HEATERS

Tankless, or on-demand, water heating systems produce hot water as required at a preset temperature. Either a gas burner or an electric element is used to heat the water as it is drawn. Therefore, unlike the storage tank water heaters, there is no reservoir of hot water on hand and they avoid standby losses completely (NRCAN, 2009). Figure 1.4 shows a schematic for an electric tankless water heating system.

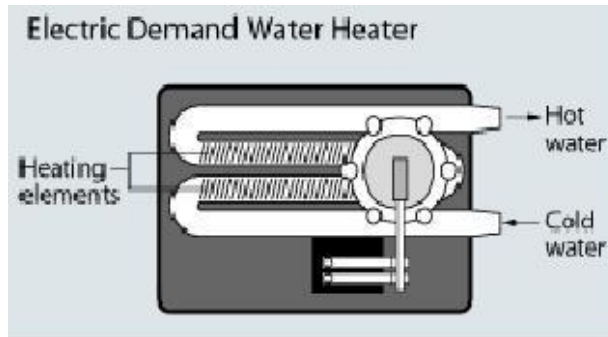


FIGURE 1.4 - ELECTRIC TANKLESS WATER HEATER (U.S. DEPARTMENT OF ENERGY, 2009)

There are two primary types of tankless systems available. The first is a *point-of-use* system which is a smaller unit used to provide hot water for only one or two places in the home. For example, this type of unit might be installed under the kitchen sink to supply hot water to the sink only. The second type is a *whole-house-use* system, which is sized large enough to provide all of the hot water needed by the home. These units are fairly large and are typically located in a utility room or garage (Wetzel, 2010).

Although there are no standby-losses associated with the tankless water heaters, and they take up less space than a storage tank system, there are still some drawbacks. The installation costs are much higher and they can only use natural gas, propane, or electricity to heat the water, where a storage tank system can also incorporate solar, geothermal, and other renewable energy sources to greatly reduce the operation costs (Wetzel, 2010).

1.3 SOLAR ENERGY

Approximately 1.74×10^{14} kW (174 PW) of solar radiation reaches the Earth's outer atmosphere. Of this solar energy, roughly thirty percent is reflected into space and the remaining seventy percent is absorbed by the oceans, landmass, and clouds in the Earth's atmosphere (Smil, 2008). Figure 1.5 shows a breakdown of the various paths of the incoming solar radiation into and out of the atmosphere.

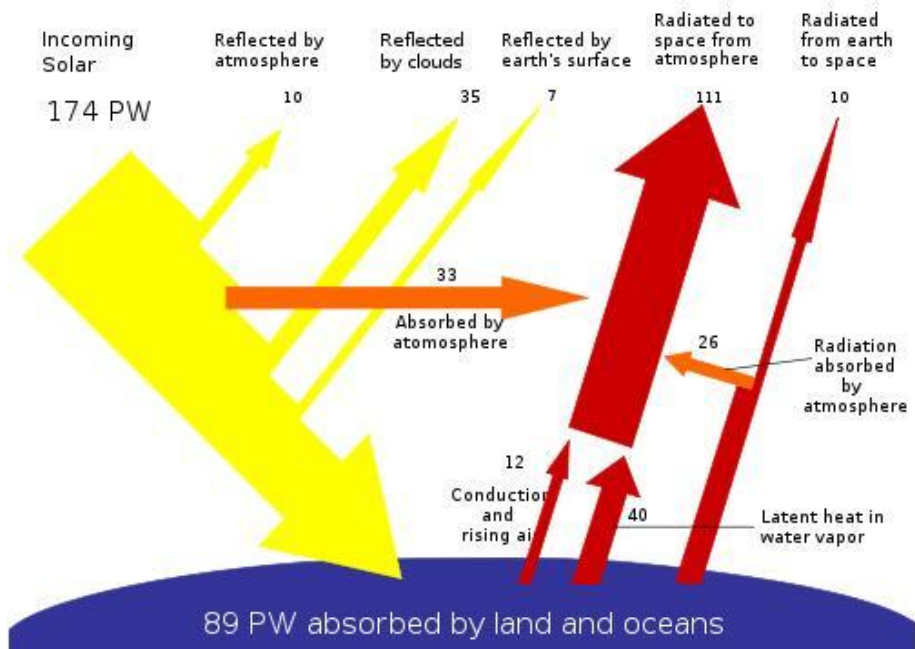


FIGURE 1.5 - SOLAR RADIATION BREAKDOWN (SMIL, 2008)

Therefore, the total amount of solar energy absorbed by the atmosphere, oceans, and landmass is about 3.85×10^{21} kJ per year. Of that total energy, just over 2.8×10^{21} kJ is absorbed by the land and oceans (Smil, 2008). According to the “Statistical Review of World Energy 2009” published by BP, the total worldwide energy consumption in 2008 was 4.74×10^{17} kJ with over eighty percent supplied from the combustion of fossil fuels (BP, 2009). Therefore, just over 5900 times more energy in the form of solar radiation was absorbed by the land and oceans than was used by the entire world in 2007. In fact, the Earth’s atmosphere absorbs enough solar radiation in just over an hour to equal the total amount of energy that the entire world used in 2007. This shows the potential for solar energy and how it can be used as an environmentally friendly alternative to reduce the reliance on fossil fuel sources.

Solar energy can be used directly or indirectly for all of our energy requirements including heating, cooling, lighting, electrical power, and more (WEC, 2007). In order to generate electricity from solar energy, photovoltaic (PV) collectors are used. These PV collectors are made up of a number of PV cells connected together that convert solar energy into direct current electricity (DC). The most

common materials used for PV cells are semi-conductor crystalline silicon or quartz (The Pembina Institute). Photovoltaic technologies are not the area of interest for this work.

1.3.1 SOLAR DOMESTIC HOT WATER (SDHW) HEATING

Solar energy is also used for thermal applications by heating various working fluids for different tasks such as space heating and cooling, and water heating. In particular, solar energy can be used for domestic water heating to greatly reduce the overall energy consumption of fossil fuels. Figure 1.6 below shows the layout of a typical SDHW system.

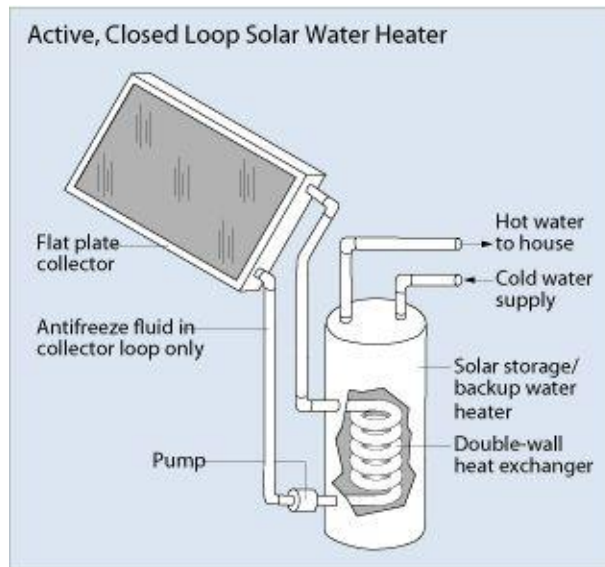


FIGURE 1.6 - TYPICAL SOLAR ASSISTED DOMESTIC HOT WATER HEATER (BUDGETSOLARSTORE.COM)

SDHW systems that are used year round in Canada have a number of general characteristics. The working fluid is typically a refrigerant to prevent freezing in the cold winter months. The collector is mounted in a location that has access to direct sunlight, usually on a roof, and the working fluid is circulated through the solar collector where the radiation from the sun heats it. The fluid then enters a heat exchanger at a relatively high temperature and transfers the collected energy into the domestic storage tank to heat the water. This lowers the temperature of the working fluid and it is pumped back through the collector again to absorb more

energy. This is just one example of a solar assisted domestic hot water heater configuration and more can be seen in Goswami et al (2000).

1.3.2 INTRODUCING A HEAT PUMP TO IMPROVE PERFORMANCE

Solar radiation and ambient temperatures are much higher during the summer months in Canada. Therefore, when using solar thermal energy to assist in domestic water heating, much more energy will be collected during the summer than in the winter. For this reason, the backup water heater (either electricity or gas) supplies a lot more of the energy during the colder months of the year in order to keep the storage tank charged.

Instead of relying on the backup heater to supply all of the energy, it is more efficient to use a heat pump to assist with the domestic water heating. Implementing a heat pump can also greatly benefit the operation of the solar loop by delivering colder fluid to the collector inlet. These benefits can be seen by looking at the typical flat plate collector efficiency plots shown in Figure 1.7. Note that, with an increase in the inlet fluid temperature, T_i , or a decrease in either the ambient temperature, T_a , or the solar irradiation on the collector, G_T , the point on the plot will shift to the right along the x-axis, resulting in a lower efficiency.

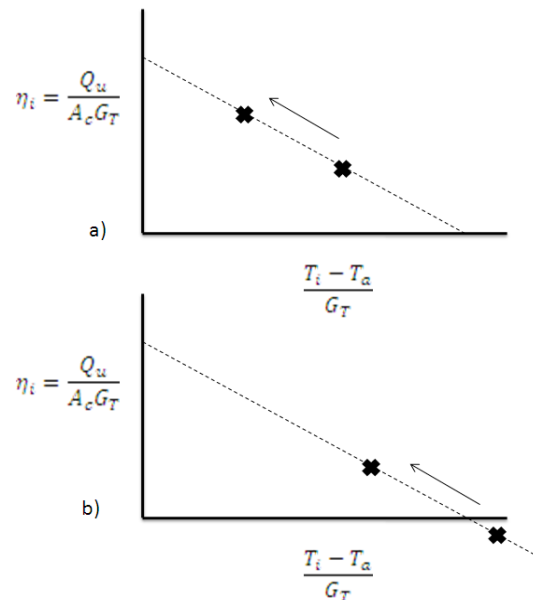


FIGURE 1.7 – TYPICAL FLAT PLATE COLLECTOR EFFICIENCY PLOTS

Figure 1.7 a) shows that colder fluid sent to the collector inlet will increase the collector efficiency (η_i) by decreasing the temperature difference between the inlet collector and ambient temperatures ($T_i - T_a$). Also, the colder fluid will potentially increase both the daily and seasonal solar runtimes by allowing the system to collect energy at times that a typical SDHW system could not, as shown in Figure 1.7 b). In a SDHW system, the lowest temperature that the working fluid could achieve before entering the collector is the temperature of the cold supply water. So if the supply water in the winter is 10°C and, with assistance from a heat pump, say it is possible to drop the working fluid to -5°C, then there is much more opportunity to collect solar energy to assist in heating the domestic water. This drop in temperature experienced by the working fluid circulated through the heat pump will also increase the collector efficiencies, as discussed regarding Figure 1.7. The cold working fluid will absorb solar energy and exit the collector at an increased temperature. Then, the fluid will receive more energy from the heat rejection process of the heat pump to further increase its temperature in order to assist with the domestic water heating. These benefits from the heat pump can help to increase the overall solar fraction of the system.

This thesis considers two configurations of an indirect heat pump assisted solar domestic hot water (i-HPASDHW) system and compares their performances to a traditional SDHW system and an electric DHW system. The performances of the two i-HPASDHW systems are also compared with each other. All of the systems are modeled using the TRNSYS software and the simulation results are used for the detailed analysis.

1.4 OUTLINE OF THESIS

This thesis contains five chapters.

Chapter 2 provides a literature review of research relevant to the thesis. Common layouts for traditional solar assisted water heating systems are presented and direct expansion solar assisted heat pumps systems are briefly introduced.

Some indirect solar assisted heat pump configurations that have been analyzed in previous work are discussed in detail.

Chapter 3 presents the configurations of the two heat pump assisted solar systems that were analyzed in this research, as well as the traditional SDHW and electric DHW systems that were used for comparison. The simulation software (TRNSYS) is introduced and the components and configurations used to model the systems are documented and justified. The final part of Chapter 3 presents detail regarding the implementation of each system in TRNSYS.

Chapter 4 includes results and discussion. The performances of all of the systems were reviewed to ensure that they were operating as expected. Next, the two heat pump systems were analyzed and compared to the two base systems and with each other. Then, overall energy comparisons and a simple cost analysis were presented.

Chapter 5 lists the conclusions and recommendations.

Chapter 2

LITERATURE REVIEW

There are many books, articles, and technical reports that focus on solar assisted water heating, but only a few consider heat pump assisted solar water heating systems. First, this chapter examines various layouts and design options of solar assisted water heaters. Next, direct expansion solar assisted heat pump (DX-SAHP) systems are introduced. Last, this chapter presents various indirect heat pump assisted solar domestic hot water (i-HPASDHW) systems previously studied and findings relevant to this work.

2.1 SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

Solar water heating is very common in both small and large applications (Goswami et al., 2000). The basic elements used in solar water heaters can be assembled in many different configurations. Some common system layouts are shown in the Figure 2.1. In these layouts, auxiliary heating is used in three different ways: auxiliary heater inside the domestic water tank [(a) and (c)], external auxiliary heater in the pipe leaving the tank to the load [(b)], and an auxiliary heater with its own storage capacity [(d)]. It is important to note that these methods are interchangeable between systems. (Duffie and Beckman, 1991)

Layout (a) is a passive water heater (thermosyphon) that operates without the use of a pump. The tank is positioned above the collector so that whenever solar energy heats the water in the collector, a natural low-flow circulation is introduced due to a density difference in the water (Duffie and Beckman, 1991).

Layouts (b), (c), and (d) are active water heaters because they require a pump to provide forced-circulation. These types of systems are usually controlled by a differential thermostat to turn the pump on when the temperature at the

outlet of the collector is higher than the temperature of the water at the bottom of the tank by a set margin (see Figure 2.1b).

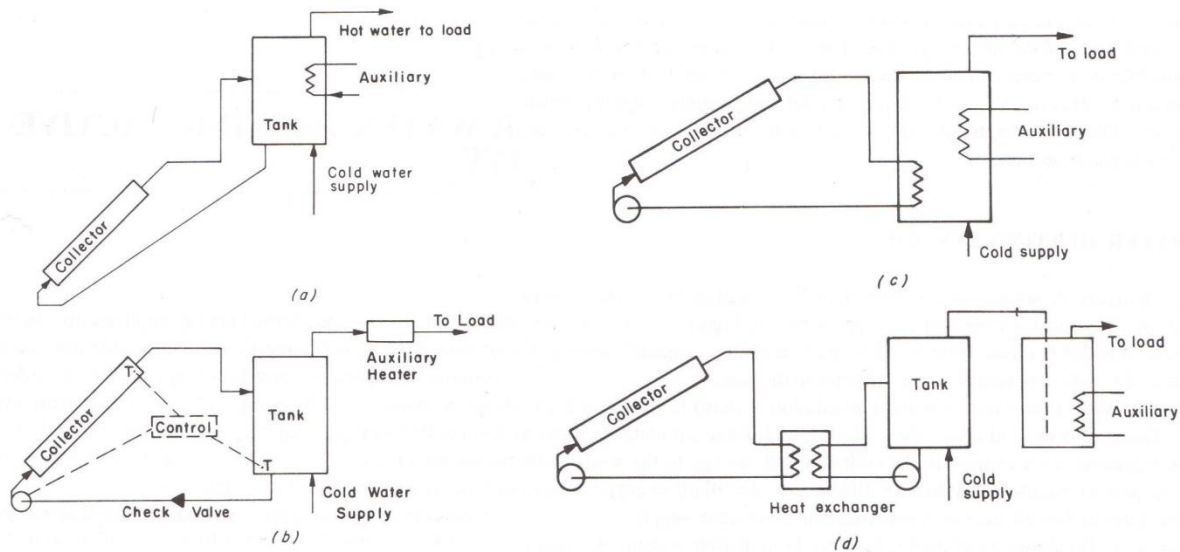


FIGURE 2.1 - SCHEMATIC OF COMMON CONFIGURATIONS OF SDHW SYSTEMS. (A) A NATURAL CIRCULATION SYSTEM. (B) ONE-TANK FORCED-CIRCULATION SYSTEM. (C) SYSTEM WITH ANTIFREEZE LOOP AND INTERNAL HEAT EXCHANGER. (D) SYSTEM WITH ANTIFREEZE LOOP AND EXTERNAL HEAT EXCHANGER. (BECKMAN AND DUFFIE, 1991)

Some common design options for active systems include (but are not limited to):

- Freeze Protection: Drain-back vs. Refrigerant

In colder climates, the system commonly uses either a drain-back approach or circulates a refrigerant in the collector loop to avoid damage from freezing. The drain-back method simply drains all of the water from the collector and piping exposed to freezing temperatures back into the tank when it is not operating. If the refrigerant method is used instead, a heat exchanger must be introduced to transfer the collected energy in the refrigerant to the water in the domestic tank to avoid mixing. This can be done with either an internal or external heat exchanger, as shown in layouts (c) and (d) respectively. Again,

these are just two common options for freeze protection. (Duffie and Beckman, 1991)

- One tank vs. Two tank systems

The collected solar energy can either be added to the domestic tank directly (one tank system) or to an additional tank (two tanks system) that is allowed to float in temperature. In the two tank systems, the additional tank supplies the domestic tank with preheated water which greatly reduces the amount of energy input required by the auxiliary heater. Figure 2.1 shows the common layouts for the one [(b) and (c)] and two [(d)] tank systems. Whenever there is a hot water draw in the two tank system, cold supply water is delivered to the bottom of the additional tank and hot water from the top of the additional tank is pumped to the domestic tank. This can be seen in layout (d). Therefore it is important for the tanks to be stratified. (Duffie and Beckman, 1991)

These are only a few common configurations and design options of solar assisted water heaters. The basic systems can also be incorporated into more complex designs to include such things as space heating and cooling. More examples of solar assisted systems can be found in Goswami et al. (2000) and Duffie et al. (1991).

2.2 HEAT PUMP ASSISTED SOLAR WATER HEATING SYSTEMS

Implementation of a heat pump into the solar thermal system can help to further improve performance because a portion of the electric loads will be used by the heat pump rather than auxiliary heaters. This is a more efficient use of the electricity. The heat pump can also extend the solar collection runtimes by sending colder fluid to the collector. There are two main types of heat pump assisted solar systems that have been studied. These are (1) direct expansion solar assisted heat pump domestic hot water (DX-SAHPDHW) systems and (2) indirect heat pump assisted solar domestic hot water (i-HPASDHW) systems.

2.2.1 DIRECT EXPANSION SYSTEMS (DX-SAHPDHW)

DX-SAHPDHW systems use the solar collector as one potential evaporator for the heat pump (Chaturvedi et al., 1998, Huang et al., 2003, Kuang et al., 2003). Therefore, the refrigerant is passed through a throttling valve just before entering the collector in order to drop its pressure and to allow it to evaporate when it collects the solar energy. The refrigerant leaves the collector as a vapour and passes through the compressor causing it to become a superheated vapour. This high temperature and pressure vapour then flows through the condenser heat exchanger where it transfers energy into the domestic water tank. An example of such a system from Huang and Lee (2003) is shown in Figure 2.2.

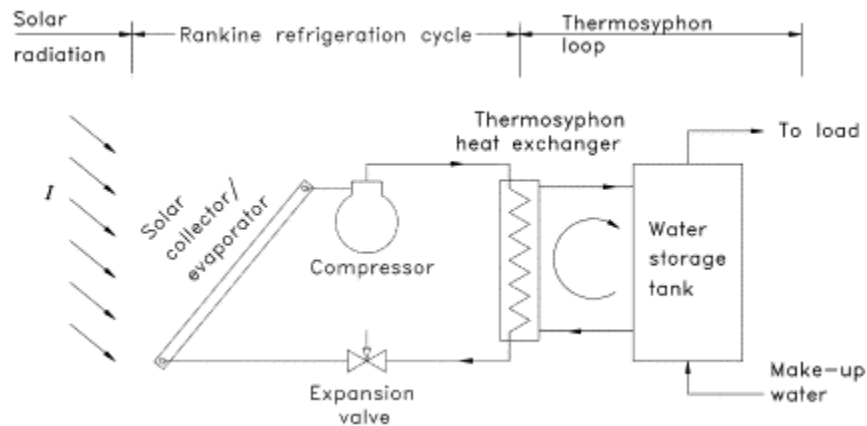


FIGURE 2.2 - AN EXAMPLE OF A DX-SAHP (HUANG ET AL., 2003)

The solar panel is usually only one of two or more sources utilized by the system as the evaporator. For example, many systems also use an air source heat exchanger when there is not sufficient solar energy (National University of Singapore 2008). Direct-expansion styled systems are not the type considered in this thesis.

2.2.2 INDIRECT SYSTEMS (I-HPASDHW)

For the i-HPASDHW systems, there are many possible configurations. Unlike the DX-SAHPDHW systems, the solar collector does not act as the evaporator for the heat pump process, but rather the heat pump is integrated into the design as

a closed unit. The heat pump is beneficial to the system because it will increase the efficiency of the solar loop by sending colder fluid to the collector inlet. In general, this will also allow the system to collect solar energy for longer periods during the days as well as extend the operation season. The solar collector benefits the heat pump as well by delivering warmer fluid to the evaporator of the heat pump which will result in a higher coefficient of performance (COP) (Bridgeman et al., 2008). Therefore, the heat pump and collector have potential to work very well together to help improve the overall performance of the system.

Bridgeman et al. (2008) produced a prototype of an i-HPASDHW system based on the system modeled in TRNSYS by Freeman et al. (1997) to validate the simulation findings. A schematic of the system is shown in Figure 2.3.

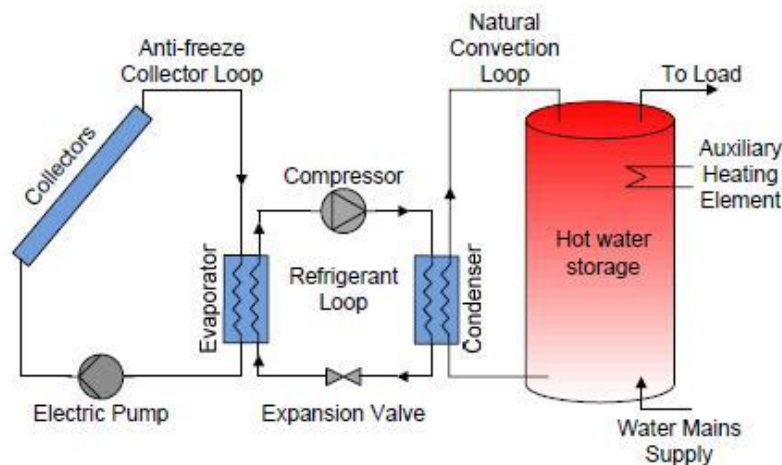


FIGURE 2.3 - I-HPASDHW SYSTEM ANALYZED BY FREEMAN ET AL. (1997) AND BRIDGEMAN ET AL. (2008)

The antifreeze collector loop is connected to the domestic hot water tank via a heat pump. This system is very similar to a standard closed loop SDHW system except that a heat pump is used rather than an external heat exchanger to transfer the collected energy to the water in the storage tank. Natural convection is used in this system to circulate the water from the domestic tank through the condenser heat exchanger of the heat pump.

In the TRNSYS simulation study by Freeman et al. (1997), this i-HPASDHW system was simulated using typical domestic hot water loads for five Canadian cities, which included: Toronto, Vancouver, Montreal, Halifax, and Winnipeg. The results were compared to simulations of an electric water heater system, a solar domestic hot water (SDHW) system, and an air-to-water heat pump system. It was determined that the i-HPASDHW system collected more solar energy during marginal weather conditions and in the winter when compared to the SDHW and air-to-water heat pump systems. It was also found that in Toronto, Montreal, and Winnipeg the i-HPASDHW and SDHW systems had similar life cycle costs, but in Halifax and Vancouver the i-HPASDHW system predicted a life cycle cost savings of 12% and 29%, respectively, compared to the SDHW system (Freeman et al., 1997).

To construct the prototype, Bridgeman et al. (2008) used an auxiliary heater to simulate the solar collector in order to perform controlled experiments. The auxiliary heater was able to supply constant temperature outputs, as well as produce typical solar collector output temperatures to the evaporator of the heat pump in order to simulate a day of operation. The other main components used to construct the system included: a 1/3 horsepower single speed compressor, a thermostatic expansion valve, two flat plate counter flow heat exchangers for the evaporator and condenser of the heat pump, a standard hot water tank (270 L), and a variable speed pump. The collector loop used a 50%-50% glycol/water solution by volume as the working fluid, and the heat pump loop used R-134a. (Bridgeman et al., 2008)

Constant source temperature tests were performed by Bridgeman et al. (2008) in order to compare to the simulation results obtained from the TRNSYS model by Freeman et al. (1997). It was determined that the TRNSYS model over predicted the COP of the heat pump due to over prediction of the effectiveness of the two heat exchangers. Once this was corrected in the TRNSYS model, the compressor power consumption and COP were within approximately 3% of the experimental results. (Bridgeman et al., 2008)

In a study by Chandrashekar et al. (1982), a detailed simulation using the program WATSUN was performed for six different heat pump assisted solar configurations, which included water and space heating, for two different building types located in Winnipeg and Vancouver. The two building styles considered were a single family residence and a 10 unit multiplex. From the simulation results for the two locations, the number of systems considered was narrowed down to two and they were simulated and analyzed in depth for more Canadian locations. The two systems analyzed included an air based (SYS 4) and a liquid based (SYS 5) dual source system. These two configurations are shown in Figure 2.4.

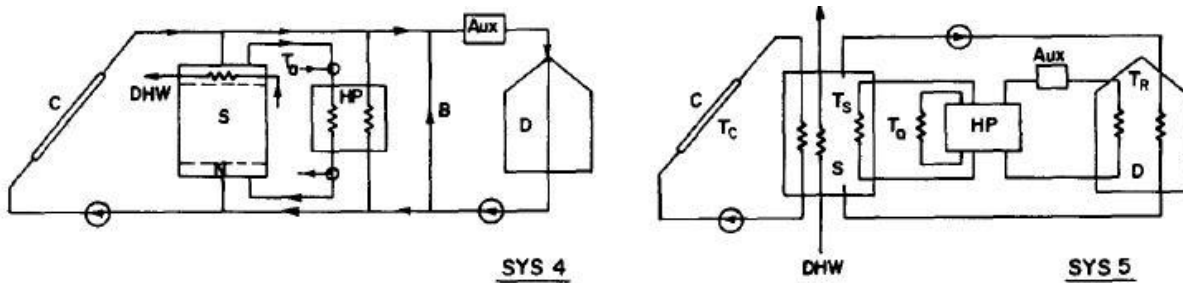


FIGURE 2.4 - AIR BASED (SYS 4) AND LIQUID BASED (SYS 5) DUAL SOURCE SYSTEM (CHANDRASHEKAR ET AL., 1982)

For the air based dual source system (SYS 4) the working fluid was air. Therefore the collector could deliver the absorbed energy to the rock bed storage (S) or directly to the space heating demand (D) without the use of heat exchangers. The heat pump was located between the storage and the dwelling and could use either the energy inside of the rock bed or from the ambient air in the evaporator side depending on which source had a higher temperature. An electric auxiliary heater was also in place in case the system could not provide sufficient energy for space heating. The domestic water was preheated using the energy in the rock bed storage. (Chandrashekar et al., 1982)

The liquid based dual source system (SYS 5) delivered all of its collected solar energy to the water storage tank through a heat exchanger. The water inside of the tank was used for both domestic hot water and space heating. For

the space heating demands (D), the hot water was drawn from the tank and circulated through a water-to-air heat exchanger in the air duct system of the building. If the storage tank was unable to supply the required demand, the heat pump was used. Just like the air based system, the heat pump could use either the stored energy in the tank (S) or the ambient air depending on which source had a higher temperature. The electric auxiliary heater was in place for situations when the entire system could not meet the demands. (Chandrashekar et al., 1982)

The study considered the energy demand for space heating and domestic hot water loads for the two different building types in Vancouver, Edmonton, Winnipeg, Toronto, Ottawa, Montreal, and Fredericton. Both the energy and economic aspects of the indirect heat pump assisted systems were compared to two reference systems, namely, a conventional electric resistance heating system and an air-to-air heat pump system.

The general conclusion to the study was that the energy savings of the heat pump assisted solar systems considered were substantial when compared to the electrical system or the air-to-air heat pump system for both building types. The simulation results also found that with the assumed economic parameters, some of the heat pump assisted solar systems with auxiliary back-up were more cost effective compared to resistance heating in multiplex buildings. However, for the single family dwellings, these systems proved not to be cost effective compared to the electric heating system at the time of the study. For all cases, the air-to-air heat pump system proved to be more economical than the heat pump assisted solar systems at the time. (Chandrashekar et al., 1982)

Nuntaphan et al. (2009) first observed the performance of an unglazed solar collector modified from corrugated metal roofing that was connected to a storage tank for water heating. The results obtained from this experiment for the collector and storage tank performances were then used to develop mathematical models. These models were implemented with a specific heat pump model and were all programmed into simulation software to determine the

effect of adding a heat pump to the system. Figure 2.5 shows a schematic of the simulated i-HPASDHW layout that they considered.

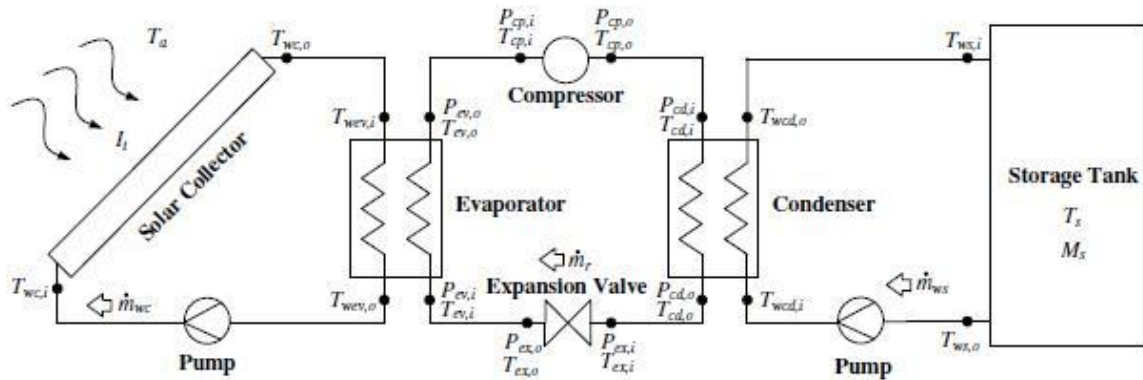


FIGURE 2.5 - I-HPASDHW SYSTEM ANALYZED BY NUNTAPHAN ET AL. (2009)

This model developed was applied to a typical day of solar radiation experienced in Thailand and the simulation findings of the system were then compared to the experimental results of the solar assisted system. It is important to note that this study only considered a single day of operation for most of the simulation analysis and observed the effects of the heat pump on the system. (Nuntaphan et al., 2009)

The study by Nuntaphan et al. (2009) concluded that, in this case, a solar collector combined with a heat pump could increase the temperature of the hot water inside the domestic tank by about 40% compared to the solar assisted system. Also, they looked at the effect of water volume on the performance of the system. It was discovered that using a larger tank decreased the energy savings of the system because of the increased amount of energy required to heat the additional thermal mass. (Nuntaphan et al., 2009)

Chapter 3

SYSTEM DESCRIPTIONS AND MODELS

Two i-HPASDHW systems of interest were simulated and analyzed for this thesis. In order to assess the performance and benefits of both i-HPASDHW systems, two standard systems were used for comparison. These included: (1) a domestic water tank with two electric heaters as the only heat sources, and (2) a traditional solar domestic hot water (SDHW) system. All four of the system layouts are described in the next section. The TRNSYS software used to model the four systems is presented and all of the components selected to construct the systems are introduced. Following this, the TRNSYS models of each system will be discussed in detail.

3.1 BASE SYSTEMS INTRODUCTION

3.1.1 ELECTRIC DOMESTIC HOT WATER (DHW) SYSTEM

The first base system considered was an electric DHW system. The only external interaction that the system had, besides the water draws, was thermal losses to the surrounding room. Two 2 kW electric heaters were located inside of the domestic water tank to provide all of the energy needed to meet the load requirements. Each heater was controlled using a thermostat that turned the respective electric heater on whenever the water at the height of the thermostat fell below a certain temperature set-point. However, the heaters operated using a master-slave mode which only allowed one heater to be on at a time. Therefore, the maximum allowed energy input into the tank at any time was the 2 kW capacity of one of the heaters. The details regarding the set-point temperatures of the auxiliary heaters are presented with the TRNSYS models in Section 3.5. An example of an electric DHW system is shown in Figure 3.1.

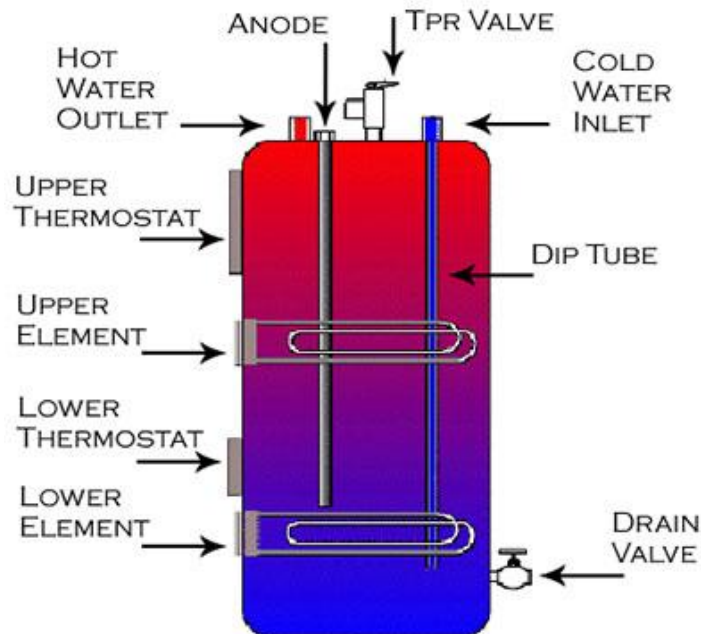


FIGURE 3.1 - ELECTRIC DWH SCHEMATIC (SEL, 2006)

As discussed in Chapter 1, the domestic tank was stratified due to the density effect of the water at different temperatures. Therefore, the cold supply water entered at the bottom of the tank and the hot domestic water was drawn from the top. This was true for the domestic water tanks in all of the systems considered.

3.1.2 TRADITIONAL SDHW SYSTEM

A traditional SDHW system was the second base system considered. A glycol-water anti-freeze mixture was used as the working fluid in the collector loop to avoid freezing in the winter months. Therefore, an external heat exchanger was used to transfer the collected solar energy into the water in the domestic tank. The schematic of the system is shown in Figure 3.2.

The traditional SDHW system used the collected solar energy to assist in meeting the hot water demands. Whenever there was solar energy to collect, the two pumps were turned on to circulate the glycol-water mixture through the collector and draw the cold domestic water from the bottom of the tank. The two fluid streams were then pumped into the external heat exchanger where the

solar energy collected by the glycol-water mixture was transferred into the domestic water. The heated water was then returned to the tank at the node closest to its temperature using a variable inlet valve to ensure that stratification was maintained. There were also two electric auxiliary backup heaters inside the domestic tank to ensure that the water remained near the set-point temperature when there was insufficient solar energy to do so.

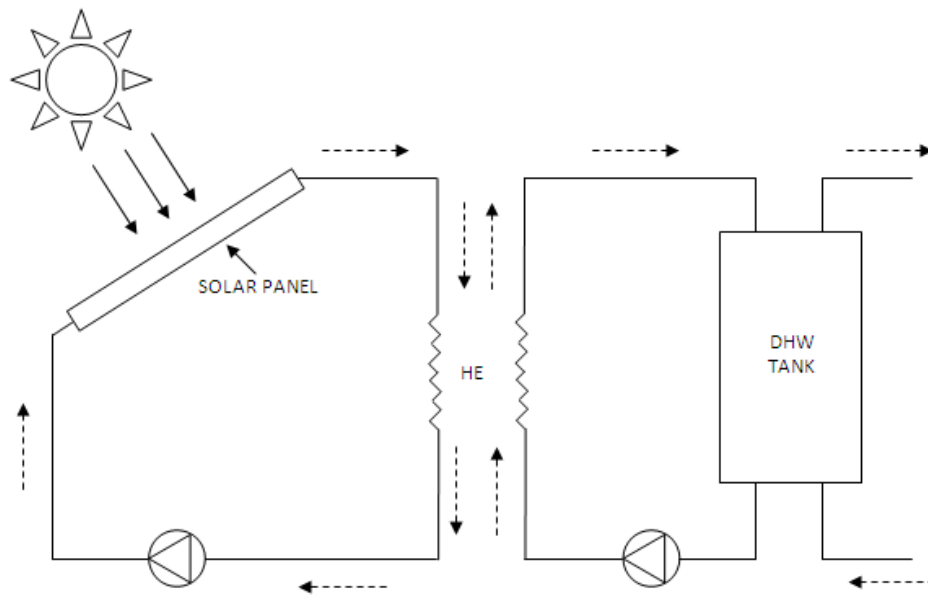


FIGURE 3.2 - TRADITIONAL SDHW SCHEMATIC

3.2 HEAT PUMP ASSISTED SOLAR SYSTEMS INTRODUCTION

3.2.1 DUAL TANK I-HPASDHW SYSTEM

A Dual tank i-HPASDHW system was the first heat pump assisted configuration considered. This system was built on the traditional SDHW system by adding a second tank and a heat pump to transfer energy between the two tanks. The tank connected to the solar collection loop was a large float tank for thermal storage that contained the glycol-water antifreeze solution. This tank was called the float tank because it was allowed to fluctuate in temperature by using very low set-point temperatures for the backup auxiliary heaters. These heaters were used only to ensure that the fluid did not freeze.

The float tank was connected to the domestic water tank via a heat pump and heat exchanger by-pass in order to transfer energy to the domestic tank. The heat exchanger by-pass was included in the system for situations when the float tank temperature was at or above the set-point temperature of the domestic tank. In these cases, the heat pump was not required to transfer the energy and, therefore, less energy was consumed. A schematic of this system is shown in Figure 3.3.

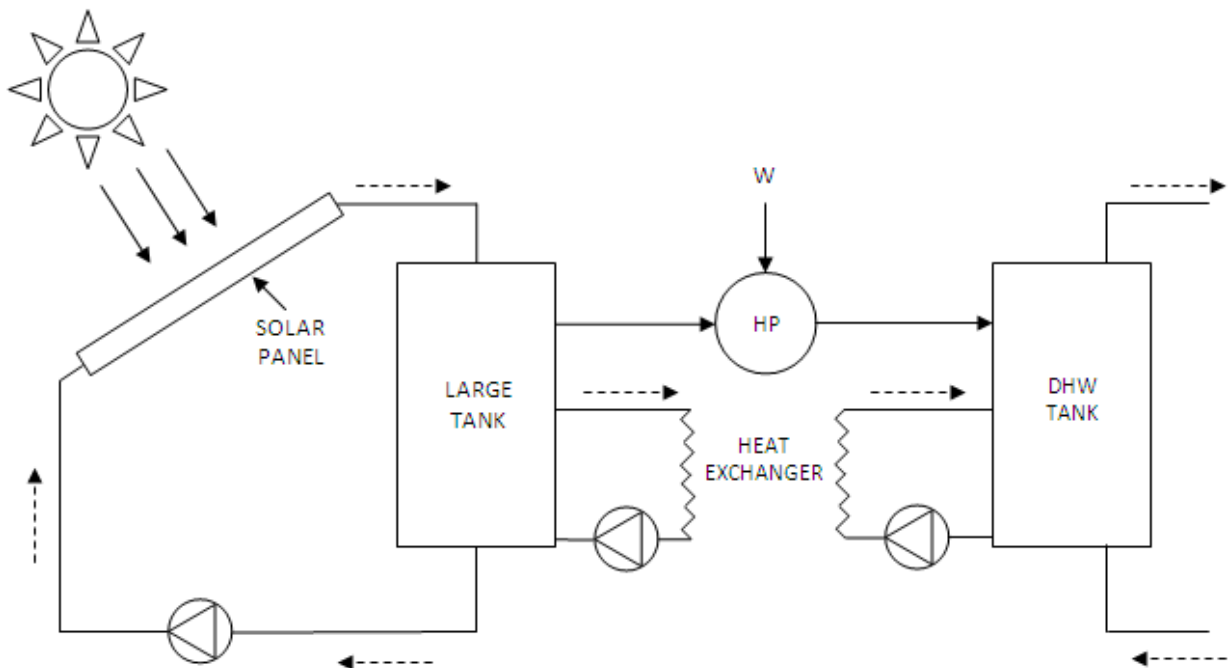


FIGURE 3.3 - DUAL TANK I-HPASDHW SCHEMATIC

The general idea was to allow the float tank to fluctuate in temperature while keeping the domestic tank close to the delivery temperature. The float tank would vary in temperature because the solar loop would add energy while the heat pump would remove energy to heat the domestic tank. These two independent and inverse effects worked well together for two reasons. First, the cooling caused by the heat pump potentially allowed for more solar energy gains due to the colder fluid circulating through the collector. Also, the solar energy collected gave the float tank energy to transfer to the domestic tank to ensure that the delivery temperature was satisfied. On a broader scale, the float tank

would also fluctuate seasonally due to the variation in the solar flux experienced throughout the year. Therefore, the lower float tank temperatures in the winter will increase the efficiencies of the collector and help to extend the solar loop run times.

3.2.2 SOLAR-SIDE I-HPASDHW SYSTEM

The second i-HPASDHW configuration considered was the Solar-side i-HPASDHW system. This system was built on the traditional SDHW system by adding a small capacity heat pump. The heat pump in this case was added into the solar loop in parallel between the inlet and outlet of the solar collector. The system layout is shown in Figure 3.4.

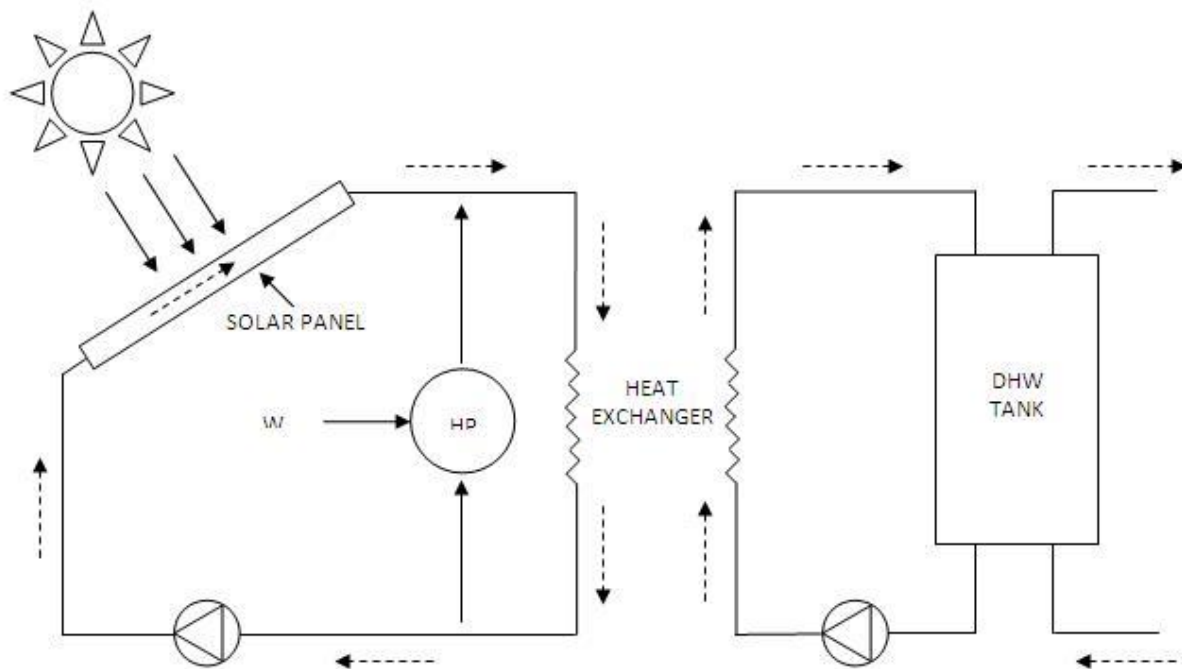


FIGURE 3.4 - SOLAR-SIDE I-HPASDHW SCHEMATIC

The heat pump in this location directly complimented the solar collection process. The evaporator of the heat pump removed energy from the working fluid just before it entered the collector. Therefore, the glycol-water mixture was sent to the collector at colder temperatures which increased the collector efficiency as well as allowed the system to operate for longer periods daily and seasonally.

After the working fluid absorbed solar energy in the collector, it entered the condenser of the heat pump where it was heated further. The hot glycol-water mixture was then circulated through the heat exchanger in order to transfer the energy to the water in the domestic tank.

This system was able to operate with or without the heat pump. When the heat pump was not used, the system essentially worked as the traditional SDHW system did. Implementing controls for deciding when and when not to use the heat pump was very complex. There were many factors that needed to be considered to ensure that the heat pump was only being used when it was beneficial to the performance of the system. For example, on hot summer days a large amount of solar energy would be collected regardless, so the heat pump was not required at all. There would also be cold days when the system could use the heat pump in the early morning and late afternoon to extend the run time. This would allow the system to collect solar energy at times when the traditional SDHW system could not. However, not just environmental conditions would determine when to use the heat pump. System factors and hot water consumption patterns also needed to be considered when developing the controls for this system.

3.3 TEMPERING VALVE

A tempering valve was included with each system to ensure that the domestic water was not delivered above the set-point temperature. Whenever there was a hot water draw, the cold mains water replaced the volume used to the bottom of the tank. If the temperature of the water at the top of the domestic tank was above the delivery set point during a draw, the tempering valve mixed a portion of the cold mains water with the hot delivery water in order to cool it to the set-point temperature. Figure 3.5 shows the layout of the tempering valve. This valve should not be used with the base electric DHW system because the auxiliary heaters kept the water at, not above, the set-point temperature.

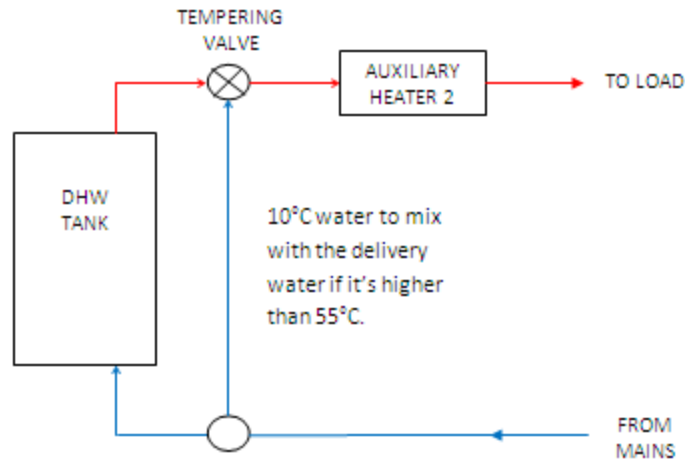


FIGURE 3.5 - TEMPERING VALVE SCHEMATIC

If a water draw occurred when the temperature at the top of the domestic tank was below the desired delivery temperature, there was a top-up 2 kW electric auxiliary heater after the tempering valve to bring the fluid up to the set-point temperature. This heater is also shown in Figure 3.5 (Auxiliary heater 2).

3.4 TRNSYS SOFTWARE

The *Transient System Simulation program* (TRNSYS) is “used by engineers and researchers around the world to validate new energy concepts” from simple individual systems to the entire design and simulation of buildings and all of the associated equipment (TRNSYS, 2006). It is a very easy-to-use program that allows the user to simply add existing components from the library into a project and connect them to the other components that they interact with in order to form the desired system. Each component is based on a mathematic model that reads in various parameters specified by the user and inputs from other components in the system with which it interacts. All of the mathematical models use their parameters and inputs to produce the various outputs of each component and are used to link the system together. The outputs can also be

sent to an external file or to a plotting component for analysis by the user. (TRNSYS, 2006)

TRNSYS deals with transient systems, so the user is required to set the time period and time step that are to be used for the simulation calculations. The time period is the total time for which the model will be simulated and the time step is the amount of simulated time between calculations performed by the mathematical models. For example, if a one hour time step is used, each component reads in the various inputs at the start of the time step and produces outputs based on a one hour period at those conditions. After that time step has been calculated, the inputs and outputs are updated and the simulation moves on to the next time step. This process continues until the set time period is reached. The time period and time step details used for this research is presented in Section 3.5 with the TRNSYS models. (TRNSYS, 2006)

3.4.1 TRNSYS COMPONENTS

All four systems considered for this thesis were modeled and simulated using TRNSYS. All of the components used are introduced in this section. The basic functions along with the various parameters, inputs, and outputs that were important for the simulation are discussed. For details on the mathematical models for each TRNSYS component, refer to Appendix B.

3.4.1.1 STRATIFIED STORAGE TANK WITH VARIABLE INLETS AND UNIFORM LOSSES

The tanks in all four systems were modeled with the Type4c stratified fluid storage tank which had variable inlets and uniform losses. The performance of the stratified storage tank was modeled by assuming that the tank consisted of N fully mixed volume segments. A schematic of the stratified tank model with N nodes is shown in Figure 3.6.

Type4c modeled variable inlet positions which allowed the entering fluid to be added to the tank at the node closest to its own temperature. This helped to

promote stratification inside of the tank by greatly reducing the amount of mixing between the fluid volumes at various temperatures.

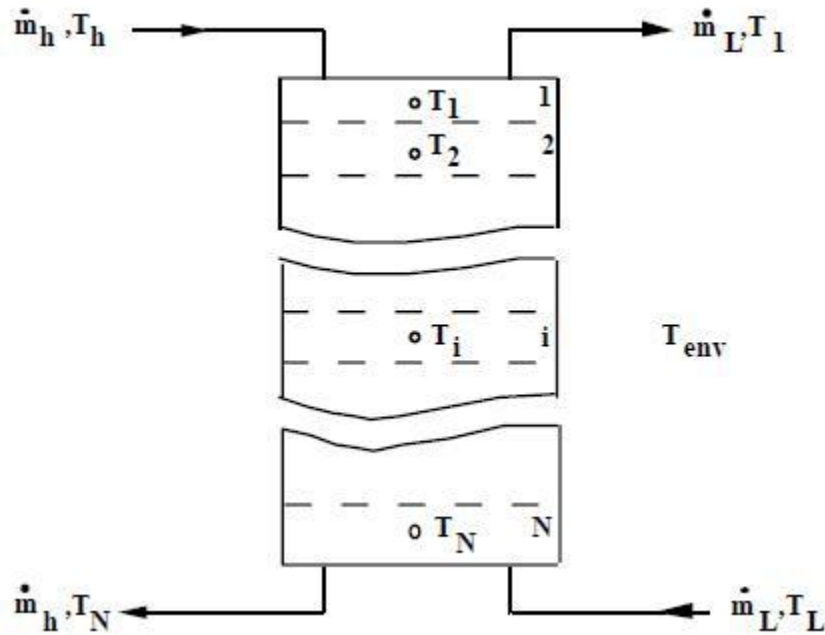


FIGURE 3.6 - TRNSYS STRATIFIED TANK MODEL (TRNSYS, 2006)

Many tank characteristics were set in the parameters menu of Type4c. These included: tank volume, fluid specific heat, fluid density, tank loss coefficient, number (N) and height of temperature nodes, number of heating elements, location of each heating elements, location of thermostats, maximum heating rate of each element, and the set point and dead-band temperatures for each element. The tanks modeled for this research all used a fluid density of 1000 kg/m^3 , $N=10$ and an overall loss coefficient of $3 \text{ kJ/hr}\cdot\text{m}^2\cdot\text{K}$. The domestic tanks used a fluid specific heat of $4.19 \text{ kJ/kg}\cdot\text{K}$ to represent water and the float tank used $3.29 \text{ kJ/kg}\cdot\text{K}$ to represent the glycol-water mixture. Also, each tank contained two internal electric heating elements that operated using the master-slave mode. This mode only allowed the bottom heater to operate when the upper heater condition was satisfied. Therefore, only one heater could be on at a time. The specific details for the heating elements in each tank will be presented in the next section with the TRNSYS models.

The Type4c stratified tank used seven inputs and seven outputs. The inputs included: hot-side temperature, hot-side flow rate, cold-side temperature, cold-side flow rate, environmental temperature, control signal for element-1, and control signal for element-2. The environment temperature was set to 22°C for all of the systems and was used to determine the tank losses. The two control signals were set to ‘1’ to allow for electric heating in the tank in conjunction with the specified set point and dead-band temperatures. The outputs included: temperature to heat source, flow rate to heat source, temperature to load, flow rate to load, thermal losses, energy rate to load, and auxiliary heating rate.

3.4.1.2 TIME DEPENDANT FORCING FUNCTION: WATER DRAW

The Type14b water draw forcing function was used in all four models to specify the draw profile that was applied to the systems. This component generated a time dependant forcing function that was created by “a set of discrete data points indicating the value of the function at various times throughout one cycle” (TRNSYS, 2006). These data points were specified by the user in the parameters of Type14b and the cycle that was created repeated throughout the entire simulation period.

The same load profile was applied to all of the models analyzed in this thesis. Four fifteen-minute water draws per day at a rate of 300 kg/hr were used to simulate a typical low flow shower at 6 a.m., 8 a.m., 8 p.m., and 10 p.m. The forcing function that was created for the water draw profile is shown in Figure 3.7. Although this consistency of water draw each day was not necessarily realistic, it was sufficient to observe and compare the performance of each system.

Type14b had two outputs: average water draw and instantaneous water draw. The generated draw profile was applied to the systems using the instantaneous water draw output of the component. It was important to note that in TRNSYS, Type14b actually supplied the cold replacement water to the bottom of the domestic tank during the water draws. The tank model assumed

that the same volume of hot water was delivered to the load from the top of the tank when the cold replacement water was being supplied.

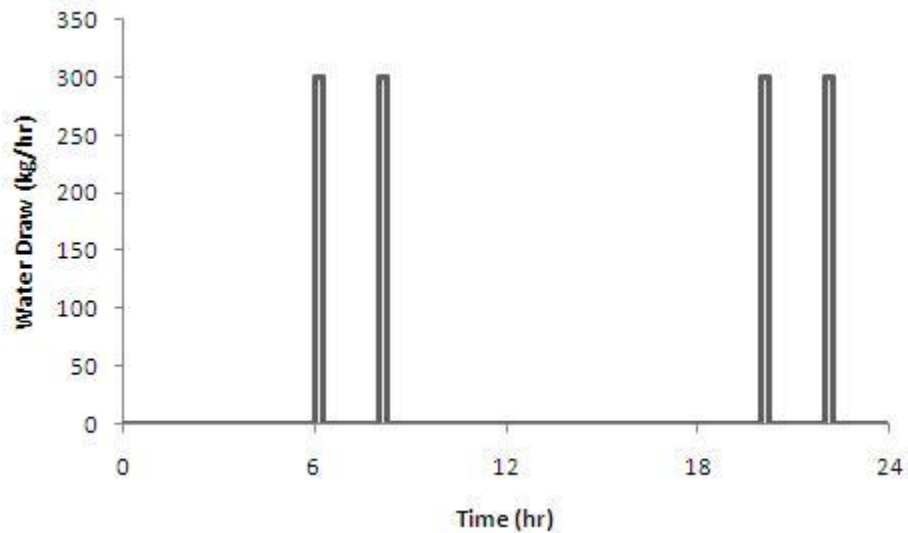


FIGURE 3.7 - DAILY WATER DRAW PROFILE

3.4.1.3 TEMPERING VALVE

The Type11b tempering valve was used in all of the modeled systems. As mentioned, this component was required for situations when the temperature of the water at the top of the domestic tank was above the desired delivery temperature of 55°C during a water draw. Figure 3.8 shows the general schematic of the tempering valve.

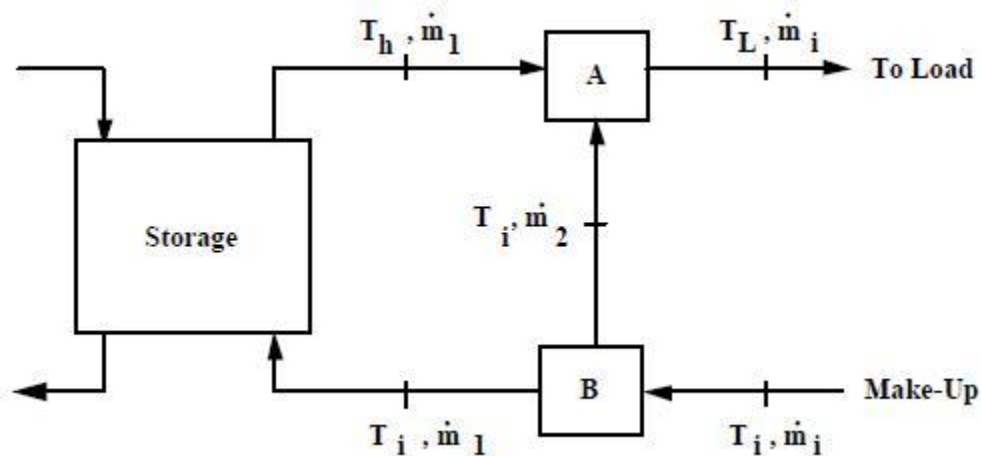


FIGURE 3.8 - TRNSYS TEMPERING VALVE MODEL (TRNSYS, 2006)

The tempering valve is usually placed in location ‘A’ in actual applications, but for simulation purposes in TRNSYS it was positioned at location ‘B’. Therefore, the tee piece mixing valve Type11h was also required at location ‘A’ in conjunction with the tempering valve to mix the hot and cold water into one outlet stream at the set point temperature. It should be noted that this was thermally equivalent to the actual layout and does not affect system performance.

The tempering valve model in TRNSYS had four inputs and five outputs. The inputs included: inlet temperature (T_i), inlet flow rate (m_{doti}), heat source temperature (T_h), and set point temperature (T_{SET}). The component then compared the heat source temperature to the 55°C set point temperature in order to determine the control function to calculate the two mass flow rates. The outputs were: temperature at outlet 1 (T_o), flow rate at outlet 1 (m_{dot1}), temperature at outlet 2 (T_o), flow rate at outlet 2 (m_{dot2}), and control function (y).

3.4.1.4 EXTERNAL AUXILIARY HEATER

The Type6 external auxiliary heater was used for the top-up heater that was positioned after the tempering valve in all of the systems. Again, this heater was used when the water at the top of the domestic tank was below the desired delivery temperature during a water draw. It was assumed that there were no losses associated with the external heater and that it had an efficiency of 1 to simulate an electric heater.

The maximum heating rate that was chosen for the top-up heater was 2 kW for the systems analyzed in this thesis and this value was entered in the parameters menu. Therefore, if the water at the top of the tank was too cold during a water draw, there were some situations when the power of the external heater was insufficient to boost the water up to the 55°C set point temperature. In those cases, the output delivery temperature that would be achieved could be determined from the Equation 3.1.

$$T_o = \frac{\dot{Q}_{aux,max}}{\dot{m}_i C_p} + T_i \quad (3.1)$$

The Type6 auxiliary heater had five inputs and five outputs. The inputs included: inlet fluid temperature (T_i), fluid mass flow rate (\dot{m}_i), control function, set point temperature (T_{SET}), and temperature of surroundings. For all four systems considered, the set point temperature was 55°C and the control function was set to 1 (ON) which allowed the heater to deliver the water at the set point temperature. When the water at the top of the tank was at or above 55°C or when there was no water draw, the heater would turn off. Again, the losses were assumed to be zero so the temperature of the surroundings was irrelevant for the cases considered. The outputs were: outlet fluid temperature (T_o), outlet fluid flow rate (\dot{m}_o), required heating rate (Q_{aux}), losses from the auxiliary heater, and rate of energy delivery to fluid stream. The rate of energy delivered to the fluid stream would be equal to the required heating rate (Q_{aux}) unless the 2-kW heater could not provide enough energy to reach the set point temperature. In that situation, the rate of energy delivery to the fluid stream would be the maximum power, 2 kW, ($Q_{aux, max}$) of the auxiliary heater.

3.4.1.5 PUMP

The Type3b single speed pumps were used to circulate the glycol mixture and water from the domestic tank in the systems with the solar loop. The pumps circulated the fluids at a flow rate of 100 kg/hr while consuming 60 kJ/hr of electrical energy during operation. These were the default parameters of the component in TRNSYS. For the systems considered for this thesis, the pumps were always operated at 100% power to provide a constant flow rate during operation.

Type3b had three inputs and three outputs. The inputs were: inlet fluid temperature, inlet mass flow rate, and control signal. It was important to note that the inlet mass flow rate was only used by Type3b for a convergence check

and was included for visualization purposes when connecting to other components (TRNSYS, 2006). The actual flow rate was output by the component and was determined by the control signal and the maximum flow rate set in the parameters of the display menu. The outputs included: outlet fluid temperature, outlet flow rate, and power consumption.

3.4.1.6 FLAT PLATE SOLAR COLLECTOR

The Type1b flat plate second order incidence angle modifier (IAM) solar collector was used in all three of the solar assisted systems. The IAM equation was used in the mathematical model in order to compensate for off-normal solar incidence angles (θ) experienced by the collector. This allowed the model to determine the amount of useful solar energy that was absorbed at each time step. The IAM correlation used is given in Equation 3.2. (ASHRAE, 2003)

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0 \left(\frac{1}{\cos \theta} - 1 \right) - b_1 \left(\frac{1}{\cos \theta} - 1 \right)^2 \quad (3.2)$$

The default values provided by TRNSYS were used for the two coefficients in the IAM equation and for the collector efficiency terms. These values are given in Table 3.1.

TABLE 3.1 - TRNSYS FLAT PLAT COLLECTOR PARAMETERS

Parameter	Value
Tested flow rate	40 kg/hr·m ²
Intercept efficiency	0.80
Efficiency slope	13.0 kJ/hr·m ² ·K
Efficiency curvature	0.05 kJ/hr·m ² ·K ²
1st order IAM coefficient (b₀)	0.2
2nd order IAM coefficient (b₁)	0.0

Type1b allowed the user to specify the collector's area, orientation, tilt, and the specific heat of the working fluid that circulated through the collector in the parameters menu. A 4 m² south facing collector with a 45° tilt angle was used for all three solar assisted systems. The working fluid was the glycol-water mixture with a specific heat of 3.29 kJ/kg·k (Engineering Toolbox, website). The eight inputs of the collector that were used included: inlet temperature, inlet flow rate, ambient temperature, incident radiation, total horizontal radiation, horizontal diffuse radiation, incidence angle, and collector slope. The outputs were: outlet temperature, outlet flow rate, and useful energy gain.

3.4.1.7 DATA READER AND RADIATION PROCESSOR

Type109-TMY2 was used to read in weather data at regular time intervals from a user-specified data file and provide the information to the model. A TMY2 weather file with data for Ottawa, Ontario was used for the three solar assisted systems considered. The data reader converted the weather information to the desired system of units and determined the direct and diffuse radiation outputs at each time step experienced by the solar collector at the specific orientation and incline. Therefore, many calculations were performed by this component throughout the simulated year. The details can be found in the TRNSYS document "Mathematical Reference" found in Appendix B (TRNSYS, 2006).

Type109-TMY2 had three inputs and over twenty outputs. The inputs were: ground reflectance, slope of surface, and azimuth of surface. The ground reflectance was used by the mathematical model to determine how much solar radiation was reflected off of the ground around the collector. A reflectance coefficient value of 0.2 (20%) is typical for grounds that are not snow covered and was used for the three solar assisted systems analyzed. The slope of the collector surface was 45° with a surface azimuth of 0° to simulate a south facing collector with a tilt angle of 45°. The outputs that were used included: ambient temperature, total radiation on tilted surface, total radiation on horizontal, sky

diffuse radiation on horizontal, angle of incidence for tilted surface, and slope of tilted surface. The tilted surface referred to the solar collector for this work.

3.4.1.8 HEAT EXCHANGER

To transfer collected solar energy in the glycol-water mixture to the domestic water, the Type5b counter flow heat exchanger was used. This heat exchanger model used an effectiveness minimum capacitance approach in the mathematical model to calculate the component's performance. A schematic of the heat exchanger is shown in Figure 3.9.

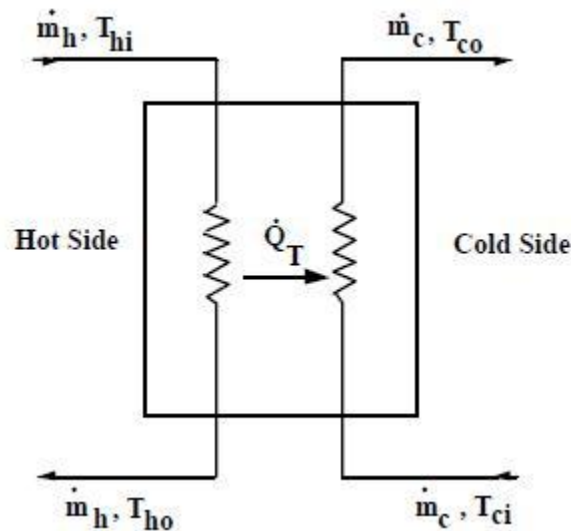


FIGURE 3.9 - TRNSYS HEAT EXCHANGER MODEL (TRNSYS, 2006)

The Type5b counter flow heat exchanger had five inputs and six outputs. The inputs were: hot side inlet temperature, hot side flow rate, cold side inlet temperature, cold side flow rate, and overall heat transfer coefficient of exchanger. The heat transfer coefficient that was used in this work was 3000 kJ/hr·K, which resulted in an average effectiveness of approximately 0.9. The outputs included: hot side outlet temperature, hot side flow rate, cold side outlet temperature, cold side flow rate, heat transfer rate, and effectiveness. It should also be noted that the specific heats of the hot and cold side fluids were entered in the parameters section of the display menu for Type5b. For the analyzed

systems, the hot side specific heat was 3.29 kJ/kg·K and the cold side specific heat was 4.19 kJ/kg·K to represent a 50%-50% glycol-water mixture and pure water, respectively (Engineering Toolbox, website). (TRNSYS, 2006)

3.4.1.9 WATER-TO-WATER HEAT PUMP

The two i-HPASDHW systems considered used the Type668 water-to-water heat pump model in the heating mode. This component's performance was based on an external file specified by the user that contained catalog data for the capacity and power consumption of the heat pump at various combinations of inlet load and inlet source temperatures. Therefore, Type668 simply read in the inlet load and inlet source temperatures entering the heat pump and used the external file to determine the capacity and power consumption for that situation. Linear interpolation was used by the heat pump model to determine these outputs at specific inlet conditions. Knowing the capacity of the heat pump, the mass flow rates, and the input temperatures, Type668 calculated the outlet load and outlet source temperatures of the heat pump for each time step. The detailed information about the specific external files used is presented with the TRNSYS models in the next section.

The user specified how many inlet load and source temperatures were used to generate the performance table for the external file in the parameters menu. The load and source specific heats were also entered by the user here. The inputs that were used for Type668 included: inlet source temperature, source flow rate, inlet load temperature, load flow rate, and heating control signal. The outputs included: outlet source temperature, source flow rate, outlet load temperature, load flow rate, heat transfer from source, heat pump power, and coefficient of performance (COP).

3.4.1.10 CONTROLLED FLOW DIVERTER

The Type11f controlled flow diverter was used in the Solar-side i-HPASDHW system to control the path of the glycol-water mixture in the solar loop. It had

one inlet and two outlets and the path that the entering fluid took was based on a control signal (γ) supplied to the component. The control signal could be any value between 0 and 1, which would split up the flow according to the schematic shown in Figure 3.10. (TRNSYS, 2006) In the Solar-side i-HPASDHW system, the diverter either sent the fluid through the heat pump or directly to the collector depending if the heat pump was on or off. Therefore, the control signal for this specific diverter was either 0 or 1 depending on the operation mode of the system.

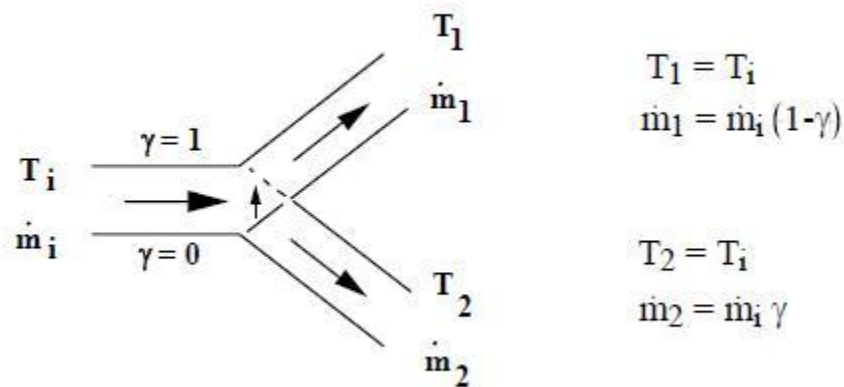


FIGURE 3.10 - TRNSYS CONTROLLED FLOW DIVERTER MODEL (TRNSYS, 2006)

This component had three inputs and four outputs. The inputs were: inlet temperature, inlet flow rate, and control signal. The outputs included: temperature at outlet 1, flow rate at outlet 1, temperature at outlet 2, and flow rate at outlet 2. (TRNSYS, 2006)

3.4.1.11 DIFFERENTIAL CONTROLLER

The Type2b differential controller was the main component that was used to control the operation of the traditional SDHW and Dual tank i-HPASDHW systems. This component generated a control function output (γ_o) that could either be 0 (off) or 1 (on). The value of the control function was determined by comparing the difference between the specified upper and lower temperatures,

T_H and T_L , with two dead-band temperature differences, ΔT_H and ΔT_L . The output control function (γ_o) was used as the input control function (γ_i) for the next time step because the new value of γ_o depended on the previous state of the controller as shown in Figure 3.11. (TRNSYS, 2006)

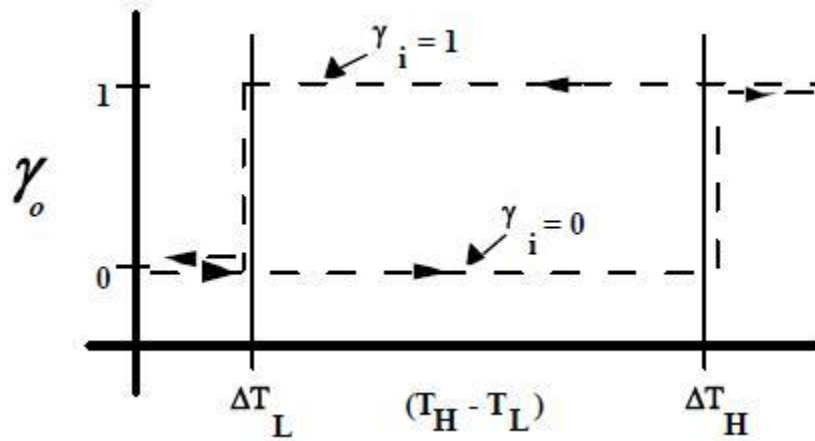


FIGURE 3.11 - TRNSYS DIFFERENTIAL CONTROLLER FUNCTION (TRNSYS, 2006)

Therefore, if the controller was on ($\gamma_i=1$), the lower dead band temperature difference, ΔT_L , was compared to the difference between the upper and lower input temperatures ($T_H - T_L$). The controller would remain on until the temperature difference fell below the lower dead-band. Similarly, if the controller was off in the previous time step ($\gamma_i=0$), the upper dead band temperature, ΔT_H , was compared to the difference between the upper and lower input temperatures ($T_H - T_L$). The control function remained off until the temperature difference became larger than the upper dead band. (TRNSYS, 2006)

For safety reasons, a high limit cut-out was also included with the Type2b controller. This was set by the user in the parameters tab of the display menu. Regardless of the dead band conditions, the control function would turn off if the monitoring temperature exceeded the high limit cut-out temperature. (TRNSYS, 2006)

Type2b had six inputs and one output. The inputs included: upper input temperature (T_H), lower input temperature (T_L), monitoring temperature, input control function (y_i), upper dead band (ΔT_H), and lower dead band (ΔT_L). The output was simply the control function (y_o).

3.4.1.12 TRNSYS/EXCEL COUPLING

The Type62 TRNSYS/Excel coupling component was used to create the complex controller for the Solar-side i-HPASDHW system. This component implemented a link with Excel through a Component Object Model (COM) interface with the FORTRAN routine for fast data transfer. The user defined specific cells as inputs and outputs in the Excel worksheet that was linked to the TRNSYS model. The various inputs selected from TRNSYS were sent to the specified cells and were used to determine the outputs based on functions inputted by the user. The calculated outputs in the Excel file became the outputs of Type62 that were utilized in the TRNSYS model. (TRNSYS, 2006)

The number of inputs and outputs required were specified in the parameters tab of the display menu. (TRNSYS, 2006) User-specified names were also given to the inputs and outputs in order to avoid confusion when connecting Type62 to the model. Details on the complex controller created with the Type62 TRNSYS/Excel coupling component for the Solar-side i-HPASDHW system will be presented in the following section of this chapter.

3.4.1.13 ONLINE GRAPHICAL PLOTTER

The online graphical plotter, Type65d, was “used to display selected system variables while the simulation was progressing” (TRNSYS, 2006). It was a very useful tool because it provided immediate graphical results that allowed the user to determine if the system was performing as expected. Once the simulation process began, the specified variables connected to Type65d were displayed in a separate plot window on the screen. When the simulation was complete, the user was able to further analyze the results by adjusting the graphics of the plot. For

example, a zoom tool was available to get a closer look at the simulation results for a select portion of the total time period.

In the parameters of Type65d, the user specified the number of variables that were of interest to plot and defined the left and right axis of the graph. The number of variables specified by the user determined the number of inputs available for the online plotter. These inputs were labeled in the display menu of Type65d to produce a colour coordinated legend and graph to differentiate between the various outputs in the plot. Once the desired input parameters for the online plotter were set, the variables of interest from the system were simply connected to their corresponding inputs in Type65d.

3.4.1.14 PRINTER

The Type25c printer was another useful tool for analyzing the simulation results. This component was used to output selected system variables at every time step to an Excel file that could be opened for analysis after the simulation was complete. Type25c was the main component used for extracting the detailed simulation results of the system.

As with the online graphical plotter, the user specified the number of variables to output to the Excel file. This created the correct amount of inputs for the printer and each input was labeled in the display menu of Type25c. The labels appeared at the top of each column in the output Excel file so the user could distinguish the results.

3.4.1.15 QUANTITY INTEGRATOR

The Type24 quantity integrator was a very useful tool in combination with the Type25c printer. It integrated a series of quantities over the entire simulation period using Equation 3.3, and the output results were then inputted into the Type25c printer for analysis.

$$Y_i = \int_0^{t_i} X_i dt \quad (3.3)$$

Therefore, the value in the Excel output file at each time step corresponded to the total integrated value (Y_i) up to that point rather than just the value of the variable (X_i) at that time step. This was useful in determining the overall energy quantities because the energy outputs from the various components (X_i) were in kJ/hr. When the Type24 quantity integrator was used in conjunction with the printer, the energy variables were displayed in the Excel output file in terms of total energy (kJ) up to that time step. Therefore, the last value in the column of an integrated energy variable gave the total amount of energy for the entire simulation period. This value was very useful for in-depth analysis of the performance of each system.

Again, the user specified the number of inputs required for the quantity integrator and an equal amount of outputs were created. Each integrated variable was labeled in the Type24 display menu to eliminate confusion when connecting the quantity integrator with the printer.

3.5 TRNSYS MODELS

Many common settings in TRNSYS were used for all of the systems. This allowed the performances of the two i-HPASDHW configurations to be evaluated and compared to each other and to the two base systems. All four systems considered were simulated for an 8760 hour time period in order to observe the performances over an entire year of operation. The time step was set to 0.015 hours (just under 1 minute) for all simulations to ensure accurate results. All systems were targeted to provide water at 55°C from the domestic tank for the four fifteen-minute draws daily at the times mentioned in the previous section. The domestic tanks were 350 L and 1.2 m tall and were split up into ten equal nodes to promote stratification.

It should be noted that none of the systems were optimized but consistency was maintained between each configuration, as mentioned above, to assure that their performances could be compared to one another. With each system there were numerous variables and components that could have been

adjusted and tested in order to optimize the designs, but that was not the scope of this research. It was desired to determine the feasibility of the two i-HPASDHW systems compared to the two base models under the same load conditions. In real applications of solar and heat pump assisted systems, the performance would vary greatly from case to case depending on numerous variables such as water draw profiles, size of the system, location, weather conditions, and many more. Therefore it was not practical to optimize each system under the chosen conditions, but rather keep consistency wherever possible for reasonable comparisons between the systems.

In order to help explain each system, for the TRNSYS layouts shown in this section, the solid lines represented the various paths for fluid flow and the dotted lines were used for all other necessary connections. For example, the dotted lines were used to connect the main system components to the printer and online plotter.

3.5.1 ELECTRIC DHW SYSTEM

The base electric DHW system was constructed with the following components: a domestic water tank (Type4c), the time dependant forcing function for the water draws (Type14b), a tempering valve (Type11b), a tee piece (Type11h), and an external auxiliary top-up heater (Type6). The electric DHW system layout in TRNSYS is shown in Figure 3.12. The other components in Figure 3.12 were for logging and displaying simulation results in order to analyze the performance of the system (Type24, Type25c, and Type65d).

The base electric DHW system used two 2 kW auxiliary heaters in the domestic water tank to provide all of the energy needed to meet the load requirements. The upper auxiliary heater (master) and its thermostat were located in the second node of the tank. This heater had a set point temperature of 55°C and a dead-band temperature of 5°C. The lower auxiliary heater (slave) and its thermostat were located in the eighth node of the tank and had set point and dead-band temperatures of 30°C and 5°C respectively. The master heater

would turn on when the water temperature at the second node fell to 50°C or below and would remain on until the temperature reached 55°C. The bottom heater worked in a similar fashion but was only allowed to operate when the condition of the master heater was satisfied.

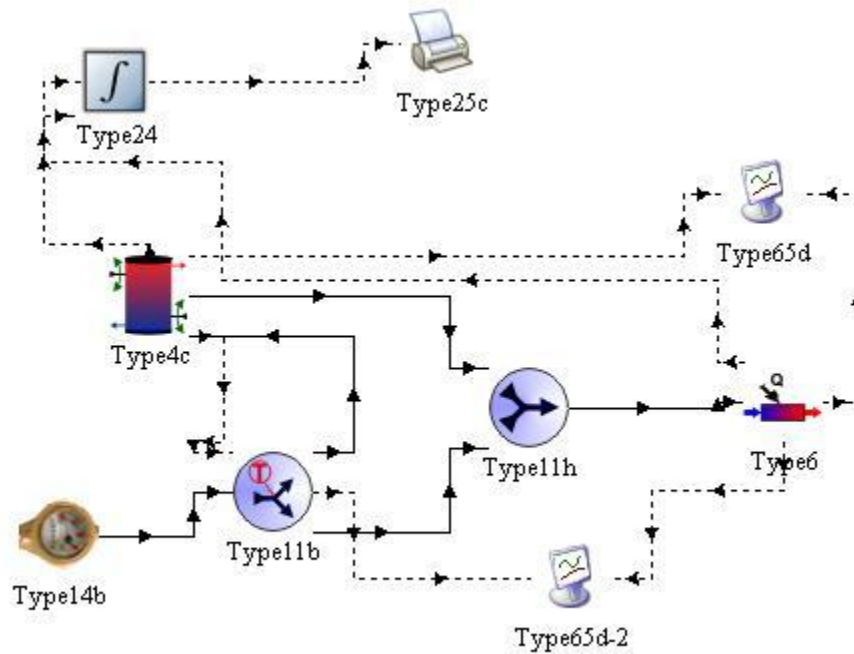


FIGURE 3.12 - ELECTRIC DHW SYSTEM LAYOUT IN TRNSYS

3.5.2 TRADITIONAL SDHW SYSTEM

The traditional SDHW system was created in TRNSYS by adding a solar loop to the electric DHW system configuration. In addition to the electric DHW model, this system required a flat plate collector (Type1b), two circulating pumps (Type3b), a heat exchanger (Type5b), a differential controller (Type2b), and the data reader (Type109-TMY2). Recall that a glycol-water mixture was circulated through the collector loop. The TRNSYS model of this system is shown in Figure 3.13.

Unlike the electric DHW system, the temperatures in the domestic tank were allowed to get much higher than the required delivery temperature of 55°C. If there was solar energy to collect, it made sense to take advantage of the

available energy and store it in the domestic water tank. This thermal storage would allow the tank to meet higher load demands during times when there was no solar energy available to recharge the tank, and greatly reduce the usage of the electric backup heaters. Therefore, it was expected that the tempering valve would be used often in this case, especially in the summer months. Due to the assistance from the collected solar energy, the set point temperatures for the upper and lower auxiliary heaters in the domestic tank were dropped to 50°C and 25°C, respectively. The two heaters were still located at nodes two and eight.

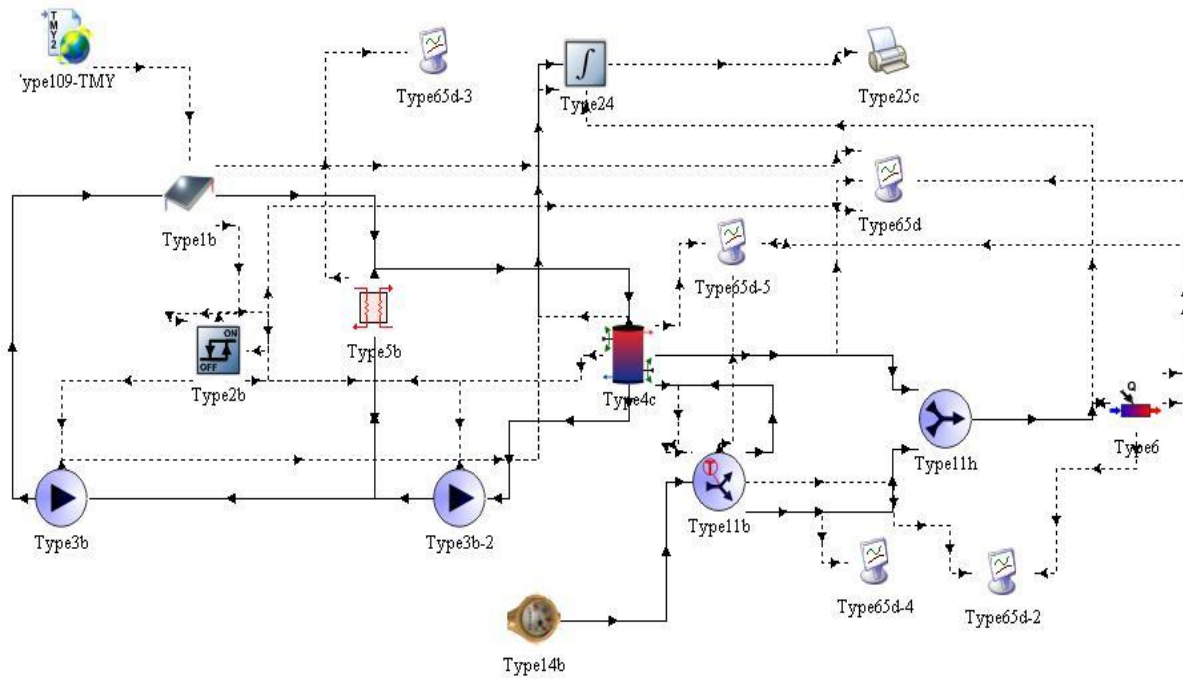


FIGURE 3.13 - TRADITIONAL SDHW SYSTEM LAYOUT IN TRNSYS

System controls had to be implemented to ensure that the solar loop was running only when there was sufficient energy to be collected. This was done in TRNSYS using the Type2b differential controller. It monitored the temperature of the cold water at the bottom of the domestic tank (T_L) and the outlet temperature of the solar collector (T_H) to determine if there was energy to be collected. If the temperature of the glycol-water mixture at the collector outlet was 5°C (ΔT_H) or more above the temperature of the water at the bottom of the

tank, then the pumps were turned on to collect this solar energy. The system would continue to operate until this temperature difference fell below 2°C (ΔT_L). The controller also monitored the temperature of the water at the top of the tank to ensure that it did not get too hot by using a high temperature cut-off of 90°C . If this temperature was reached during operation, the pumps would stop so that the water in the domestic tank did not boil.

3.5.3 DUAL TANK I-HPASDHW SYSTEM

The Dual tank i-HPASDHW system in TRNSYS was built on the traditional SDHW system discussed above by adding a second tank (Type4c), a water-to-water heat pump (Type668), and another differential controller (Type2b). The TRNSYS model is shown in Figure 3.14.

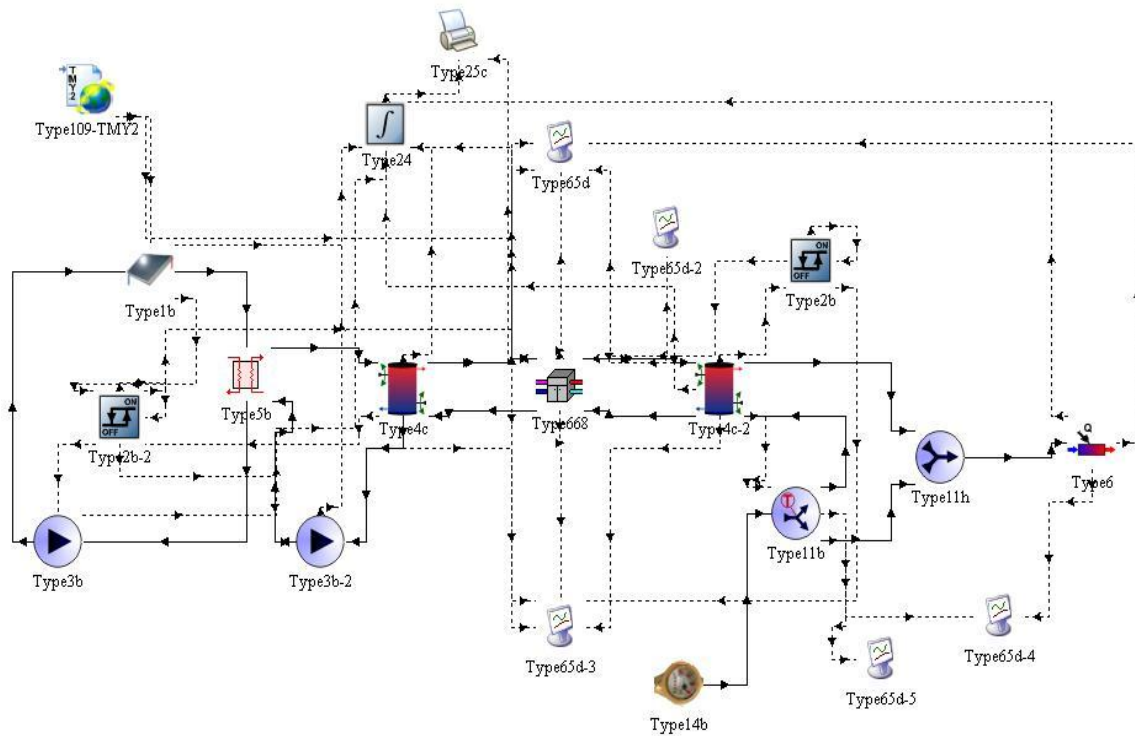


FIGURE 3.14 - DUAL TANK I-HPASDHW SYSTEM LAYOUT IN TRNSYS

The Dual tank i-HPASDHW system was intended to operate in the following way. The collector side operated in a similar manner as the traditional SDHW system. However, the storage tank was determined to need relatively

large thermal capacity, and was therefore sized to contain 500 L of collector fluid. This tank was called the float tank because its temperature was allowed to fluctuate. The entire tank was assumed to contain the 50%-50% glycol-water mixture. The domestic water side was designed to operate in much the same way as the electric DHW system. In this case, however, when the domestic tank needed heat input, the energy was supplied from the float tank using either the heat pump or heat exchanger by-pass loop instead of auxiliary heaters in the tank.

Both tanks in the system contained two 2 kW auxiliary heaters. The upper and lower auxiliary heaters in the float tank used set point temperatures of -5°C and -10°C , respectively, with a 5°C dead-band. The reason that the float tank was allowed to fall below 0°C was because the fluid in the tank was assumed to be the same glycol-water antifreeze mixture that was circulated through the collector loop. The heaters in the domestic tank had set point temperatures of 45°C and 15°C and both used a 5°C dead-band.

As mentioned in the previous section, the Type668 heat pump required an external file to determine the power consumption and energy transfer characteristics of the heat pump based on the inlet load and inlet source temperatures. The profile created for this system used three inlet load temperatures and seven inlet source temperatures to generate a table that specified the heat pump characteristics for all combinations of these temperatures. The three inlet load temperatures (from domestic tank) were 10°C , 35°C , and 55°C and the seven inlet source temperatures (from float tank) were -10°C , 10°C , 30°C , 50°C , 55°C , 55.1°C , and 70°C . The external file can be found in the Appendix A.

When the temperature at the top of the float tank was above 55°C , only a heat exchanger was necessary to transfer energy to the domestic tank. This heat exchanger by-pass loop was shown in the schematic in Figure 3.3. However, in the TRNSYS model the heat exchanger by-pass loop was simulated by hard-coding it into the external heat pump file. The 55°C and 55.1°C inlet source

temperatures (from the float tank) used in creating the external file modeled the switch-over from the heat pump to the heat exchanger and vice-versa. Therefore, heat pump characteristics were used for the inlet source temperatures of 55°C and below and heat exchanger characteristics for the inlet source temperatures of 55.1°C and above. A plot is shown in Figure 3.15 for the inlet load temperature of 10°C that gives the power consumption and energy transfer rates used in the external file at the various inlet source temperatures. Notice the switch-over at the 55°C source temperature. The power consumption was decreased for the heat exchanger by-pass loop because only pump power was required for transferring the energy, whereas the heat pump required more power to operate the compressor. However, the greatest change for the heat exchanger was in the energy transfer rate because the benefits of the heat pump were no longer present. The other two load temperatures (35°C and 55°C) that were used to generate the external file had similar output characteristic profiles as seen in Figure 3.15. It should be noted that the output characteristics used were preliminary values and were not based on a specific heat pump or heat exchanger. The purpose was to attempt to model a variable capacity heat pump that used scroll compressor technology to increase the efficiency of the system.

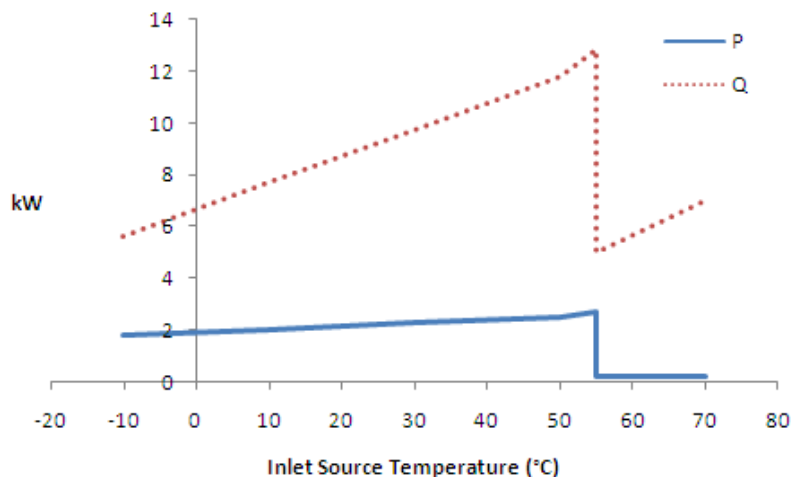


FIGURE 3.15 - DUAL TANK I-HPASDHW SYSTEM HEAT PUMP CHARACTERISTICS (FOR INLET LOAD TEMPERATURE OF 10°C)

The controls were very important to insure that the Dual tank i-HPASDHW system was running efficiently. There were two separate loops that needed to be controlled: the solar loop and the heat pump loop. The solar loop was controlled exactly the same way as in the traditional SDHW system. Therefore when the fluid temperature at the outlet of the collector was 5°C (upper dead-band) hotter than the water at the bottom of the float tank, the pumps in the solar loop were turned on. Like the traditional SDHW system, a lower dead-band temperature of 2°C was used for the controller as well. The collected solar energy was stored in the float tank. The second loop to control was the heat pump and heat exchanger by-pass, which was used to supply energy to the domestic water tank. The same type of controller was used in TRNSYS (Type2b) but was utilized in a different fashion. The temperature at the top of the domestic tank was read by the controller as the lower input temperature and the fixed set point temperature of 55°C was entered into the controller as the upper input temperature. The controller compared the temperature at the top of the domestic tank to the 55°C set point and used upper and lower dead-bands of 3°C and 0°C respectively. Therefore the heat pump turned on when the water at the top of the domestic tank fell below 52°C and stayed on until it was heated to 55°C. This tight temperature range was used to ensure that the domestic water tank was always charged and able to meet various water draws. Just like the domestic tank in the electric DHW system, the tempering valve was not used because the water was never heated above the 55°C set-point.

3.5.4 SOLAR-SIDE I-HPASDHW SYSTEM

The Solar-side i-HPASDHW system was built on the traditional SDHW system by adding a water-to-water heat pump (Type668), the Type62 TRNSYS/Excel coupling component, two controlled flow diverters (Type11f), and two tee piece valves (Type11h). The TRNSYS model is shown in Figure 3.16.

In this configuration a small capacity heat pump (Type668) was connected in parallel between the inlet and outlet of the collector in the solar loop. The system was able to operate with or without the heat pump depending on various factors. Therefore the two controlled flow diverters (Type11f) directed the flow accordingly. The two tee pieces (Type11h) were used to reconnect the fluid path through the heat pump to the main solar loop.

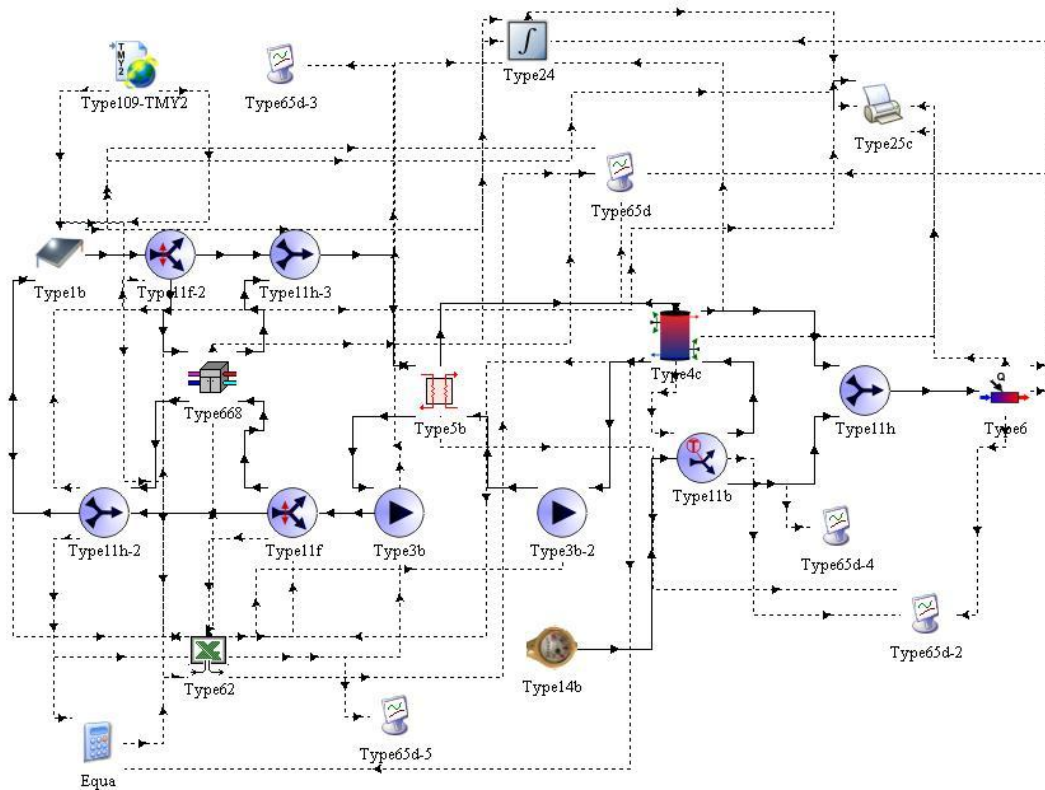


FIGURE 3.16 - SOLAR-SIDE I-HPASDHW SYSTEM LAYOUT IN TRNSYS

The upper and lower auxiliary heaters in the domestic tank had set point temperatures of 45°C and 15°C, respectively, and both used a 5°C dead-band. The two heaters were located in the same nodes.

The Type668 water-to-water heat pump required an external file, just as in the previous model, to provide the output characteristics of the heat pump. The profile created for this system used three inlet load temperatures and six inlet source temperatures. The inlet load temperatures were 10°C, 35°C and 80°C and the inlet source temperature were -10°C, 10°C, 30°C, 50°C, 60°C, and

80°C. The external file for this model contained only heat pump characteristics because there was no heat exchanger by-pass associated with the heat pump in this system. Figure 3.17 shows the power consumption (P) and the capacity (Q) of the heat pump for an inlet load temperature of 10°C. The external file can be found in Appendix A.

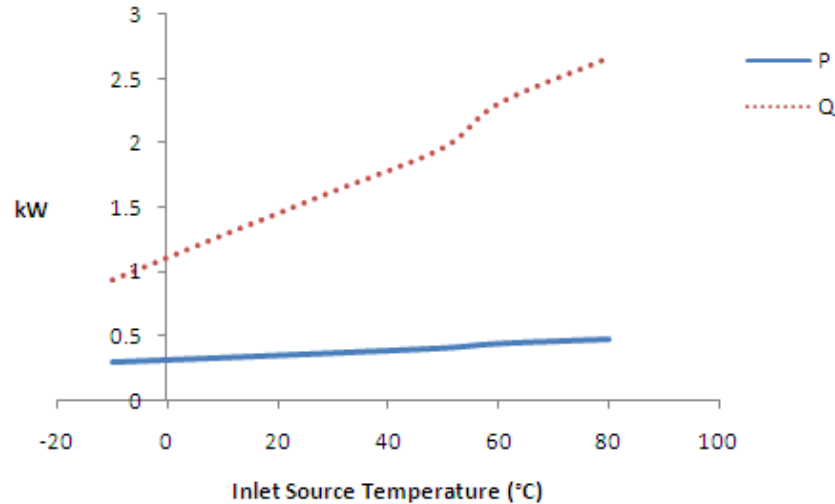


FIGURE 3.17 - SOLAR-SIDE I-HPASDHW SYSTEM HEAT PUMP CHARACTERISTICS (FOR INLET LOAD TEMPERATURE OF 10°C)

The controls for this model were very complex due to the many changing factors that influenced the system. In order to run efficiently, the controller had to determine when to operate the system with and without assistance from the heat pump. Therefore the simple temperature differential controller used in the other two solar assisted models was not sufficient in this case because it did not consider enough factors. A complex controller was created in an Excel spreadsheet and then linked to the model using the TRNSYS/Excel coupling component (Type62). Numerous inputs from the model were inserted into the spread sheet throughout the simulation and a variety of calculations and checks were performed to analyze the current state of the system and the environmental conditions. The controller then decided if the solar loop should be operating and if assistance from the heat pump was desired by providing control

signal outputs to the relevant components in the model. The Excel controller consisted of eight inputs and two outputs. The inputs are presented in Table 3.2.

TABLE 3.2 - EXCEL CONTROLLER INPUTS

INPUT	Description
Input 1	Simulation time (hrs)
Input 2	Outlet fluid temperature of collector
Input 3	Bottom tank temperature
Input 4	Outlet fluid temperature of 1 st flow diverter
Input 5	Rate of energy transfer from source in heat pump
Input 6	Solar flux on collector surface
Input 7	Top tank temperature
Input 8	Inlet fluid temperature of collector

The two outputs determined in the spreadsheet were used to control the solar loop and the heat pump in the system. *Output1* was the control signal for the two circulating pumps (CS_{PUMP}) and *Output2* was the control signal for the heat pump and the two flow diverters (CS_{HP+DIV}). Both outputs were determined in the Excel spreadsheet based on answers calculated for four specific questions. Each question was answered with either yes (1) or no (0) at each time step based on one or multiple checks. With the answers to the four questions, overall checks were performed in the Excel spreadsheet to determine the two outputs which controlled the solar loop. The four questions in the spreadsheet are presented and discussed below.

Question 1: Is the top of the tank temperature below the 80°C high limit cut-off?

The first question was used to ensure that the water in the domestic tank did not reach the boiling temperature. This was a safety feature and if ever the water did reach this point, the entire solar collection portion of the system would

shut down. The answer to Question 1, CS1 (control signal 1), was determined by using Equation 3.4 in Excel.

$$CS1 = IF(Input7 > 80, 0, 1) \quad (3.4)$$

Therefore Excel compared the temperature of the water at the top of the domestic tank to the 80°C cut-off and determined the value of CS1 to be either 0 or 1. Again, if CS1 was equal to 0 the entire solar loop was shut down.

Question 2: Is there enough energy to collect without assistance from the heat pump?

This portion of the controller closely resembled the function of the standard differential controller. It compared the temperature of the fluid at the outlet of the collector to the temperature of the water at the bottom of the tank. However, if the system was currently running with assistance from the heat pump, the outlet temperature of the collector would be lower than if it was running without the heat pump. This was due to the fact that the heat pump lowered the fluid temperature before it entered the collector. Therefore, a theoretical outlet collector temperature was calculated using Equation 3.5 to be used when the heat pump was on.

$$T_{c,o}^* = \frac{\dot{Q}_s A_c}{\dot{m} c_p} + T_{t,b} \quad (3.5)$$

Equation 3.6 was used to determine the temperature difference in the spreadsheet. Notice that if the heat pump was on (Output2 = 1), Excel used the theoretical collector outlet temperature to calculate the difference instead of the input value from TRNSYS.

$$T_{c,o} - T_{t,b} = IF(Output2 = 1, T_{c,o}^*, Input2) - Input3 \quad (3.6)$$

Just as with the differential controller, this temperature difference was compared to an upper dead-band of 5°C when the solar loop was off and to a lower dead-band of 2°C when it was on. Equation 3.7 was used in Excel to answer Question 2, CS2.

$$CS2 = IF([T_{c,o} - T_{t,b}] > IF(Output1 = 0, 5, 2), 1, 0) \quad (3.7)$$

Notice how the two temperature dead-bands were incorporated into the equation and the one that was used depended on *Output1*. If CS2 was equal to 1, the system was able to collect solar energy without assistance from the heat pump.

Question 3: Is there energy to collect with assistance from the heat pump?

It is important to note that whenever the system was able to collect solar energy without the heat pump, it was also able to do so with the heat pump. However, there could be times when the system would only collect energy with assistance from the heat pump.

In order to determine if the system could operate with the heat pump, the controller looked at the difference between the collector inlet and outlet temperatures. When the heat pump was not on, the controller assumed that the heat pump would remove approximately 400 W (1500 kJ/hr) of energy from the inlet source fluid in order to estimate the inlet collector temperature using Equation 3.8.

$$T_{c,i}^* = T_{t,b} - \frac{\dot{Q}_{HP,source}}{\dot{m}c_p} \quad (3.8)$$

The energy removal specified was a conservative number that assumed the heat pump would send fluid to the collector approximately 4.5°C colder than the temperature of the water at the bottom of the tank. This simplification was made because the heat pump model did not provide output information unless it

was on. Therefore this assumption was only used until the heat pump turned on in order to predict its benefits. Once it was running, the controller looked at the actual inlet collector temperature that was supplied by the heat pump in TRNSYS.

Equation 3.9 was used to calculate the difference between the collector inlet and outlet temperatures in the Excel spreadsheet for Question 3.

$$T_{c,o} - T_{c,i} = Input2 - IF(Output2 = 0, T_{c,i}^*, Input8) \quad (3.9)$$

The controller then looked at the calculated temperature difference found using Equation 3.9 to determine the answer to Question 3, CS3. Again, upper and lower dead-band temperatures of 5°C and 2°C, respectively, were used to calculate CS3 in Equation 3.10.

$$CS3 = IF([T_{c,o} - T_{c,i}] > IF(Output1 = 0, 5, 2), 1, 0) \quad (3.10)$$

If CS3 was equal to 1 then the system was able to collect solar energy with assistance from the heat pump.

Question 4: Should the heat pump be on?

The controller had to decide if the heat pump should be on or off in the cases when the system could operate with or without the heat pump. This was the tricky part of the controller because there were so many variables that could have been considered. It was decided to look at three specific factors in order to determine the answer for Question 4, CS4. Each factor produced its own control signal value of '1' when it desired the heat pump to be on and '0' when it desired it to be off.

The first factor considered was the solar flux on the collector surface. If this flux was below the low threshold value of 300 W/m², it was assumed to be beneficial for the system to operate with the heat pump in order to send colder

fluid to the collector. This would allow the system to collect more solar energy. Equation 3.11 was used in Excel to determine the control signal for factor one, CS4_A. The reason that Input6 was divided by 3600 was to convert it from kJ/hr to kW.

$$CS4_A = IF\left(\frac{Input6}{3600} < 0.3, 1, 0\right) \quad (3.11)$$

Factor two was based on the time of day at the current time step. The draw profile assumed that there were no water draws from 8:15 a.m. until 8:00 p.m. Therefore, there was no hurry to charge the tank and thus, no need to operate the system with the heat pump between the prime collection hours of 9:00 a.m. and 4:00 p.m. However, outside of this specific time period the heat pump was desired in order to gain more energy in the morning and charge the tank further in the afternoon before the sun went down. The time of day, in hours, was calculated using Equation 3.12.

$$Time\ of\ day = \left[\left(\frac{Input1}{24} \right) - INT\left(\frac{Input1}{24} \right) \right] \times 24 \quad (3.12)$$

The 'INT' function in Excel rounded the number down to the nearest integer so that the solution in the square brackets varied from 0 to 1 to represent a day. Therefore when multiplied by 24 (hours/day), the hour of the day was given. Using the time of day, Equation 3.13 was used in Excel to determine the control signal for the second factor, CS4_B.

$$CS4_B = IF[OR(Time\ of\ day < 9, Time\ of\ day > 16), 1, 0] \quad (3.13)$$

The third and final factor considered for Question 4 was the temperature of the water at the top of the domestic tank. When this temperature was above 50°C, the water was nearly at the required delivery temperature of 55°C and it was decided that assistance from the heat pump was not desired. Therefore, the

control signal for factor three, CS4_C, was determined using Equation 3.14 in Excel.

$$CS4_C = IF(Input7 < 50, 1, 0) \quad (3.14)$$

The controller then looked at all three of the calculated control signals found for Question 4 and had to decide on the overall answer, CS4, at each time step. In order to do this, every possible combination of the control signals generated for the three factors were considered. For each combination, the desired overall answer for CS4 was decided and is shown in Table 3.3.

TABLE 3.3 - EXCEL CONTROLLER QUESTION 4 DECISION MATRIX

Case	Solar Flux	Time of Day	Tank Temp.	Overall (CS4)
1	1	1	1	1
2	1	1	0	0
3	1	0	1	1
4	1	0	0	0
5	0	1	1	1
6	0	1	0	0
7	0	0	1	0
8	0	0	0	0

There were three combinations that desired the heat pump to be on and gave an overall control signal of ‘1’ for Question 4. The three combinations included:

1. When all three factors desired the heat pump to be on. (CS4_A = 1, CS4_B = 1, CS4_C = 1)
2. When the solar flux was below the minimum threshold value and the top tank temperature was below 50°C. (CS4_A = 1, CS4_B = 0, CS4_C = 1)
3. When the time of day was before 9:00 a.m. or after 4:00 p.m. and the temperature in the tank was lower than 50°C. (CS4_A = 0, CS4_B = 1, CS4_C = 1)

These three cases were implemented into the Excel controller using Equation 3.15 to give the overall control signal for Question 4, CS4.

$$CS4 = IF[OR[AND(CS4_A = 1, CS4_B = 1, CS4_C = 1), AND(CS4_A = 1, CS4_B = 0, CS4_C = 1), AND(CS4_A = 0, CS4_B = 1, CS4_C = 1)], 1, 0] \quad (3.15)$$

Equation 3.15 simply provided a value of '1' for CS4 whenever any of the three specified combinations of the factors occurred. A value of '0' was given for all of the other situations.

The final step of the Excel controller was to calculate the two actual outputs to be used in the TRNSYS model based on the answers to the four questions. The first output was the control signal for the two circulating pumps, CS_{PUMP}. Whenever the water at the top of the tank was below the high limit cut-off temperature and the system was able to collect solar energy (with or without the heat pump), the pump control signal was set to '1' in order to operate the solar loop. This was implemented in the Excel controller using Equation 3.16.

$$CS_{PUMP} = IF[AND(CS1 = 1, CS3 = 1), 1, 0] \quad (3.16)$$

The reason that CS3 was used in the equation instead of CS2 was because the pumps also operated when the system was running with assistance from the heat pump. As mentioned before, whenever the system was able to collect solar energy without the heat pump, it could also do so with the heat pump. Therefore using CS3 here ensured that the circulating pumps were on for both cases.

The second output of the Excel controller was the control signal for the heat pump and the two flow diverters, CS_{HP+DIV}. Whenever the heat pump was required, this output would become '1' in order to turn the heat pump on and to direct the fluid through the diverters to the heat pump. There were two cases when the heat pump would be operating. The first was if the system could only collect solar energy with assistance from the heat pump. The second was in

situations when the solar loop could operate with or without assistance from the heat pump, and the answer to Question 4 indicated that the heat pump was desired. These two circumstances were implemented into the second output, CS_{HP+DIV} , in the Excel controller using Equation 3.17.

$$CS_{HP+DIV} = IF[OR[AND(CS2 = 0, CS3 = 1), AND(CS2 = 1, CS4 = 1), 1, 0]] \quad (3.17)$$

The second output, CS_{HP+DIV} , could not be on unless the first output was also on because the heat pump required the pumps for circulating the fluid through the solar loop. However, the first output, CS_{PUMP} , would be on without the second output whenever the system was collecting solar energy without assistance from the heat pump.

These calculations performed in Excel required an iterative approach in order to solve the equations provided. This was allowed by selecting ‘enable iterative calculations’ in the formula tab found in ‘Excel Options’ for the controller.

There were many different options for creating the complex controller for this system. It was believed that the strategies used here produced a reliable controller that performed as anticipated. When the simulations were run, the Excel controller was visible and was monitored to ensure the functions were operating as expected. More discussion and proof of the functionality of the controller will be presented in the next chapter.

Chapter 4

RESULTS AND DISCUSSION

The performance of each system is presented and analyzed in this chapter. First, the simulation results and performance validation for each system are presented along with the overall energy balance of the systems. The second section compares and contrasts the two i-HPASDHW systems to the two base systems to investigate the benefits of including a heat pump in the design. The third part of this chapter examines the performance and functionality of the two i-HPASDHW systems compared to one another. In each of these three sections, the basis of comparison will be typical operating days as well as overall annual energy quantities. The overall energy consumptions and estimated annual operational costs of each system are presented in the fourth section.

The typical operating days considered in the analysis included a sunny February day, a cloudy March day, a sunny July day, and a sunny December day. The following plots show the solar irradiation and the ambient temperature profiles for each day.

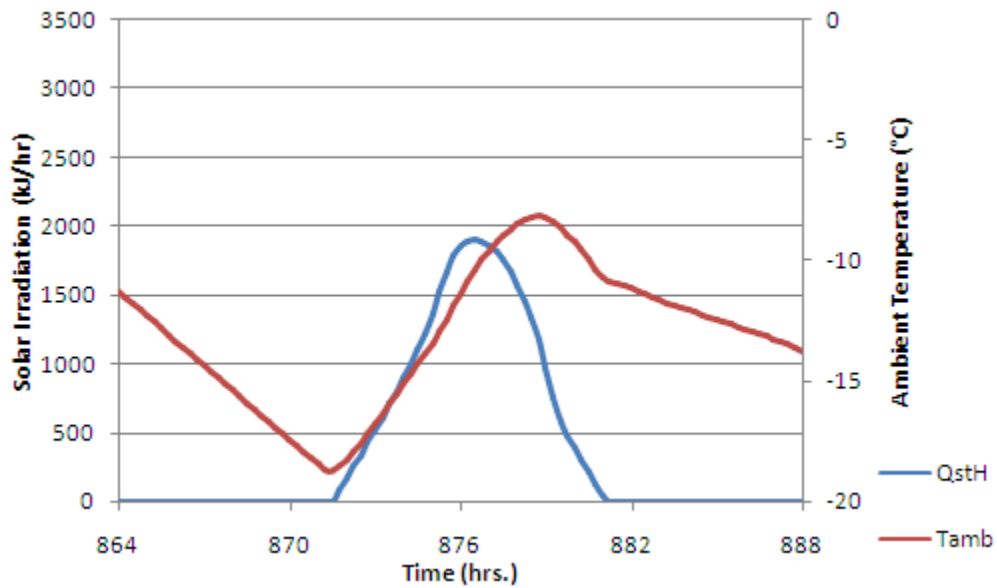


FIGURE 4.1 - SOLAR IRRADIATION AND AMBIENT TEMPERATURE FOR A TYPICAL FEBRUARY DAY

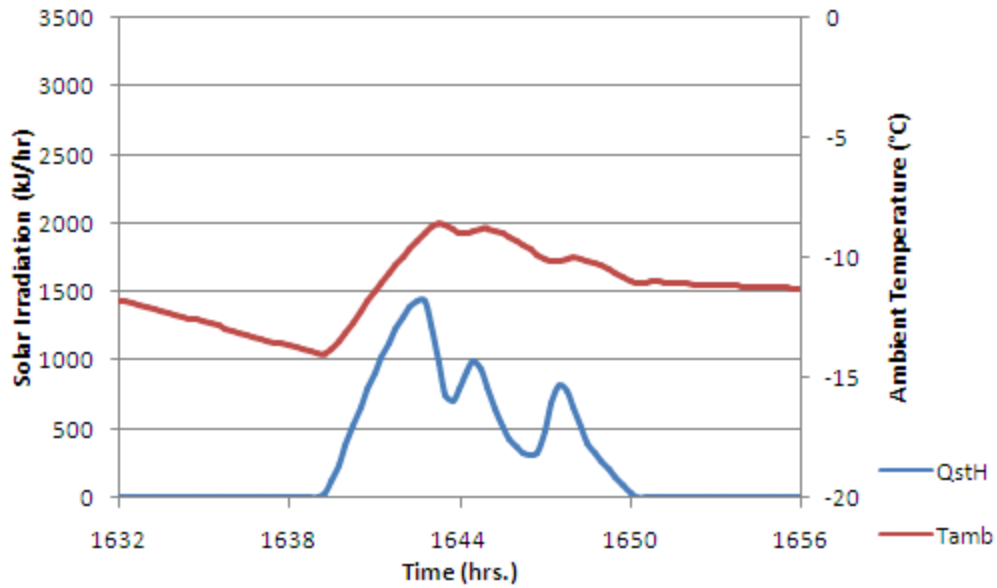


FIGURE 4.2 - SOLAR IRRADIATION AND AMBIENT TEMPERATURE FOR A CLOUDY MARCH DAY

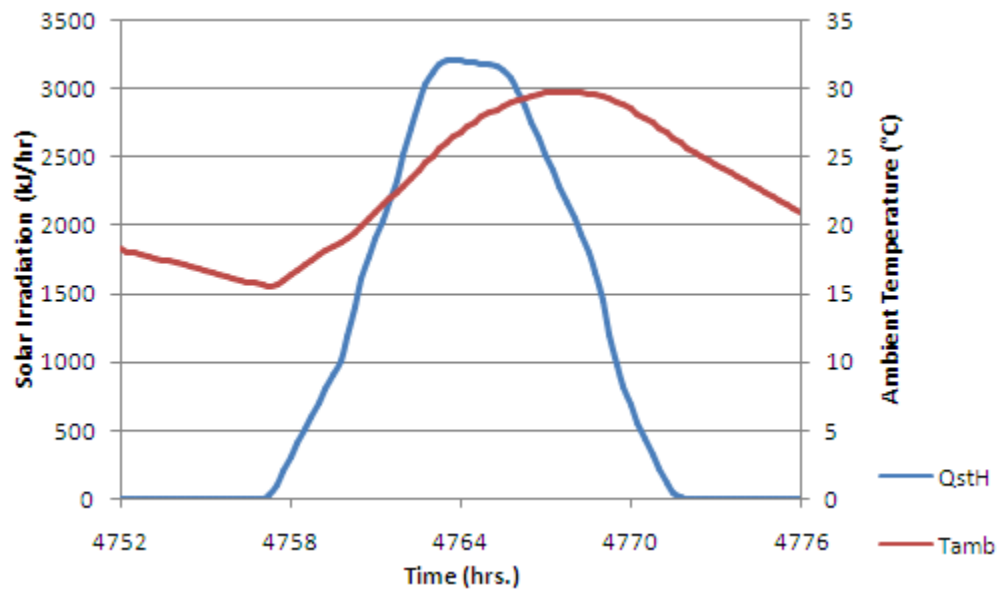


FIGURE 4.3 - SOLAR IRRADIATION AND AMBIENT TEMPERATURE FOR A TYPICAL JULY DAY

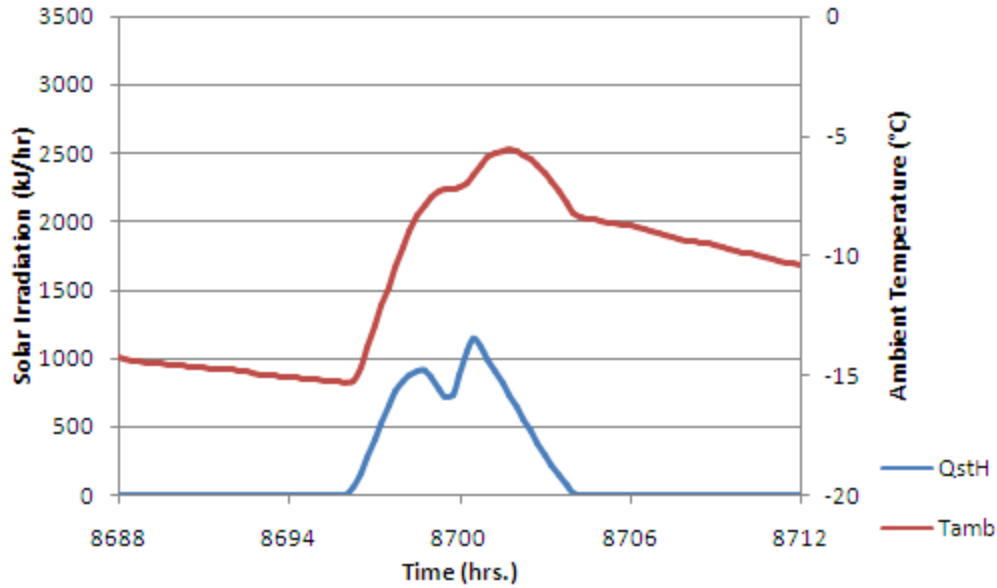


FIGURE 4.4 - SOLAR IRRADIATION AND AMBIENT TEMPERATURE FOR A TYPICAL DECEMBER DAY

4.1 SIMULATION RESULTS AND PERFORMANCE JUSTIFICATION

4.1.1 ELECTRIC DHW SYSTEM

The energy balance on the DHW system is rudimentary. The auxiliary heaters inside of the domestic tank ($Q_{AUX, TANK}$) and the top-up auxiliary heater located after the tempering valve ($Q_{AUX, TOP UP}$) supplied all of the energy to the system. The energy out of the system included the hot delivery water at 55°C (E_{LOAD}) and the losses from the tank to the surroundings ($Q_{LOSS, TANK}$). The overall energy balance of the system for the simulated year is given in Equation 4.1.

$$Q_{AUX, TANK} + Q_{AUX, TOP UP} = E_{LOAD} + Q_{LOSS, TANK} \quad (4.1)$$

This system had no connection with the outdoor environment, so the water temperatures in the domestic tank and the operation of the auxiliary heaters were very similar from day to day (see Figure 4.5). This was expected because the water draws were consistent each day and the auxiliary heaters aimed to keep the water at the top of the tank near the set point of 55°C. The

only external interaction that the system had, excluding the water draws, was losses to the surrounding room environment at 22°C. The top, middle, and bottom tank temperatures along with the control signal for the two internal auxiliary heaters are shown in Figure 4.5 for the simulated days of a typical sunny February day (top) and a typical sunny July day (bottom). For all figures shown in this chapter, a control signal of '1' means ON and '0' means OFF. It should be noted that the control signal shown in Figure 4.5 included both heaters.

The four sudden temperature drops correspond to the water draws from the domestic tank. When the top tank temperature fell below 50°C, the upper auxiliary heater turned on until the water was heated to 55°C. Once the temperature at the node with the upper heater reached the set point, the bottom slave heater turned on. This can be seen in Figure 4.5 by looking at the top and middle temperature profiles of the tank and the control signal for the auxiliary heaters. Notice that the top and middle tank temperatures both started to drop at the same time at the beginning of each water draw but the middle temperature delayed before it was heated back up to 30°C. That was because the bottom slave heater was not able to turn on until the upper heater brought the water in the top two nodes to the 55°C set point temperature. At that point, there was still a very slight delay before the middle tank temperature started to rise because the lower heater was located near the bottom of the tank. Therefore it took time for the middle node to see the effects. It is noted that the auxiliary heaters only turned on as a result of the four water draws. The auxiliary heaters operated for approximately six hours and fifty minutes throughout the course of a day.

The slow decrease in the top and middle tank temperature profiles was due to the losses to the colder surroundings. Similarly, the slight increase in the temperature at the bottom of the tank between draws was due to heat transfer from the warmer surroundings and from the water in the tank at higher temperatures.

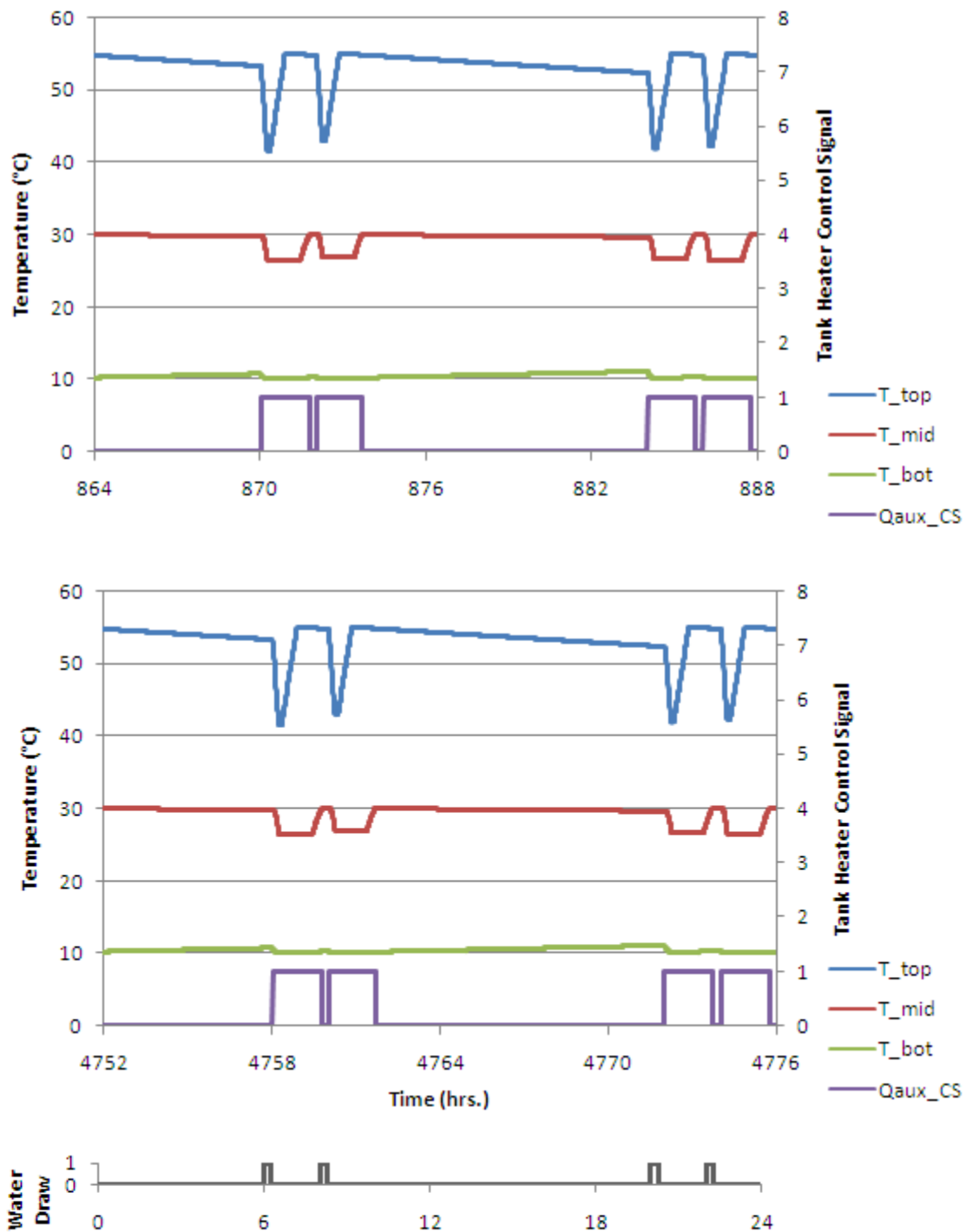


FIGURE 4.5 - ELECTRIC DHW SYSTEM OPERATION ON MARCH 1ST (TOP) AND AUGUST 1ST (BOTTOM)

From all these observations presented, the electric system ran as expected. The electrical consumption and the total losses from the tank for the system during the simulation period are presented in Table 4.1.

TABLE 4.1 - ELECTRIC DHW SYSTEM OVERALL SIMULATION RESULTS

Auxiliary Heaters	18 002 MJ
Top-up Heater	2 068 MJ
Total Electric Consumption	20 070 MJ
Total Tank Losses	621 MJ

4.1.2 TRADITIONAL SDHW SYSTEM

The energy balance of the traditional SDHW system is only a moderate increase in complexity over the electric DHW system. The addition of the solar loop to this system introduced solar energy (Q_{SOLAR}) to assist in the water heating. In order to collect the energy, electric pumps (P_{PUMP}) were required to circulate the fluid through the collector and the heat exchanger. The overall energy balance of this system for the simulated year is given in Equation 4.2.

$$Q_{AUX,TANK} + Q_{AUX,TOP\ UP} + Q_{SOLAR} + P_{PUMP} = E_{LOAD} + Q_{LOSS,TANK} \quad (4.2)$$

Unlike the electric heating system discussed previously, the conditions and performance of the traditional SDHW system were greatly influenced by the outdoor environment. With that in mind, the temperature profiles of the water in the domestic tank and the times when the auxiliary heaters and solar loop were used varied from day to day throughout the year. Figure 4.6 shows the domestic tank temperature profiles, auxiliary heaters control signal, and solar loop control signal for a typical winter day in February (top) and a typical summer day in July (bottom).

The solar loop on the typical February and July days shown ran for approximately six hours and forty-five minutes and ten hours and thirty-five minutes respectively. Therefore, the solar loop operated for almost four hours more on the July day and, as expected, the system was able to collect much more solar energy. The intensity of the solar energy was much higher on the July day

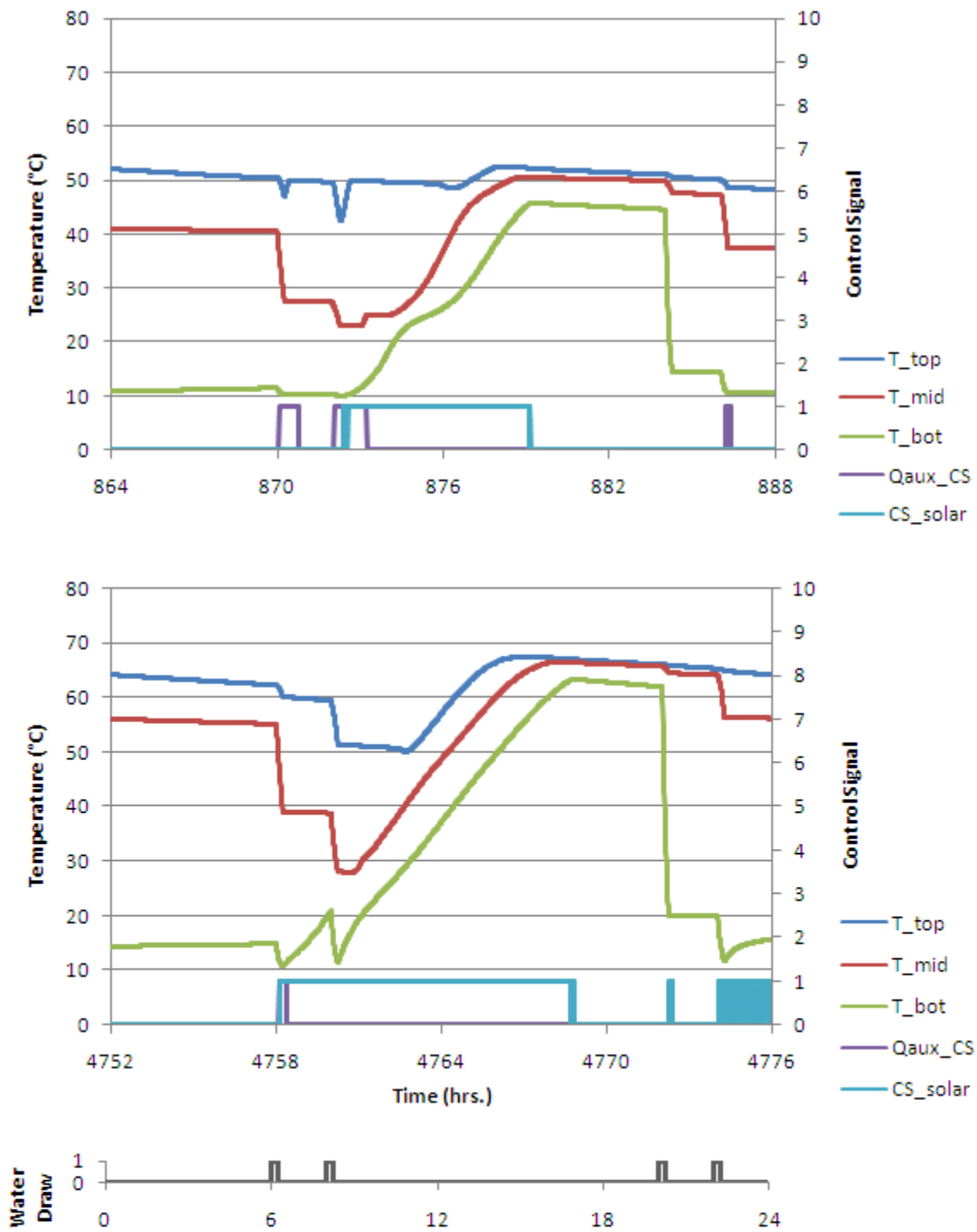


FIGURE 4.6 - TRADITIONAL SDHW SYSTEM OPERATION ON A TYPICAL FEBRUARY DAY (TOP) AND A TYPICAL JULY DAY (BOTTOM)

as well and this was reflected in the higher tank temperatures that were achieved. During operation on the February day, the temperature increase was mostly seen at the bottom and middle of the tank and only very slightly at the top of the tank. On the July day however, the top tank temperature also increased a significant amount up to approximately 68°C. In fact, the entire tank was charged to nearly 65°C at the peak. Notice that in both cases the bottom tank temperature started to increase first, followed by the middle and then lastly the top. Also, the bottom temperature was the last profile to peak during solar collection on both days. These two characteristics were due to the solar intensity profile of a typical day. The intensity started off low in the morning, peaked at solar noon, and then lowered again throughout the afternoon. Therefore, at the start and end of the solar collection period, the fluid was not being heated as much and thus helped to charge the bottom and middle portions of the tank. Recall that a variable inlet valve was used to return the water from the solar loop to the appropriate temperature node in order to keep the tank stratified.

Because of the large amount of solar energy collected on the typical July day, the auxiliary heaters inside of the tanks were not used nearly as often when compared to the cold winter day in February. In fact, the upper auxiliary heater was not used at all during the July day because the top tank temperature never fell below the 45°C dead-band limit. However, the lower slave auxiliary heater turned on once for only approximately fifteen minutes just after the 6:00 a.m. water draw. At this time, the solar loop also began to collect energy to assist in heating the domestic water (see Figure 4.6). The auxiliary heaters were not used again for the entire day and the top tank temperature was still at approximately 65°C at the end of the day from the collected solar energy. On the typical February day, the auxiliary heaters were used for about two hours in total. During this time, the upper auxiliary heater was only used for approximately thirty minutes just after the 8:00 a.m. water draw. The top tank temperature fell below the 45°C dead-band limit and the upper heater was used to bring this

temperature back to the 50°C set point. The lower auxiliary heater was used for the rest of the operation times because the top tank temperature did not drop below 45°C again.

The addition of the solar loop greatly reduced the reliance on the auxiliary heaters inside of the domestic tank, as shown in the two examples in Figure 4.6. Even on the cold winter day in February, the auxiliary heaters were only used for roughly two hours compared to almost seven hours with the electric DHW system. Approximately 58% (solar fraction) of the total energy into the traditional SDHW system during the simulated year was supplied by the collected solar energy. The solar fraction was determined using Equation 4.3. This value will be used for comparison and for assisting in evaluating the performance of each solar assisted system.

$$SF = \frac{Q_{coll}}{Q_{coll} + E_T} \quad (4.3)$$

From all of the observations presented, the traditional SDHW system ran as expected. The overall electrical consumption, useful solar energy collected, solar fraction, and tank losses for the entire simulation period are given in Table 4.2.

TABLE 4.2 - TRADITIONAL SDHW SYSTEM OVERALL SIMULATION RESULTS

Auxiliary Heaters	6 696 MJ
Top-up Heater	1 838 MJ
Pumps	181 MJ
Total Electric Consumption (E_T)	8 714 MJ
Solar Energy Collected (Q_{coll})	12 077 MJ
Total Tank Losses (Q_{loss})	1 186 MJ
Solar Fraction (SF)	0.58

4.1.3 DUAL TANK I-HPASDHW SYSTEM

Introducing a second tank and a heat pump (P_{HP}) into the system created more electric load sources and an additional tank that will have losses to the environment. The energy balance of the Dual tank i-HPASDHW system for the simulated year is given in Equation 4.4.

$$Q_{AUX,TANK1} + Q_{AUX,TANK2} + Q_{AUX,TOPIUP} + Q_{SOLAR} + P_{PUMP} + P_{HP} = E_{LOAD} + Q_{LOSS,TANK1} + Q_{LOSS,TANK2} \quad (4.4)$$

Just like the traditional SDHW system, the outdoor environmental conditions greatly influenced the performance and state of the Dual tank i-HPASDHW system. Figure 4.7 shows the tank temperature profiles and control signals for the solar loop (CS_solar) and heat pump (CS_HP) for the same typical February (top) and July (bottom) days. The three temperature profiles marked as 'Tf' were for the float tank and the one marked 'Td' was for the domestic tank.

The effects of the outdoor weather conditions can be observed in Figure 4.7. The operation time of the solar loop for the February and July days were seven hours and seven minutes and ten hours and nine minutes, respectively. Again as expected, the solar collection time was longer during the July day due to longer exposure time to the solar radiation. Also, as mentioned, the intensity of the solar radiation was higher in the summer months, which was reflected by the higher float tank temperatures achieved. On both days the collected solar energy caused the entire float tank temperature profiles to start increasing approximately at the same time. This was due to the fact that when the system began collecting energy, all of the fluid in the tank was roughly within 5°C. However, during the solar collection period the top tank temperature profile in the float tank peaked first, followed by the middle and then lastly the bottom on both days. Just as with the traditional SDHW system, this was due to the solar intensity profile experienced on a typical day. The lower solar intensities later in

the day were able to help further charge the middle and bottom portions of the stratified float tank.

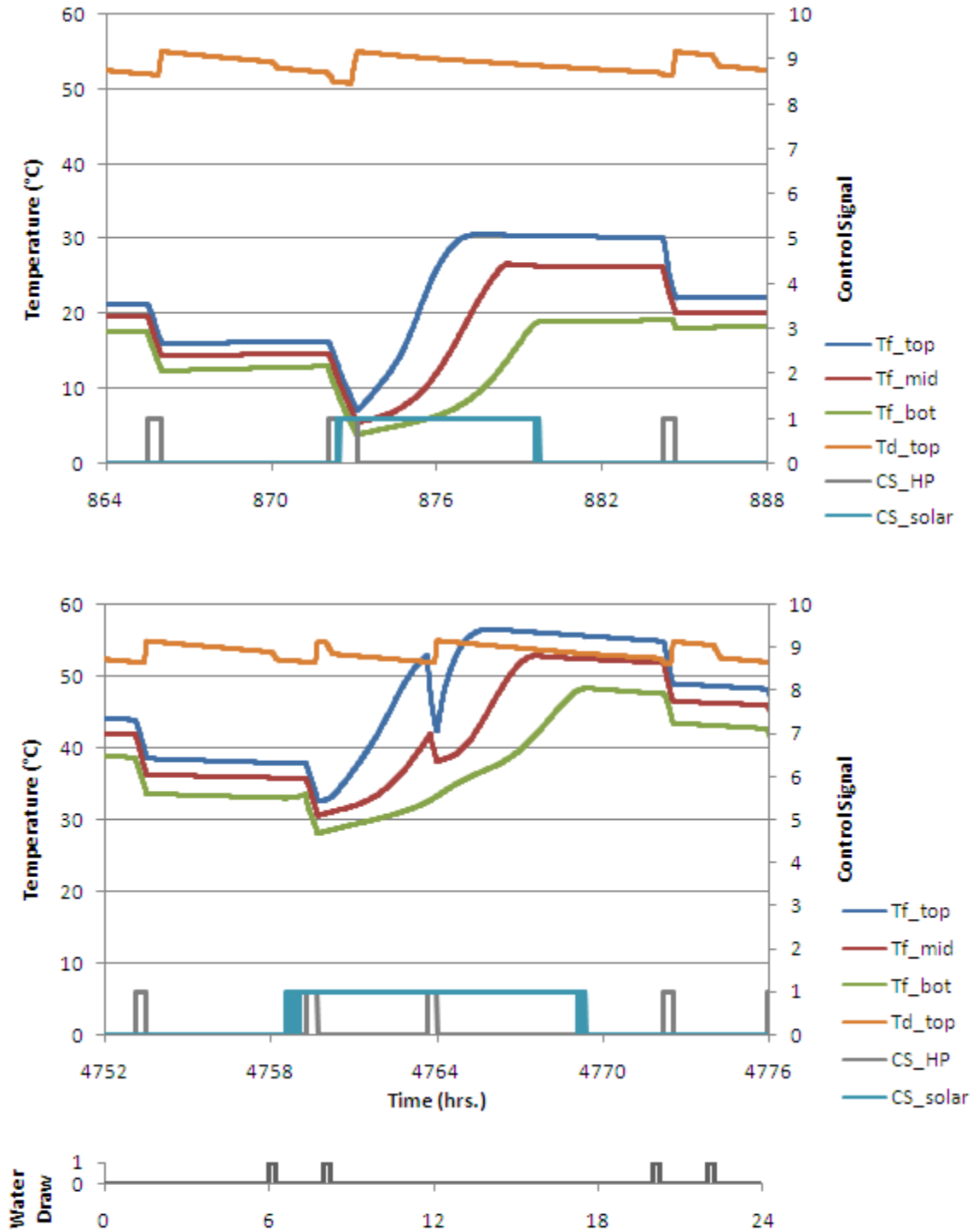


FIGURE 4.7 - DUAL TANK I-HPASDHW SYSTEM OPERATION ON A TYPICAL FEBRUARY DAY (TOP) AND A TYPICAL JULY DAY (BOTTOM)

The domestic tank was not influenced by the outdoor conditions and behaved in a similar manner to the tank in the electric DHW system. The main difference between these two tanks was that, in this system, the heat pump and heat exchanger by-pass were used to supply the energy to the tank rather than the electric auxiliary heaters. Whenever the top of the domestic tank fell below 52°C, energy was transferred from the float tank via the heat pump or the heat exchanger by-pass to bring the fluid back up to 55°C. Notice in Figure 4.7 that the temperature profile of the top of the domestic tank (T_{d_top}) was similar for both days and was only affected by the heat pump, water draws, and losses to the surroundings.

The overall heat pump run times for the February and July days were one hour and fifty-seven minutes and one hour and twenty-eight minutes, respectively. Because the float tank temperatures were higher in July, energy was able to transfer via the heat pump at a higher rate and delivered higher temperatures. Therefore it did not take as long to bring the domestic tank back up to the set-point temperature, which was reflected in the two heat pump run times. When the heat pump was on, the temperatures in the float tank decreased and the temperature at the top of the domestic tank increased until it reached 55°C. Notice that the heat pump turned on around noon during the July day (see Figure 4.7). This was due to the timing of the operation of the heat pump in conjunction with the water draws. The heat pump turned on just after the 8:00 a.m. water draw on the February day to recharge the domestic tank, but on the July day the tank was recharged just before this water draw. Therefore the top domestic tank temperature initially decreased quicker on the July day once the heat pump had recharged the tank. This caused the water at the top of the domestic tank to fall below the 52°C dead-band limit just before noon, thus activating the heat pump.

The auxiliary heaters in the float tank did not turn on at all during either of the two days shown. The set point temperatures for the upper and lower heaters were -5°C and -10°C respectively and these temperature lows did not

occur. Also, the auxiliary heaters in the domestic tank were not used at all during the entire simulation period because the heat pump and heat exchanger by-pass supplied all of the energy from the float tank.

Recall that the external heat pump file used for the Dual tank i-HPASDHW system modeled the switch-over between the heat pump and heat exchanger by-pass when the temperature at the top of the float tank exceeded 55°C. All of the switch-over cases occurred between July and September due to the higher float tank temperatures achieved from the increased amount of solar energy collected in the summer. Approximately 90% of these cases occurred just after the fifteen minute water draw at 8:00 p.m. had finished. In these cases the float tank was able to charge during the day to elevate the temperature at the top above 55°C. After the water draw started, the temperature at the top of the domestic tank eventually dropped below 52°C and the heat pump model turned on operating with the heat exchanger by-pass characteristics. When the temperature at the top of the float tank fell below 55°C, the heat pump model switched over to heat pump characteristics. An example can be seen in Figure 4.8.

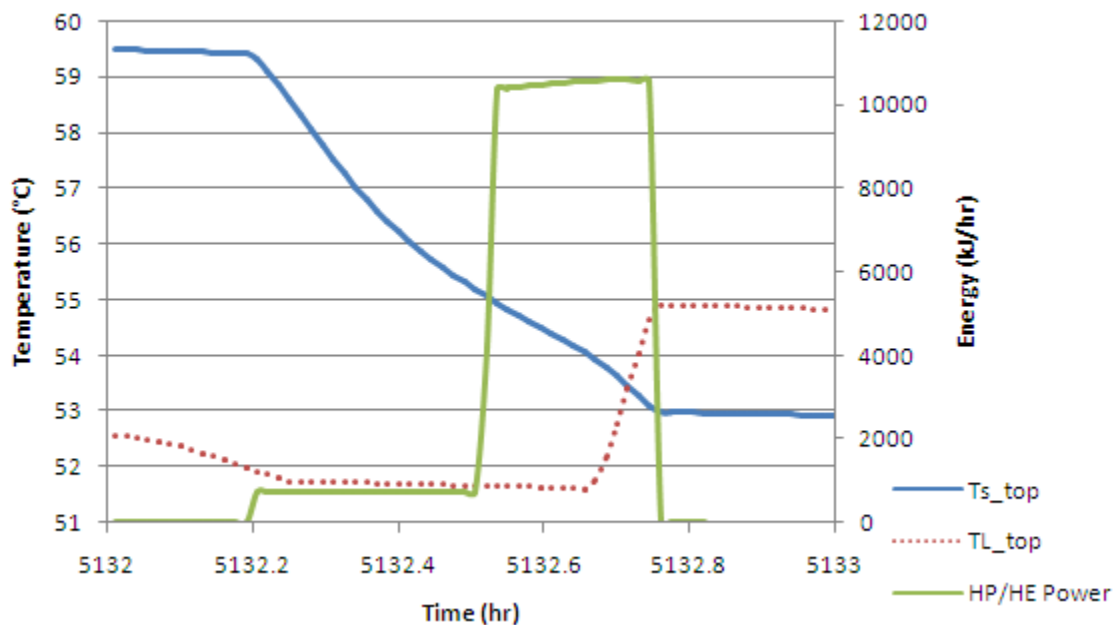


FIGURE 4.8 - HEAT EXCHANGER BY-PASS AND HEAT PUMP SWITCH-OVER EXAMPLE ON AUGUST 1ST

The example shown in Figure 4.8 started at approximately 8:10 p.m. on August 1st. The heat pump model ran for approximately twenty-five minutes in order to bring the domestic tank back up to 55°C. The top temperature of the float tank (source) and domestic tank (load) were labeled as ‘Ts_top’ and ‘TL_top’ respectively. The dashed line represents the power consumption of the heat pump model, which simulated both the heat pump and heat exchanger by-pass loop, and was labeled as ‘HP/HE Power’ in Figure 4.8. During this operation period, just over the first half was modeled using the heat exchanger by-pass characteristics because the temperature at the top of the float tank was greater than 55°C. As soon as the float tank temperature fell below this switch-over temperature, heat pump characteristics were used. This was shown by the large increase of ‘HP/HE Power’ in Figure 4.8. Notice that there was a delay before the domestic tank started to increase in temperature. This was due to the large amount of water in the tank that was heated.

From the observations presented, the Dual tank i-HPASDHW system ran as expected. The overall energy quantities and solar fraction are given in Table 4.3. Notice that the auxiliary heaters in the domestic tank were not used. This was because the heat pump was used to maintain the temperature instead. The heaters were included for backup and it was found that they were not required.

TABLE 4.3 - DUAL TANK I-HPASDHW SYSTEM OVERALL SIMULATION RESULTS

Auxiliary Heaters (Float)	241 MJ
Auxiliary Heaters (Domestic)	0 MJ
Top-up Heater	912 MJ
Pumps	210 MJ
Heat Pump	6 024 MJ
Total Electric Consumption (E_T)	7 387 MJ
Solar Energy Collected (Q_{coll})	14 805 MJ
Total Tank Losses (Q_{loss})	1 687 MJ
Solar Fraction (SF)	0.67

4.1.4 SOLAR-SIDE I-HPASDHW SYSTEM

The configuration of the Solar-side i-HPASDHW system was similar to the traditional SDHW system except for the addition of the heat pump located between the inlet and outlet of the collector. The overall energy balance for the Solar-side i-HPASDHW system is given below.

$$Q_{AUX,TANK} + Q_{AUX,TOP\ UP} + Q_{SOLAR} + P_{PUMP} + P_{HP} = E_{LOAD} + Q_{LOSS,TANK} \quad (4.5)$$

The outdoor environmental conditions had a huge impact on the state and performance of the Solar-side i-HPASDHW system throughout the simulation. It was expected that the heat pump would be used to extend the collection periods in the early morning and late afternoon, especially during the colder months of the year. Figure 4.9 shows the tank temperature profiles and the control signals for the circulating pumps (CS_pump), heat pump (CS_HP), and the internal auxiliary heater (Qaux_CS) on a typical winter day in December (top) and a summer day in July (bottom). Recall that the solar loop could operate with and without the heat pump. Whenever the heat pump was on, the circulating pumps were also on. When only the circulating pumps were on, the system was operating as a traditional SDHW system.

The effects of the outdoor weather conditions on the system can be seen in Figure 4.9. In general, the temperatures experienced in the domestic tank were much higher during the typical day in July compared to the day in December. Just as with the other two solar assisted systems, this was due to the warmer outdoor temperatures and higher solar intensities experienced. Notice the large increase in the operation time of the solar loop for the July day compared to the December day as well. The total solar loop run times, including both with and without the heat pump, for the December and July days were approximately five hours and fifty minutes and twelve hours respectively. On the December day,

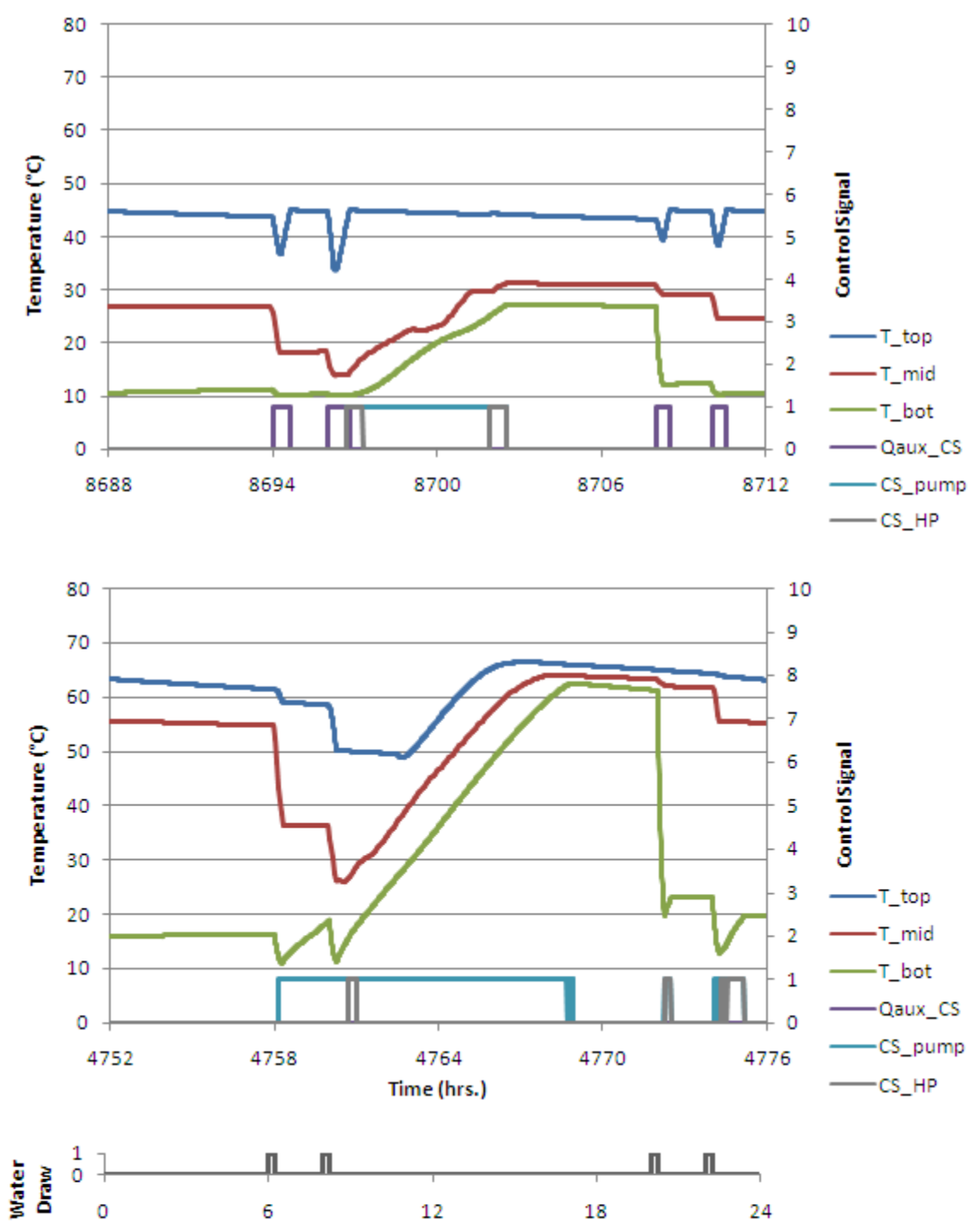


FIGURE 4.9 - SOLAR-SIDE I-HPASDHW SYSTEM OPERATION ON A TYPICAL DECEMBER DAY (TOP) AND A TYPICAL JULY DAY (BOTTOM)

the solar loop operated with assistance from the heat pump for one hour and ten minutes in total. As shown in Figure 4.9, approximately half of this time was in the morning at the start of the collection period and the other half was in the afternoon at the very end of the collection period. This shows how the heat pump was able to extend the run time of the solar loop on the cold winter day, as expected. On the July day, the solar loop also operated with assistance from the heat pump for approximately one hour and ten minutes in total. Notice though that only about a quarter of that time occurred during the main solar collection period (see Figure 4.9). For the most part, the system operated just as the traditional SDHW system would during the day but was able to use the heat pump at night to take advantage of the warm outdoor temperatures after the two evening water draws to collect energy (see Figure 4.9). This was another example of how the heat pump was able to extend the run times of the solar loop in the Solar-side i-HPASDHW system. Also notice that the solar loop actually ran without assistance from the heat pump for a short period during the 10:00 p.m. water draw. This occurred because the bottom tank temperature had cooled substantially from the incoming replacement water at 10°C and was able to collect energy from the warmer outdoor environment.

Recall that the set point temperatures for the upper and lower heaters were 45°C and 15°C, respectively with a 5°C dead-band. On the July day the lowest that the top tank temperature reached was approximately 50°C, so the heaters were not required at all. However, the auxiliary heaters were used on the typical winter day in December for approximately two hours and twenty-five minutes because of the low outdoor temperatures and low solar intensities experienced during the cold winter day. Notice that the heaters were on for four separate occasions, all of which occurred as a result of the water draws. Once the top tank temperature fell below 40°C ($T_{\text{SET}} - T_{\text{DB}}$), the upper heater was turned on and brought the water back up to the 45°C set point.

From the observations presented, the Solar-side i-HPASDHW system ran as expected. The energy consumption for the various components, the tank losses, and the solar fraction of the system are presented in Table 4.4.

TABLE 4.4 - SOLAR-SIDE I-HPASDHW SYSTEM OVERALL SIMULATION RESULTS

Auxiliary Heaters	3 212 MJ
Top-up Heater	1 949 MJ
Pumps	181 MJ
Heat Pump	1 182 MJ
Total Electric Consumption (E_T)	6 524 MJ
Solar Energy Collected (Q_{coll})	12 824 MJ
Total Tank Losses (Q_{loss})	967 MJ
Solar Fraction (SF)	0.66

4.2 COMPARISON OF I-HPASDHW SYSTEMS WITH THE TWO BASE SYSTEMS

4.2.1 DUAL TANK I-HPASDHW VS. ELECTRIC DHW

Unlike the electric DHW system, the Dual tank i-HPASDHW system received assistance from a heat pump and solar loop to heat the domestic water. Table 4.5 summarizes all of the key energy quantities and the annual operating costs of these two systems for comparison.

The most important observation was that the Dual tank i-HPASDHW system consumed approximately 63% less electricity overall compared to the electric DHW system. This was the case because the collected solar energy greatly reduced the requirements of the auxiliary heaters in the system (see Table 4.5). The solar energy input could be thought of as “free” energy because the electricity required by the circulating pumps to operate the solar loop was included in the total electric consumption. Also, using the heat pump to

maintain the temperatures in the domestic tank, rather than electric heaters, was a much more efficient use of the power.

TABLE 4.5 - ELECTRIC DHW AND DUAL TANK I-HPASDHW SYSTEMS COMPARISON

	Electric DHW	Dual tank i-HPASDHW
Auxiliary Heaters	18 002 MJ	241 MJ
Top-up Heater	2 068 MJ	912 MJ
Pumps	N/A	210 MJ
Heat Pump	N/A	6 024 MJ
Total Electric Consumption (E_T)	20 070 MJ	7 387 MJ
Solar Energy Collected (Q_{coll})	N/A	14 805 MJ
Total Tank Losses (Q_{loss})	621 MJ	1 687 MJ
Solar Fraction (SF)	0	0.67

Notice that the total tank losses for the Dual tank i-HPASDHW system were approximately 2.7 times higher than the electric DHW system. This was true for two reasons. First, the domestic tank in the Dual tank i-HPASDHW system was, on average, warmer due to a tighter dead-band temperature on the heat pump controller. Second, the Dual tank i-HPASDHW system had two tanks that experienced losses to the surroundings. Therefore on a hot summer day, both the float tank and domestic tank could be at relatively high temperatures and losing energy to the surroundings.

The domestic tank in the two systems operated in a similar fashion. The only difference was that in the Dual tank i-HPASDHW system, the heat pump was used to keep the tank charged rather than the electric heaters. Figure 4.10 shows the top temperature profiles of the domestic tank on the typical day in February for the electric DHW system (top) and the Dual tank i-HPASDHW system (bottom). Notice that whenever these two temperature profiles fell below their respective dead-band limit, the heat source used in each case turned on to

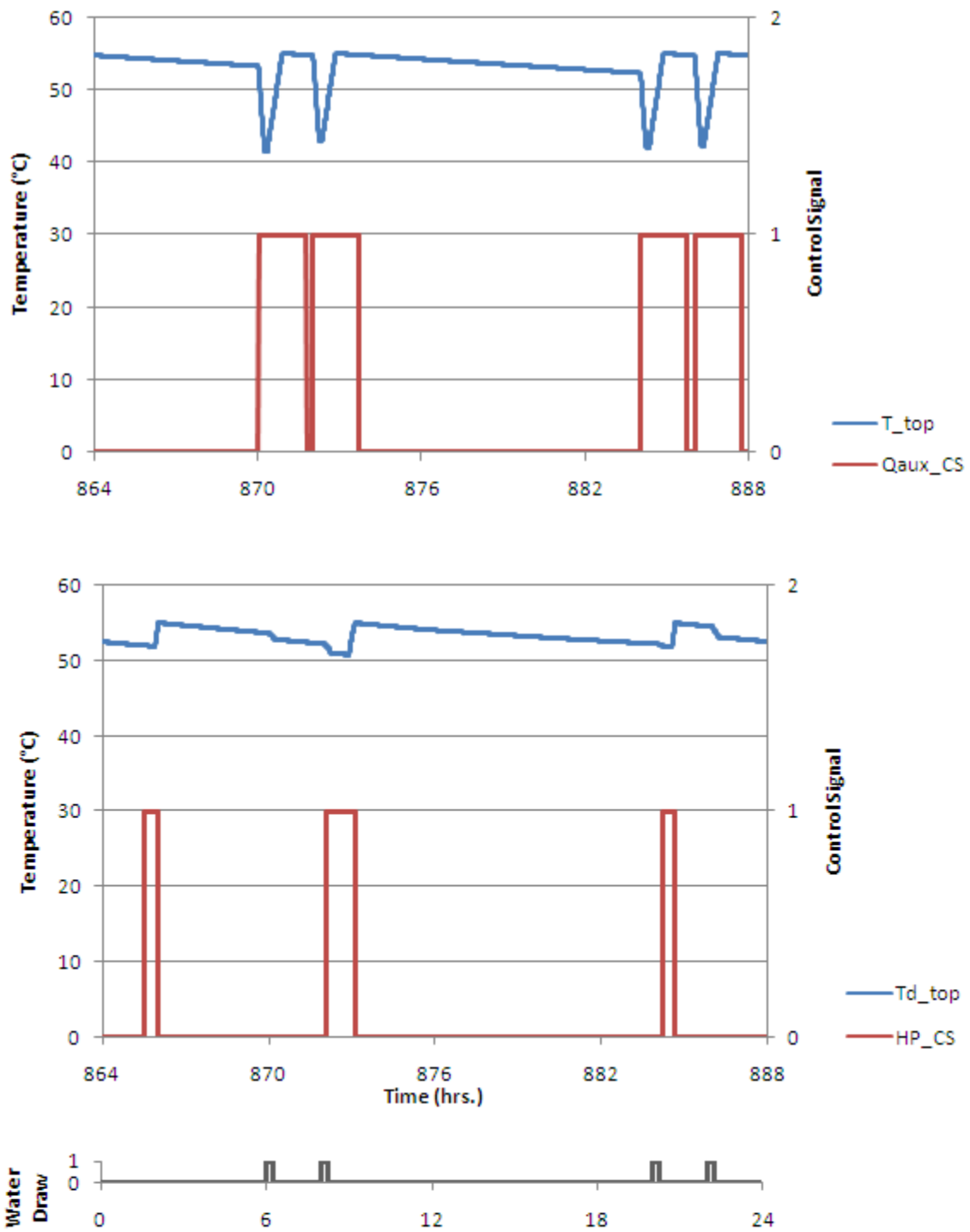


FIGURE 4.10 – DOMESTIC TANK OPERATION OF ELECTRIC DHW (TOP) AND DUAL TANK I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL FEBRUARY DAY

bring the fluid back to 55°C. The reason that the temperature drops in the domestic tank of the electric DHW system were more drastic was because the heat pump generally charged a significant portion of the water in the domestic tank of the Dual tank i-HPASDHW system. This is discussed in more detail in the comparison to the traditional SDHW system.

4.2.2 DUAL TANK I-HPASDHW VS. TRADITIONAL SDHW

These two systems use solar energy to assist in the domestic water heating. The effects of adding a heat pump and a second tank to the solar assisted configuration were examined by comparing the various overall energy quantities given in Table 4.6. Also, the performances of the two systems were examined in detail by comparing and contrasting their operation on specific days of the year using plots generated from simulation results.

TABLE 4.6 - TRADITIONAL SDHW AND DUAL TANK I-HPASDHW SYSTEMS COMPARISON

	Traditional SDHW	Dual tank i-HPASDHW
Auxiliary Heaters	6 696 MJ	241 MJ
Top-up Heater	1 838 MJ	912 MJ
Pumps	181 MJ	210 MJ
Heat Pump	N/A	6 024 MJ
Total Electric Consumption (E_T)	8 714 MJ	7 387 MJ
Solar Energy Collected (Q_{coll})	12 077 MJ	14 805 MJ
Total Tank Losses (Q_{loss})	1 186 MJ	1 687 MJ
Solar Fraction (SF)	0.58	0.67

The overall electric consumption was approximately 15% lower for the Dual tank i-HPASDHW system compared to the traditional SDHW system. This was because the heat pump and the extra thermal storage allowed the float tank to send colder fluid to the collector which increased the efficiencies and run times of the system. Therefore, more solar energy was collected by the Dual tank

i-HPASDHW system and the overall electric energy required decreased (see Table 4.6). Notice that just over 80% of the total electric consumption for the Dual tank i-HPASDHW system was used by the heat pump and approximately 77% for the traditional SDHW system was used by the auxiliary heaters in order to keep the domestic tank charged. Therefore, this can be thought of as redirecting a large portion of the electric energy that was consumed by the auxiliary heaters in the traditional SDHW system to the heat pump instead in order to heat the domestic tank. As mentioned, this was a much more efficient use of the power. It should be pointed out again that the auxiliary heaters in the domestic tank of the Dual tank i-HPASDHW system were not used because the heat pump provided all of the heating requirements. Another important note was that the domestic tank in the Dual tank i-HPASDHW system was not directly connected to the solar loop so it only received energy from the heat pump. However, the domestic tank in the traditional SDHW system received energy from the auxiliary heaters and the solar loop as well. Even though the domestic tank in the Dual tank i-HPASDHW system only received energy from the heat pump, the electric consumption of the heat pump was still less than the back-up auxiliary heaters in the traditional SDHW system. This helps to further demonstrate the benefits of the heat pump.

The losses for the Dual tank i-HPASDHW system were approximately 42% higher compared to the traditional SDHW system. This was expected because the water at the top of the domestic tank in the Dual tank i-HPASDHW system was held near the delivery temperature by the heat pump with a tight temperature dead-band for the entire year. It was also discovered that the heat pump elevated the entire tank temperature profile, not just the top portion, as shown in Figure 4.11 whenever it charged the domestic tank. In Figure 4.11, the entire tank was above 45°C for a large portion of the February day, which greatly increased the losses. However, this total tank charge by the heat pump helped to greatly reduce the amount of energy required by the top-up heater (see Table 4.6). Although the domestic tank in the traditional SDHW system may

have experienced higher losses during hot summer days because of the solar input, the losses for the Dual tank i-HPASDHW system were consistently high every day and proved to be more significant overall. Another thing to consider is that the Dual tank i-HPASDHW system had a higher amount of thermal mass due to the additional tank in the configuration. On a hot summer day, both the float tank and domestic tank would be at relatively high temperatures. Therefore, the system would be losing a large amount of energy from the two tanks to the surroundings instead of just from the domestic tank as in the traditional SDHW system.

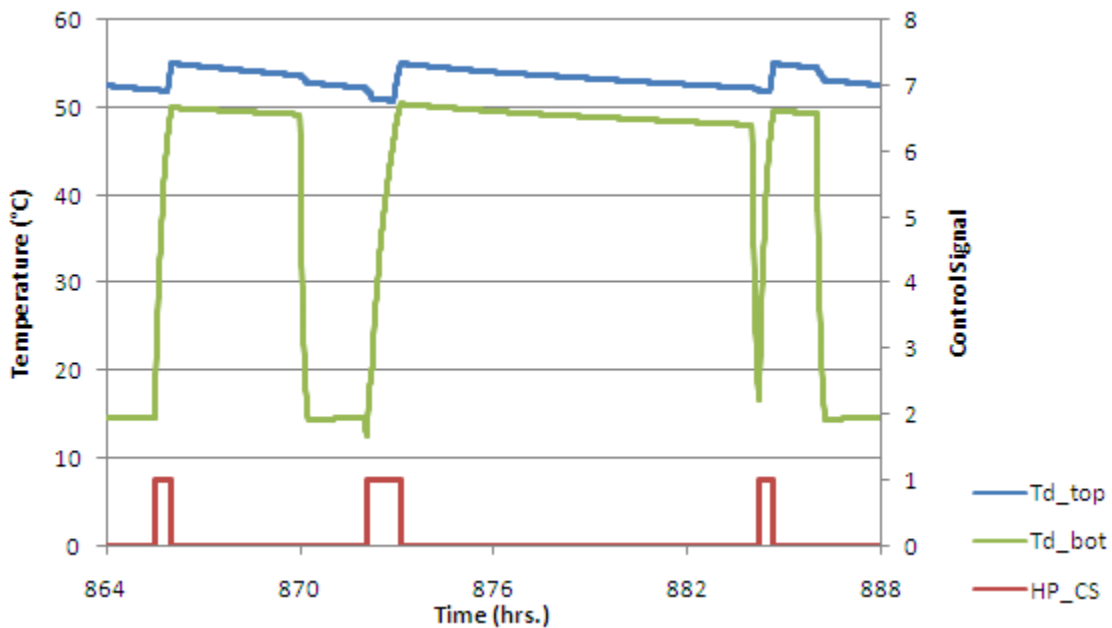


FIGURE 4.11 - DUAL TANK I-HPASDHW SYSTEM TYPICAL DAILY DOMESTIC TANK OPERATION

Figure 4.12 shows the operation of the traditional SDHW system (top) and the Dual tank i-HPASDHW system (bottom) for a typical summer day in July. For the Dual tank i-HPASDHW system, the temperature profiles for the float tank were marked as 'Tf' and for the domestic tank as 'Td'. Only the top temperature profile was included for the domestic tank because it was not directly linked to the solar loop.

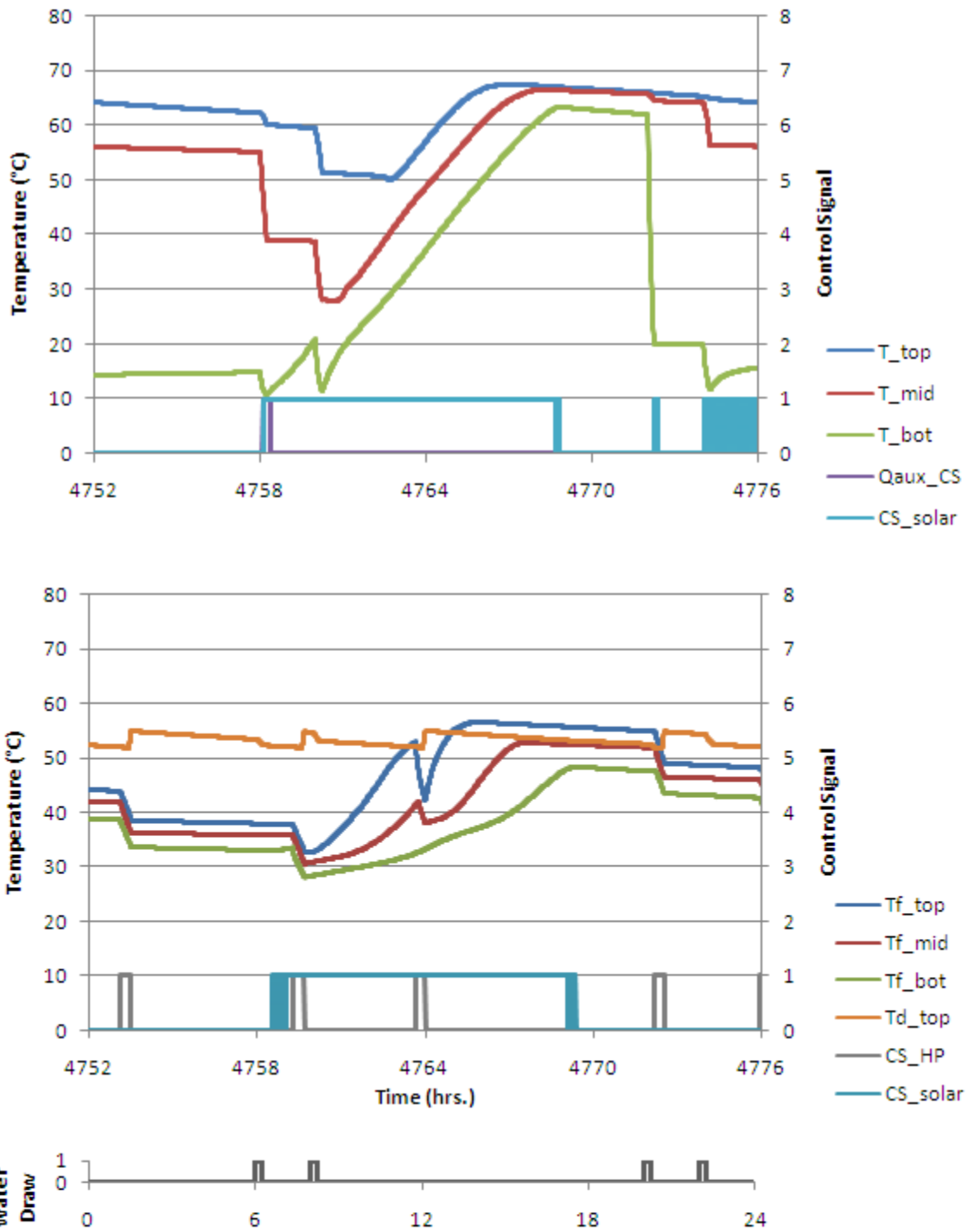


FIGURE 4.12 - OPERATION OF TRADITIONAL SDHW (TOP) AND DUAL TANK I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL JULY DAY

The temperature profiles in the float tank were different from the profiles in the domestic tank of the traditional SDHW system on the day shown in Figure 4.12. Recall that these were the tanks connected to the solar loop for the two systems. Notice that the three temperature profiles for the float tank followed each other much closer when compared to the temperature profiles for the domestic tank in the traditional SDHW system, especially outside of the solar collection period. This was because the cold replacement water at 10°C did not enter the float tank during the water draws to cool the fluid. However, in the traditional SDHW system, whenever there was a water draw, the bottom domestic tank temperature dropped due to the cold replacement water entering the tank. That was why the bottom tank temperature was so much colder at the start and end of the day for the traditional SDHW system (see Figure 4.12). Also, the peak temperatures achieved by all three profiles (top, middle, and bottom) were significantly higher in the domestic tank of the traditional SDHW system because of two reasons. The first was that the tank size connected to the solar loop was smaller and therefore had less thermal mass. Second, in the Dual tank i-HPASDHW system, the heat pump lowered the entire float tank temperature profiles whenever energy was transferred to the domestic tank. Notice the decrease in all three temperature profiles in Figure 4.12 whenever the heat pump was turned on.

The solar loop run times for the traditional SDHW system and the Dual tank i-HPASDHW system were approximately ten hours and thirty-five minutes and ten hours and nine minutes, respectively. The main solar collection period was similar for the two systems on this July day, but the solar loop in the Dual tank i-HPASDHW system was able to operate slightly longer in the afternoon. This was due to the colder temperatures at the bottom of the float tank compared to the domestic tank of the traditional SDHW system near the end of the collection period (see Figure 4.12). The reason that the collection time was actually slightly higher for the traditional SDHW system was because of the extra energy collected in the evening. The cold replacement water caused the

bottom domestic tank temperature to drop to 20°C after the 8:00 p.m. draw and to approximately 12°C after the 10:00 p.m. draw. Therefore, this lower temperature fluid at the bottom of the domestic tank was able to collect energy from the warmer outdoor environment. However, in the Dual tank i-HPASDHW system case, the temperatures in the float tank during the evening were too high (40°C – 55°C) to collect energy from the outdoor environment (see Figure 4.12).

The auxiliary heaters were used for approximately fifteen minutes in the traditional SDHW system and not at all in the Dual tank i-HPASDHW system on the typical July day. Only the heat pump was used in the Dual tank i-HPASDHW system to keep the domestic tank charged as shown in Figure 4.12 and operated for one hour and twenty-eight minutes. The auxiliary heaters in the float tank were not required on this day because the tank temperatures never came close to the -5°C and -10°C set point temperatures due to the collected solar energy

The operation of the traditional SDHW system (top) and the Dual tank i-HPASDHW system (bottom) on a typical February day are shown in Figure 4.13. Again, only the top tank temperature profile for the domestic tank in the Dual tank i-HPASDHW system was shown because the profiles were very similar from day to day.

Just as with the typical day in July, the three temperature profiles in the float tank closely followed each other and decreased whenever the heat pump turned on to charge the domestic tank. During the solar collection period, all three temperature profiles of the float tank increased by a significant amount due to their low temperatures at the start. However, with the domestic tank in the traditional SDHW system, only the bottom and middle tank temperatures increased significantly during the collection period. The top domestic tank temperature was maintained near the delivery temperature with the 50°C set point of the upper auxiliary heater in order to meet the hot water draws. Also, notice that the peak temperatures achieved by the bottom, middle, and top

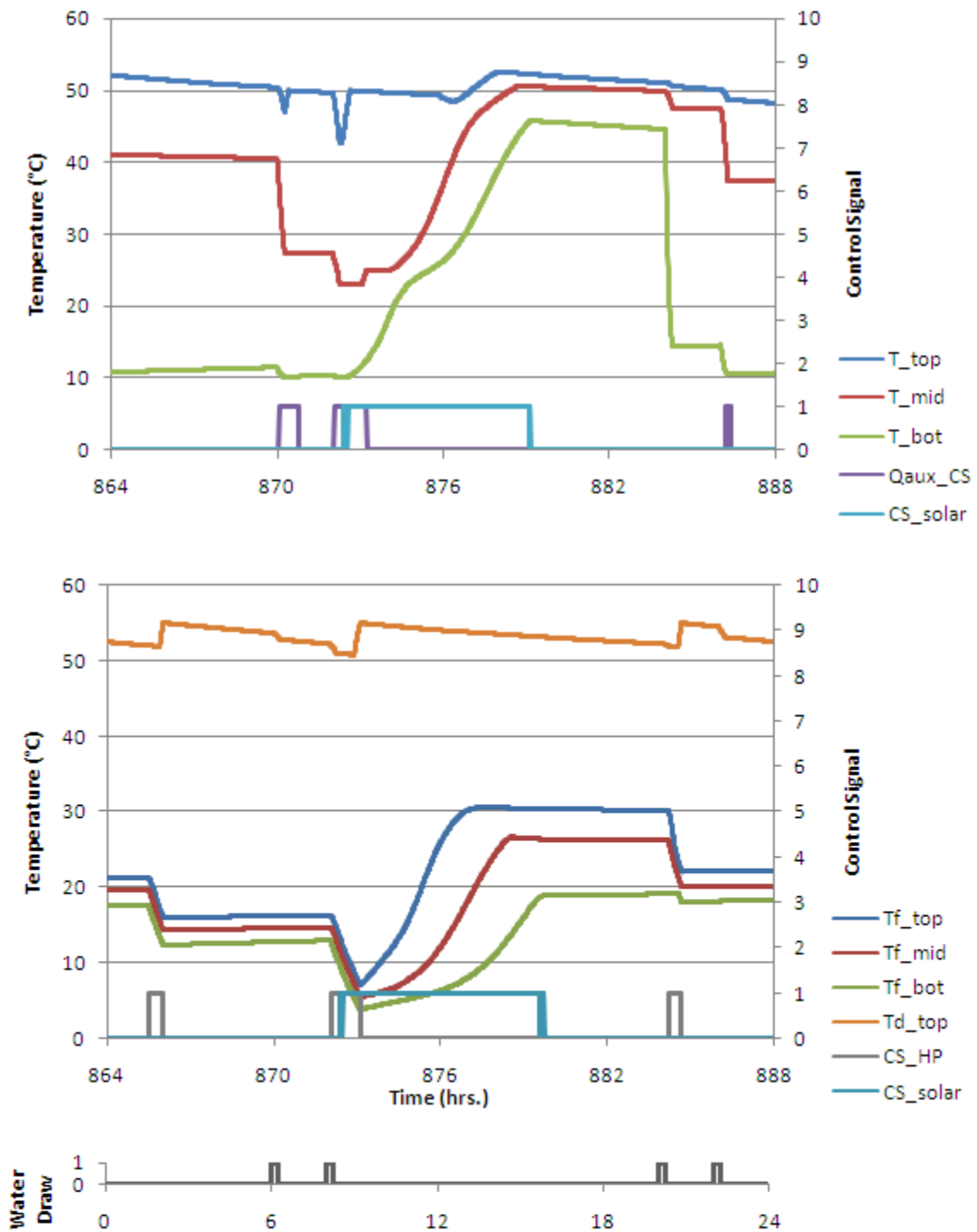


FIGURE 4.13 - OPERATION OF TRADITIONAL SDHW (TOP) AND DUAL TANK I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL FEBRUARY DAY

temperature profiles in the domestic tank of the traditional SDHW system were significantly higher compared to the profiles in the float tank. This was true for two reasons. First, the volume of the float tank was much larger and therefore required more energy in order to experience the same temperature rise. Second, the float tank temperatures were much lower than the temperatures in the domestic tank of the traditional SDHW system at the start of the solar collection period. Notice that the entire float tank was below 8°C and within a 5°C range when the solar loop began to operate, whereas the bottom, middle, and top temperatures in the domestic tank were approximately 10°C, 23°C, and 42°C respectively (see Figure 4.13). This was because of the energy input from the two auxiliary heaters with set point temperatures of 50°C and 25°C. Therefore, not only was there more fluid in the float tank being heated by the solar energy input, but it also started at significantly lower temperatures.

The solar-loop run times on the typical February day for the traditional SDHW system and the Dual tank i-HPASDHW system were six hours and forty-five minutes and seven hours and seven minutes, respectively (see CS_solar in Figure 4.13). As expected, the colder fluid temperatures in the float tank on the winter day allowed the Dual tank i-HPASDHW system to collect more solar energy by extending the run time of the solar-loop by approximately twenty minutes.

The auxiliary heaters inside of the domestic tank in the traditional SDHW ran for approximately two hours, while the ones in the float tank were not used at all. The fluid inside of the float tank did not fall below the set point temperatures of the two auxiliary heaters. However, electric energy was used by the heat pump in the Dual tank i-HPASDHW system, instead of the auxiliary heaters, in order to maintain the temperatures inside of the domestic tank. In fact, the heat pump operated for just under two hours, which was essentially the same run time of the auxiliary heaters in the domestic tank of the traditional SDHW system (see Figure 4.13). Therefore, the electric demand that was used by the auxiliary heaters in the traditional SDHW system was redirected to the

heat pump in the Dual tank i-HPASDHW system. This is a much more efficient use of the electricity.

The addition of the heat pump and float tank were able to help increase the run times of the solar loop in the Dual tank i-HPASDHW system on cool days with low solar intensities. Figure 4.14 shows the operation of the traditional SDHW system (top) and the Dual tank i-HPASDHW system (bottom) for a cold and cloudy day in March. The solar loop run times on this day for the traditional SDHW system and the Dual tank i-HPASDHW system were approximately four hours and six hours, respectively. However, the last two collection periods (approximately half hour each) for the traditional SDHW system were not continuous (see Figure 4.14). Therefore, the solar loop in the Dual tank i-HPASDHW system ran for over two hours longer compared to the traditional SDHW system. Both systems began collecting solar energy around 8:15 a.m., but because of the colder fluid in the float tank, the Dual tank i-HPASDHW system was able to collect solar energy for longer periods throughout the day.

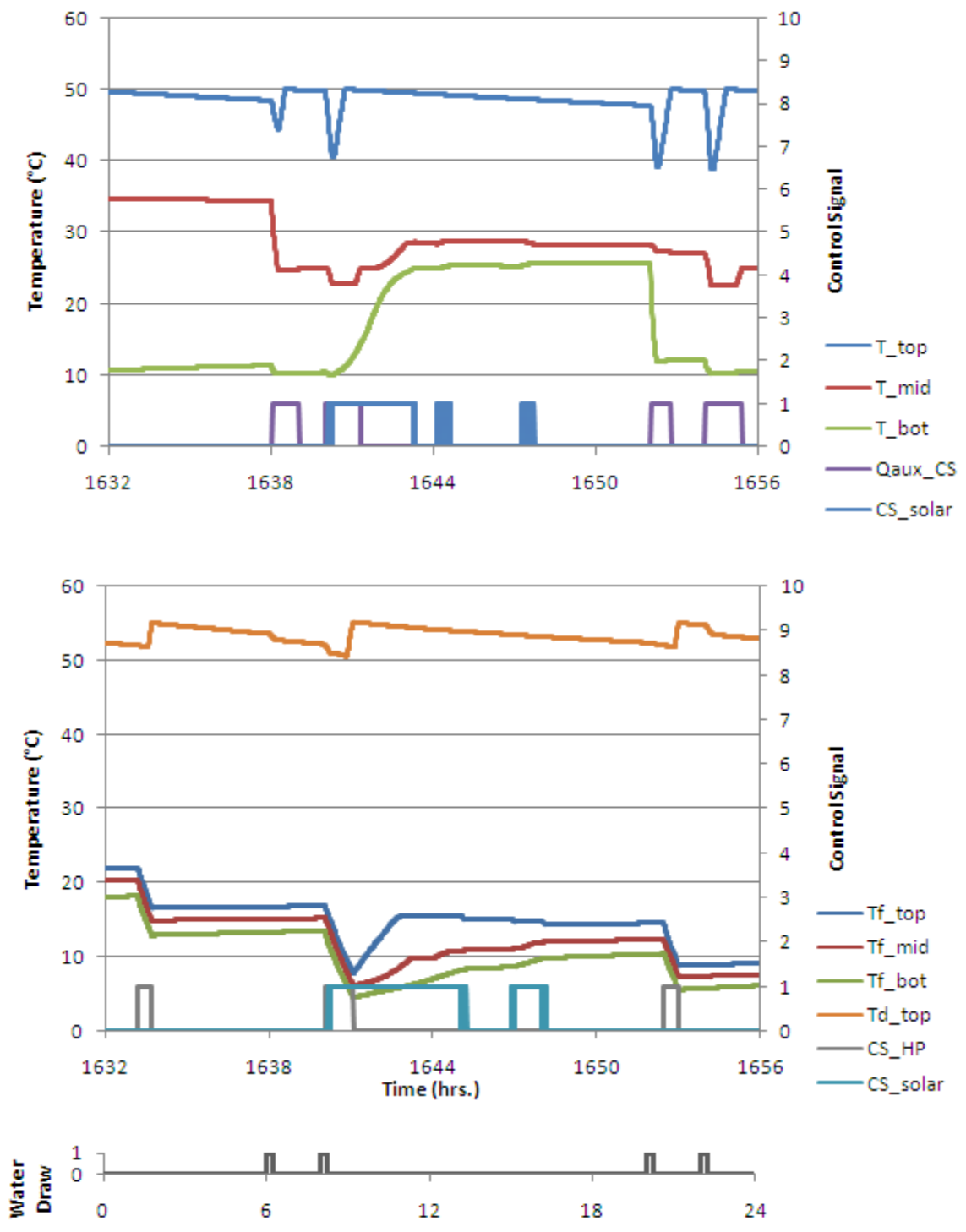


FIGURE 4.14 - OPERATION OF TRADITIONAL SDHW (TOP) AND DUAL TANK I-HPASDHW (BOTTOM) SYSTEMS ON A CLOUDY MARCH DAY

4.2.3 SOLAR-SIDE I-HPASDHW VS. ELECTRIC DHW

The Solar-side i-HPASDHW system had assistance from the solar loop and a heat pump in an attempt to improve on the performance compared to the electric DHW system. All of the key overall energy quantities and the annual operational costs for the electric DHW and Solar-side i-HPASDHW systems are given in Table 4.7.

TABLE 4.7 - ELECTRIC DHW AND SOLAR-SIDE I-HPASDHW SYSTEMS COMPARISON

	Electric DHW	Solar-side i-HPASDHW
Auxiliary Heaters	18 002 MJ	3 212 MJ
Top-up Heater	2 068 MJ	1 949 MJ
Pumps	N/A	181 MJ
Heat Pump	N/A	1 182 MJ
Total Electric Consumption (E_T)	20 070 MJ	6 524 MJ
Solar Energy Collected (Q_{coll})	N/A	12 824 MJ
Total Tank Losses (Q_{loss})	621 MJ	967 MJ
Solar Fraction (SF)	0	0.66

The Solar-side i-HPASDHW system used approximately 67% less electricity compared to the electric DHW system. This was because of the assistance from the collected solar energy and the use of the heat pump. The solar loop greatly reduced the amount of energy input required from the auxiliary heaters and gave the system a solar fraction of 0.66. Therefore, rather than supplying all of the energy requirements with the auxiliary heaters, 66% was met by the collected solar energy. An example of the operation during a typical July day for the electric DHW (top) and Solar-side i-HPASDHW (bottom) systems are shown in Figure 4.15. Notice that on the typical summer day in July, the auxiliary heaters for the Solar-side i-HPASDHW system were not required. All of the energy added to the tank to heat the water came from the solar loop, operating both with and without assistance from the heat pump.

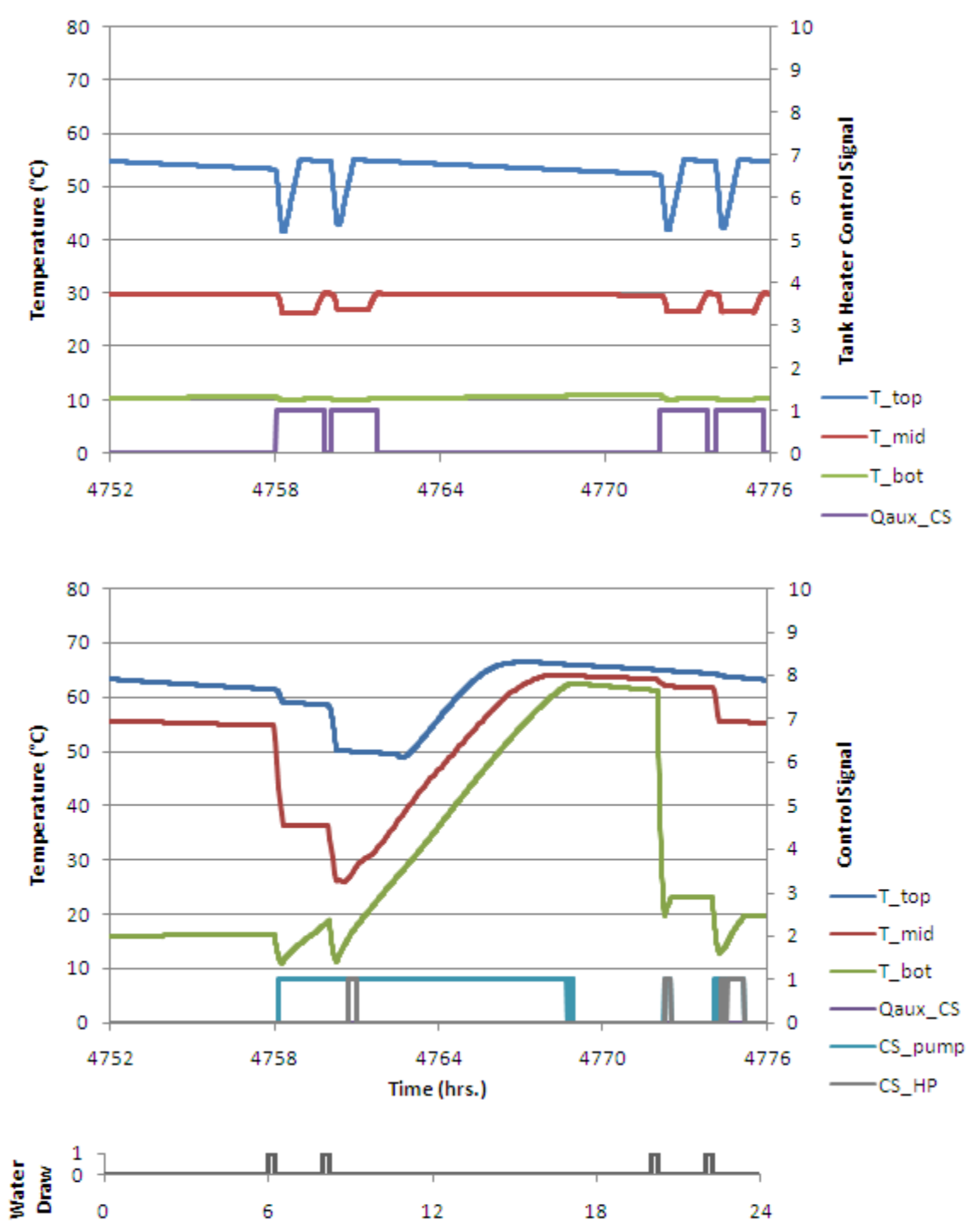


FIGURE 4.15 - OPERATION OF ELECTRIC DHW (TOP) AND SOLAR-SIDE I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL JULY DAY

The losses for the Solar-side i-HPASDHW system were approximately 1.56 times higher than the base electric DHW system. This was to be expected because the addition of the solar loop allowed the domestic tank to store water at temperatures higher than the set point at times when the outdoor conditions were sufficient to do so. The tank temperatures experienced on this July day in the Solar-side i-HPASDHW system were generally much hotter for the entire day (see Figure 4.15). Therefore the tank losses to the surroundings were higher.

4.2.4 SOLAR-SIDE I-HPASDHW VS. TRADITIONAL SDHW

The configurations of these two systems were very similar. The Solar-side i-HPASDHW system simply added a heat pump in parallel between the inlet and outlet of the solar collector that operated whenever it was beneficial to the system. The effects of adding this heat pump to the configuration were examined by comparing the various overall energy quantities given in Table 4.8. Also, the performances of the two systems were examined closer by comparing and contrasting their state and operation on specific days of the year using plots generated from simulation results.

TABLE 4.8 - TRADITIONAL SDHW AND SOLAR-SIDE I-HPASDHW SYSTEMS COMPARISON

	Traditional SDHW	Solar-side i- HPASDHW
Auxiliary Heaters	6 696 MJ	3 212 MJ
Top-up Heater	1 838 MJ	1 949 MJ
Pumps	181 MJ	181 MJ
Heat Pump	N/A	1 182 MJ
Total Electric Consumption (E_T)	8 714 MJ	6 524 MJ
Solar Energy Collected (Q_{coll})	12 077 MJ	12 824 MJ
Total Tank Losses (Q_{loss})	1 186 MJ	967 MJ
Solar Fraction (SF)	0.58	0.66

The total electric consumption was approximately 25% lower for the Solar-side i-HPASDHW system compared to the traditional SDHW system. This was because the heat pump was able to slightly increase the amount of solar energy collected by extending the run times of the solar loop. When the solar loop was operating with assistance from the heat pump, colder fluid was sent to the inlet of the collector. This allowed the Solar-side i-HPASDHW system to collect energy at times the traditional SDHW system could not. Also, the lower set point temperatures for the two auxiliary heaters in the domestic tank of the Solar-side i-HPASDHW system ended up having an impact on decreasing the overall electric consumption. This is discussed further with regard to the system losses.

The losses experienced by the domestic tank in the Solar-side i-HPASDHW system were about 18% lower than the traditional SDHW system (see Table 4.8). This was the opposite of what was expected because the Solar-side i-HPASDHW system collected more solar energy. However, the set point temperatures for the two auxiliary heaters inside of the domestic tank were lowered to 45°C (upper) and 15°C (lower). In the traditional SDHW system, the set point temperatures for the upper and lower auxiliary heaters were 50°C and 25°C respectively. These set points temperatures were lowered in an attempt to maximize the assistance of the heat pump. Therefore, during the colder months of the year, the tank was generally maintained at a lower average temperature in the Solar-side i-HPASDHW system. This was reflected in the slight increase in the energy consumption of the top-up heater compared to the base traditional SDHW system. Also, the heat pump was used mostly to assist in collecting energy during times of low solar intensities. Therefore the temperatures achieved by the collecting fluid were likely relatively low and assisted to charge the lower portions of the domestic tank.

Figure 4.16 shows the operation of the traditional SDHW system (top) and the Solar-side i-HPASDHW system (bottom) for a typical summer day in July.

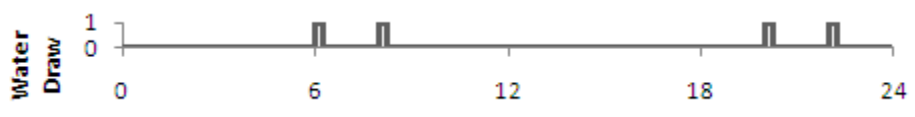
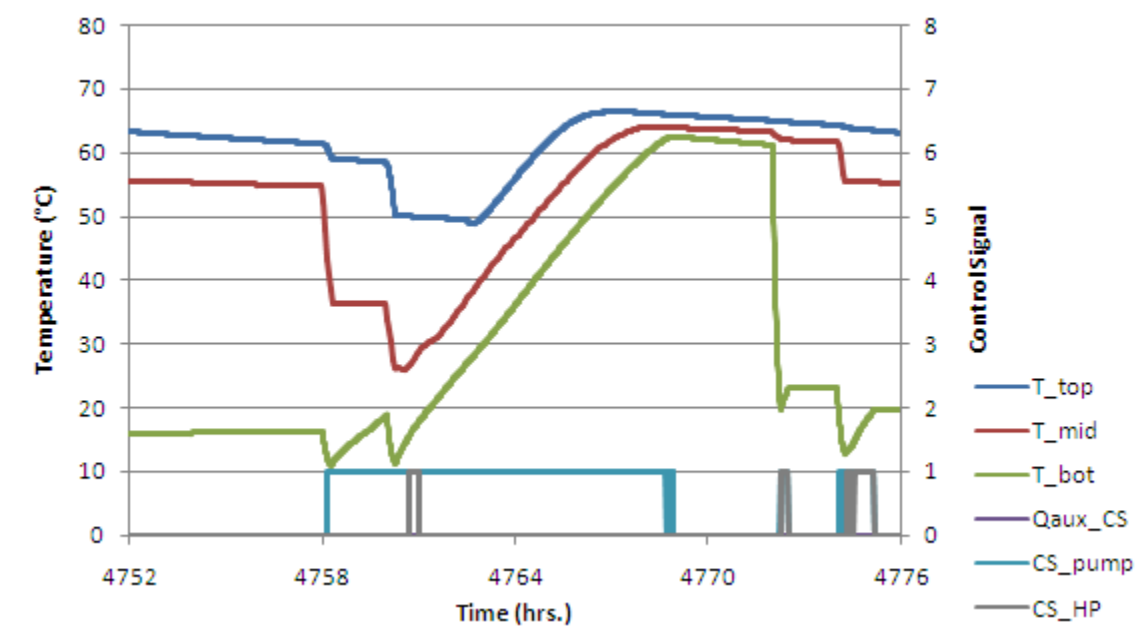
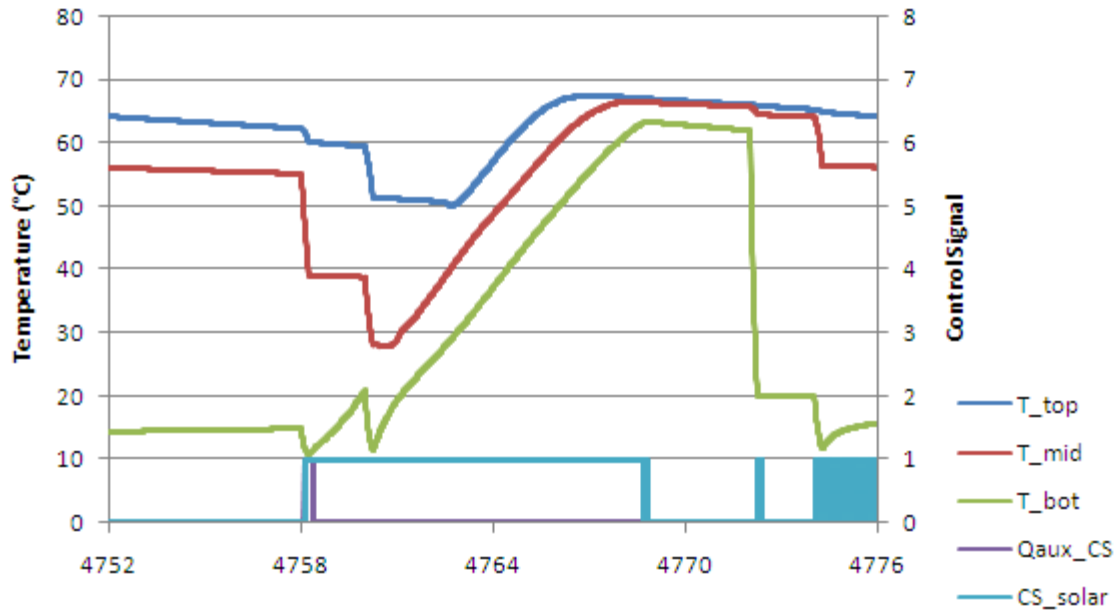


FIGURE 4.16 - OPERATION OF TRADITIONAL SDHW (TOP) AND SOLAR-SIDE I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL JULY DAY

Notice that the temperature profiles in the two domestic tanks were nearly identical on this day. The main difference was the small variation in the bottom tank temperatures in the evening starting around the 8:00 p.m. water draw. Figure 4.16 shows that the Solar-side i-HPASDHW system was operating with assistance from the heat pump during the two evening collection periods. Therefore the solar loop was able to increase the bottom tank temperature approximately 5°C higher, compared to the traditional SDHW system, after the two evening water draws. Beside that minor difference, as expected, the Solar-side i-HPASDHW system operated very much like the traditional SDHW system on the hot summer day.

The run times of the solar loop on the typical July day for the traditional SDHW system and the Solar-side i-HPASDHW system were approximately ten hours and thirty-five minutes and twelve hours respectively. Therefore, the heat pump was able to increase the amount of time that the solar loop was able to collect energy by about an hour and twenty-five minutes. Notice in Figure 4.16 that the main collection period from just after 6:00 a.m. until just before 5:00 p.m. was essentially the same for the two systems on this day. The difference occurred during the two evening collection periods. The heat pump was able to extend the operation of the solar loop. Also notice that the solar loop during the last collection period of the traditional SDHW system was continuously turning on and off. The assistance from the heat pump was able to help greatly reduce this indecisiveness experienced by the controller and increased the operation time.

Because of the large amount of solar energy collected by both systems on the hot summer day in July shown in Figure 4.16, the auxiliary heaters inside the domestic tanks were not required to provide much energy. In fact, the Solar-side i-HPASDHW system did not use the auxiliary heaters at all on this day. The traditional SDHW system only used the lower slave heater once for approximately fifteen minutes just after the 6:00 a.m. water draw.

Figure 4.17 shows the operation of the traditional SDHW system (top) and the Solar-side i-HPASDHW system (bottom) for a typical sunny winter day in December. Notice that the domestic tank temperature profiles for the Solar-side i-HPASDHW system were generally lower compared to the traditional SDHW system. As mentioned before, this was due to the lower set point temperatures of the two auxiliary heaters inside the domestic tank. Therefore on a cold winter day, like the typical day in December shown in Figure 4.17, the losses from the tank were less for the Solar-side i-HPASDHW system. However, because of the lower temperature of the water at the top of the domestic tank, the energy input required from the top-up heater was greater during the water draws compared to the traditional SDHW system.

The run times of the solar loop on the typical December day for the traditional SDHW system and the Solar-side i-HPASDHW system were approximately five hours and thirty minutes and five hours and fifty minutes respectively. Therefore, the assistance from the heat pump was able to slightly increase the solar collection time by twenty minutes on the typical day in December. The heat pump was used at the start and end of the collection period when the solar intensities experienced were lowest.

The domestic tanks in the two systems required more energy input from the auxiliary heaters during cold winter days, like the typical day in December shown in Figure 4.17. The overall total time on this day that an auxiliary heater was on in the traditional SDHW system and the Solar-side i-HPASDHW system was approximately four hours and two hours and twenty-five minutes, respectively. Therefore, because of the lower set point temperatures of the auxiliary heaters and the increase in solar energy collected, the Solar-side i-HPASDHW system required less energy from the auxiliary heaters. Again, because the top tank temperatures were colder for the Solar-side i-HPASDHW system, the top-up auxiliary was required to provide more energy in order to meet the delivery temperature.

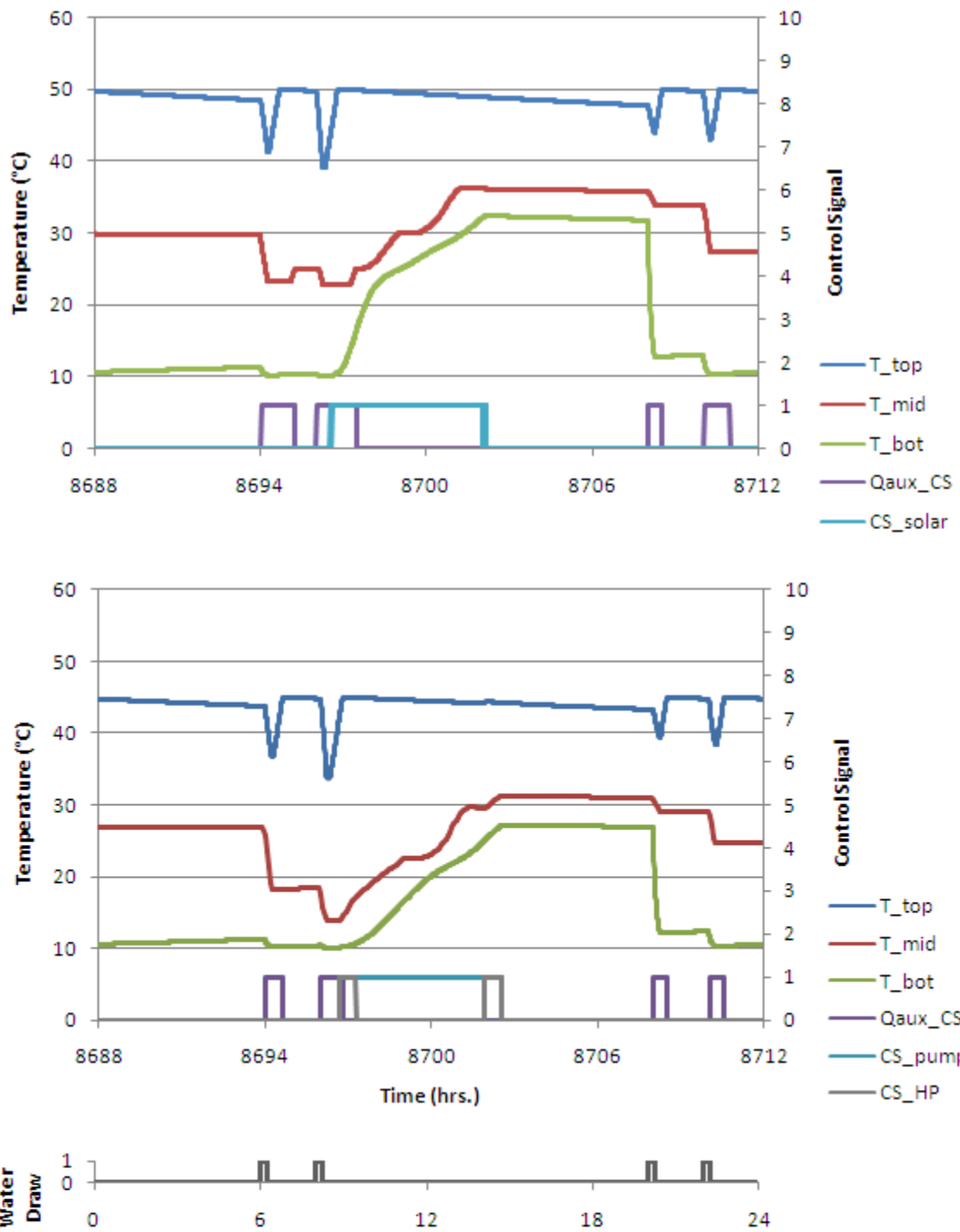


FIGURE 4.17 - OPERATION OF TRADITIONAL SDHW (TOP) AND SOLAR-SIDE I-HPASDHW (BOTTOM) SYSTEMS ON A TYPICAL DECEMBER DAY

The addition of the heat pump was also able to help increase the run time of the solar loop on cool days with low solar intensities. Figure 4.18 shows the operation of the traditional SDHW system and the Solar-side i-HPASDHW system for a cloudy day in March. The run times for the traditional SDHW and Solar-side i-HPASDHW systems were approximately four hours and four hours and fifty-five minutes, respectively. Although the traditional SDHW system began collecting solar energy approximately forty-five minutes earlier, notice that the Solar-side i-HPASDHW system continued to collect solar energy into the afternoon while the traditional SDHW system did not. When the traditional SDHW system stopped collecting energy around 11:15 a.m., the Solar-side i-HPASDHW system continued to operate with assistance from the heat pump until about 1:00 p.m. Also notice that the solar loop in the traditional SDHW system continuously turned off and on for approximately a half hour just after noon and again around 3:15 p.m. During these times, the Solar-side i-HPASDHW system was able to collect more energy because it operated continuously. This was shown in Figure 4.18 by observing that the bottom and middle temperature profiles in the tank increased at a significantly higher rate during these times for the Solar-side i-HPASDHW system.

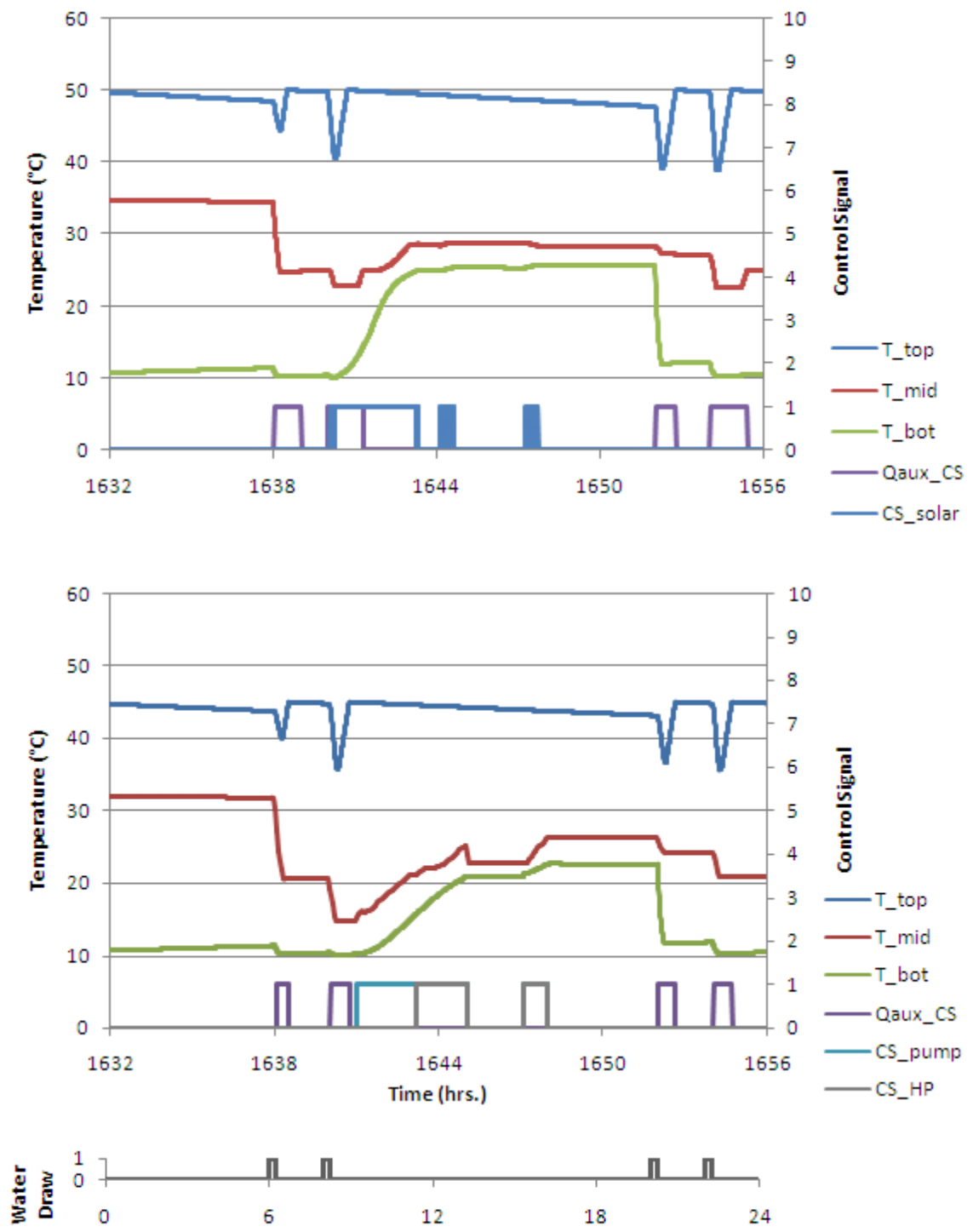


FIGURE 4.18 - OPERATION OF TRADITIONAL SDHW (TOP) AND SOLAR-SIDE I-HPASDHW (BOTTOM) SYSTEMS ON A CLOUDY MARCH DAY

4.3 DUAL TANK VS. SOLAR-SIDE I-HPASDHW

The configurations of the two i-HPASDHW systems were very different. The Solar-side i-HPASDHW system used a heat pump directly to assist the solar loop, whereas the Dual tank i-HPASDHW system used a heat pump to transfer energy into the domestic tank. Therefore, the domestic tank in the Dual tank system was not directly connected to the solar loop like the Solar-side system. The two systems were compared by examining the various overall energy quantities given in Table 4.9. Also, the performances of these two systems were examined closer by comparing their state and operation on specific days of the year using plotted simulation results.

TABLE 4.9 - DUAL TANK AND SOLAR-SIDE I-HPASDHW SYSTEMS COMPARISON

	Dual Tank i-HPASDHW	Solar-side i-HPASDHW
Auxiliary Heaters	241 MJ	3 212 MJ
Top-up Heater	912 MJ	1 949 MJ
Pumps	210 MJ	181 MJ
Heat Pump	6 024 MJ	1 182 MJ
Total Electric Consumption (E_T)	7 387 MJ	6 524 MJ
Solar Energy Collected (Q_{coll})	14 805 MJ	12 824 MJ
Total Tank Losses (Q_{loss})	1 687 MJ	967 MJ
Solar Fraction (SF)	0.67	0.66

The total electric consumption for the Solar-side i-HPASDHW system was approximately 12% lower than the Dual tank i-HPASDHW system. The main difference was seen in the power consumption of the heat pump and auxiliary heaters (see Table 4.9). The Solar-side i-HPASDHW system used a lower capacity heat pump and the times when it was used depended on the outdoor conditions. Therefore it used about five times less electricity compared to the larger capacity heat pump in the Dual tank i-HPASDHW system that was used regularly each day to maintain the temperatures in the domestic tank. This

large amount of electricity usage by the heat pump in the Dual tank i-HPASDHW system greatly reduced the amount energy required by the auxiliary heaters and top-up heater in the system.

The losses for the Dual tank i-HPASDHW system were approximately 75% higher compared to the Solar-side i-HPASDHW system (see Table 4.9). This was expected because the domestic tank in the Dual tank i-HPASDHW system was held near the delivery temperature by the heat pump with a tight temperature dead-band for the entire year. As mentioned, the heat pump elevated the temperatures of the entire tank by a significant amount which resulted in much higher losses on a consistent basis. Also the two tanks in the system resulted in more exposed area that was subjected to losses to the surroundings.

The operation of the Dual tank (top) and Solar-side (bottom) i-HPASDHW systems on a typical July day are shown in Figure 4.19. Again, notice how the float tank temperature profiles closely followed each other, especially outside of the solar collection period. However, in the domestic tank of the Solar-side i-HPASDHW system, the temperature profiles separated outside of the collection period. This was due to the 10°C replacement water that was added to the domestic tank during a water draw and the higher set point temperatures of the auxiliary heaters. Also notice how the temperature profiles in the domestic tank of the Solar-side i-HPASDHW system became very close near the end of the solar collection on this day. That was because the tank was being charged by the collected solar energy and there were no water draws during this period to add cold water. Again, the temperatures in the domestic tank of the Dual tank i-HPASDHW system were maintained with the heat pump and did not vary much from day to day. The top tank temperature profile is shown in Figure 4.19 along with the heat pump control signal.

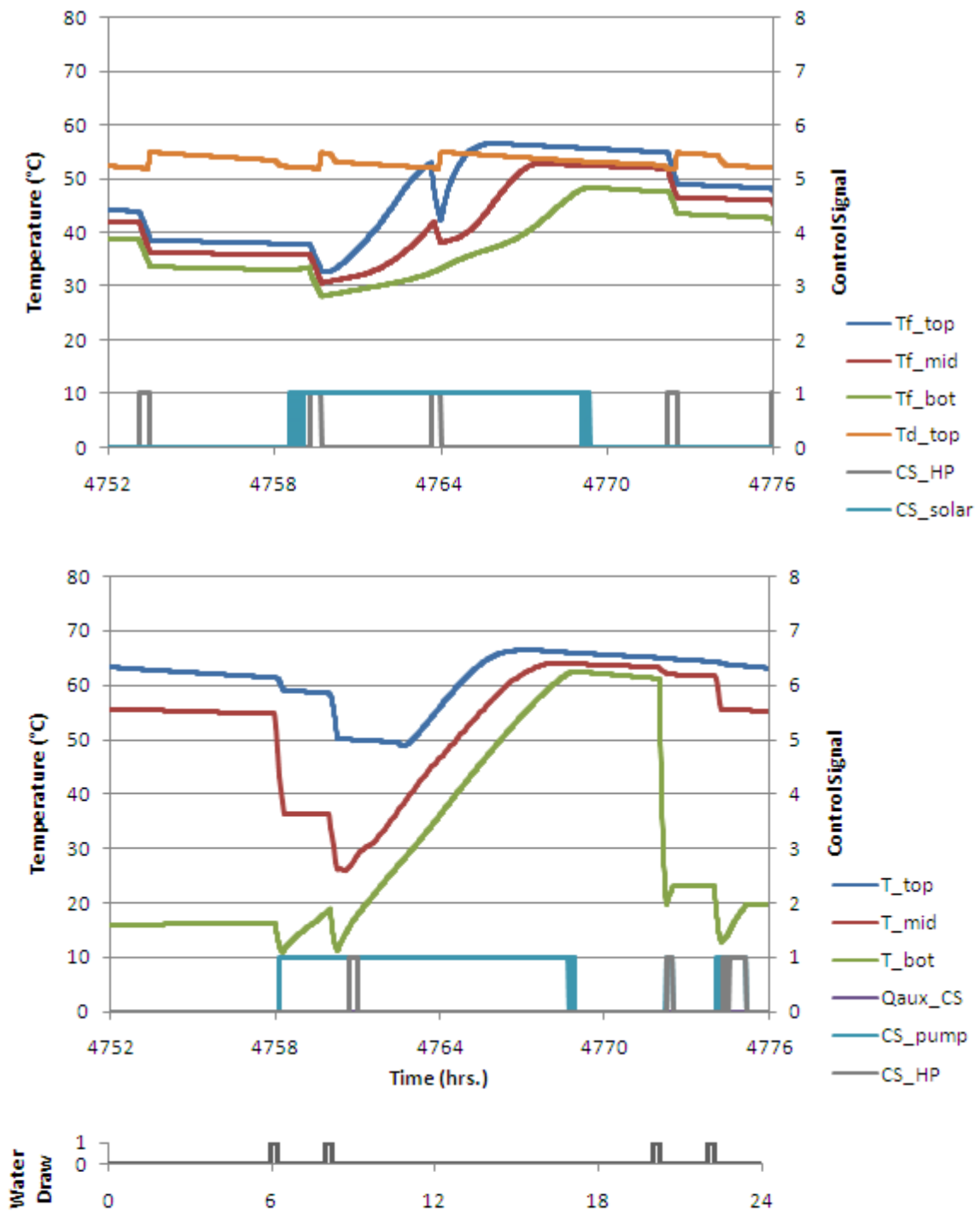


FIGURE 4.19 - OPERATION OF DUAL TANK (TOP) AND SOLAR-SIDE (BOTTOM) I-HPASDHW SYSTEMS ON A TYPICAL JULY DAY

The solar loop run times on this July day for the Dual tank and Solar-side i-HPASDHW systems were ten hours and nine minutes and twelve hours, respectively. Notice that the Solar-side i-HPASDHW system was able to begin collecting solar energy much earlier in the morning compared to the Dual tank i-HPASDHW system on the July day (see Figure 4.19). This was due to the fact that the water at the bottom of the domestic tank was much colder compared to the float tank. Therefore, colder fluid was sent to the inlet of the collector and allowed the solar loop to start much earlier. However, notice that the Dual tank i-HPASDHW system collected energy slightly later into the afternoon. The larger volume of the float tank did not allow the fluid to reach as high of a peak temperature as the domestic tank in the Solar-side i-HPASDHW system. Therefore, the relatively colder fluid in the float tank permitted the Dual tank i-HPASDHW system to collect a little later into the afternoon. The Solar-side i-HPASDHW system was also able to collect energy from the warm outdoor environment during the evening with assistance from the heat pump. This was because of the cold replacement water introduced to the bottom of the domestic tank during the water draws that allowed the solar loop to send colder fluid to the collector inlet at these times.

Notice that the small capacity heat pump in the Solar-side i-HPASDHW system was used less than the heat pump in the Dual tank i-HPASDHW system on this hot July day. The heat pumps for the Dual tank and Solar-side i-HPASDHW systems operated for approximately one hour and thirty minutes and one hour and ten minutes, respectively. Also, as expected, neither system required any energy input from the auxiliary heaters inside of the tanks on the hot summer day.

Figure 4.20 shows the operation of the Dual tank and Solar-side i-HPASDHW systems on a typical day in December. Notice how low the temperature profiles were in the float tank compared to the domestic tank of the Solar-side i-HPASDHW system. This was due to the fact that the float tank was

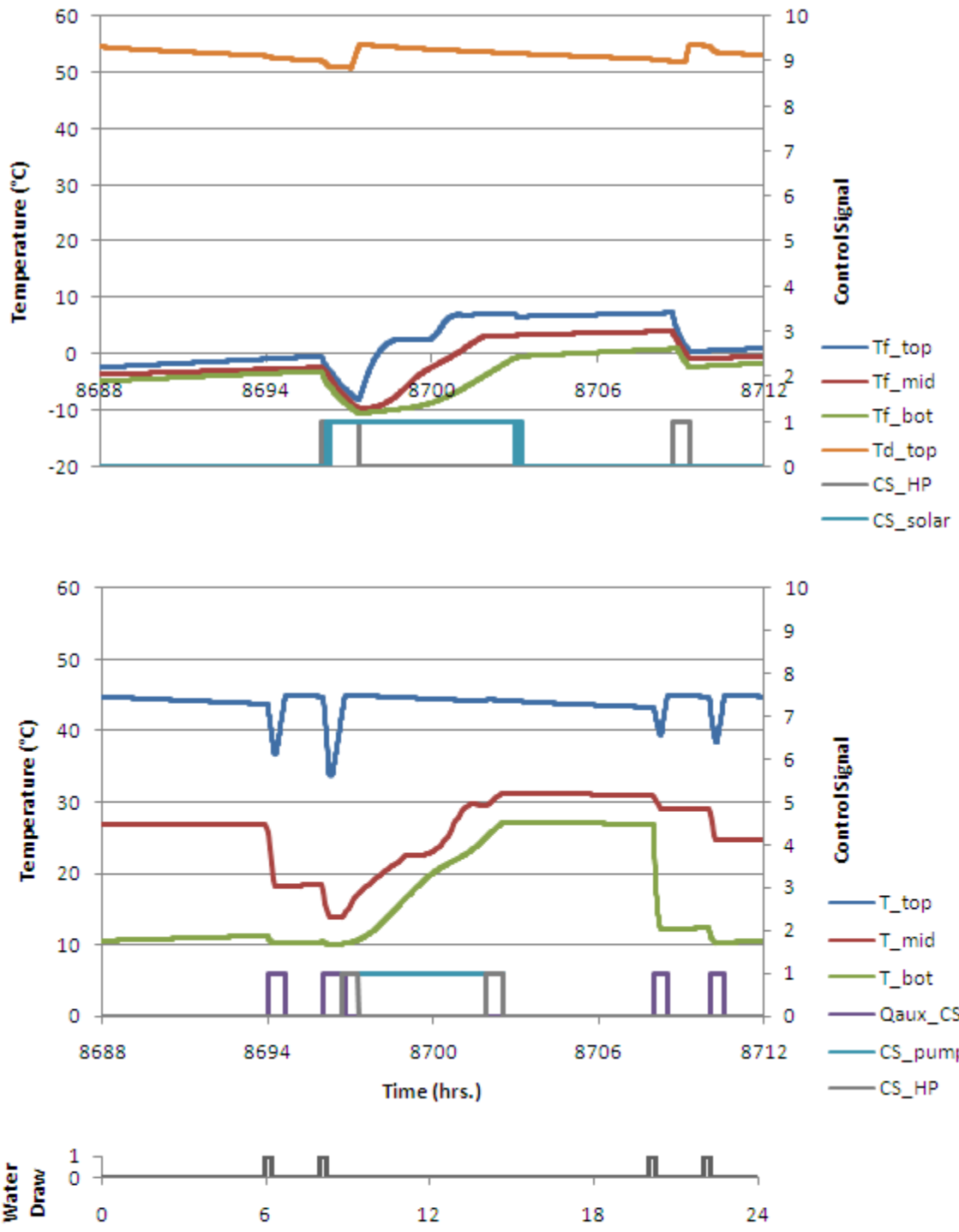


FIGURE 4.20 - OPERATION OF DUAL TANK (TOP) AND SOLAR-SIDE (BOTTOM) I-HPASDHW SYSTEMS ON A TYPICAL DECEMBER DAY

allowed to fluctuate in temperature depending on the outdoor conditions by using the -5°C and -10°C set point temperatures of the upper and lower auxiliary heaters. Therefore, during the winter, the temperatures were low due to the cold outdoor conditions and because of the energy removed by the heat pump to charge the domestic tank. It was not important to keep the float tank charged because the water draws were taken from the domestic tank instead. However, in the Solar-side i-HPASDHW system, the domestic tank was connected directly to the solar loop and supplied the hot water for the draws. Therefore, the auxiliary heaters were required in order to keep the domestic tank of the Solar-side i-HPASDHW system partially charged at all times, but were not used in the float tank on this cold day as shown in Figure 4.20.

The solar loop run times on this December day for the Dual tank and Solar-side i-HPASDHW systems were approximately six hours and fifty minutes and five hours and fifty minutes, respectively. The Dual tank i-HPASDHW system was able to start collecting solar energy earlier in the morning and also operated later into the afternoon. Looking at the temperature profiles of the two tanks shown in Figure 4.20, this was due to the lower temperatures in the float tank. Even with assistance from the heat pump in the Solar-side i-HPASDHW system, the Dual tank i-HPASDHW system was still able to send colder fluid to the inlet of the collector. Therefore, the operation of the solar loop was extended by an hour compared to the Solar-side i-HPASDHW system.

The heat pumps for the Dual tank and Solar-side i-HPASDHW systems operated for approximately one hour and fifty-six minutes and one hour and ten minutes, respectively. Although the heat pump in the Dual tank i-HPASDHW system was used fewer times on this December day compared to the day in July, the overall run time was twenty-five minutes longer. This was because the colder fluid temperatures in the float tank did not allow the heat pump to transfer energy to the domestic tank at as high of a rate compared to the summer when the float tank was much hotter. Therefore, it took longer for the heat pump to bring the top of the domestic tank back up to the set point

temperature (see Figure 4.19 and Figure 4.20). The small capacity heat pump in the Solar-side i-HPASDHW system operated for the same amount of time on the December day compared to the typical July day. This was just because the heat pump was used on the July day to allow the solar loop to operate during the evening. However, on this cold December day, the heat pump was used for roughly thirty-five minutes in the morning and then again for approximately the same amount of time in the afternoon in order to extend the collection period, as shown in Figure 4.20. On both the typical July and December days, the higher capacity heat pump in the Dual tank i-HPASDHW system was used longer compared to the heat pump in the Solar-side i-HPASDHW system. This helps to show why the energy consumption of the heat pump in the Dual tank system was five times higher compared to the heat pump in the Solar-side system.

The auxiliary heaters in the float tank of the Dual tank i-HPASDHW system were not required at all, whereas the ones in the domestic tank of the Solar-side i-HPASDHW system operated for approximately two hours and twenty-three minutes. As shown in Figure 4.20, the two heaters in the float tank were not used because the temperatures did not fall below either of the dead-band limits. It was not important to keep the float tank charged because it was not used for the water draws. However, the domestic tank in the Solar-side system required energy input from the auxiliary heaters on this cold winter day to help keep the tank partially charged so that the hot water draws could be met.

The operation of the Dual tank (top) and Solar-side (bottom) i-HPASDHW systems on a cold and cloudy day in March are shown in Figure 4.21. Similar to the December day, the temperature profiles in the float tank were much lower compared to the domestic tank in the Solar-side i-HPASDHW system because of the outdoor conditions and the allowance for temperature fluctuations in the float tank. Also, the domestic tank in the Solar-side i-HPASDHW system received energy input from the auxiliary heaters to keep the tank partially charged in order to meet the hot water draws.

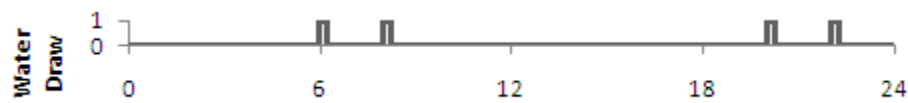
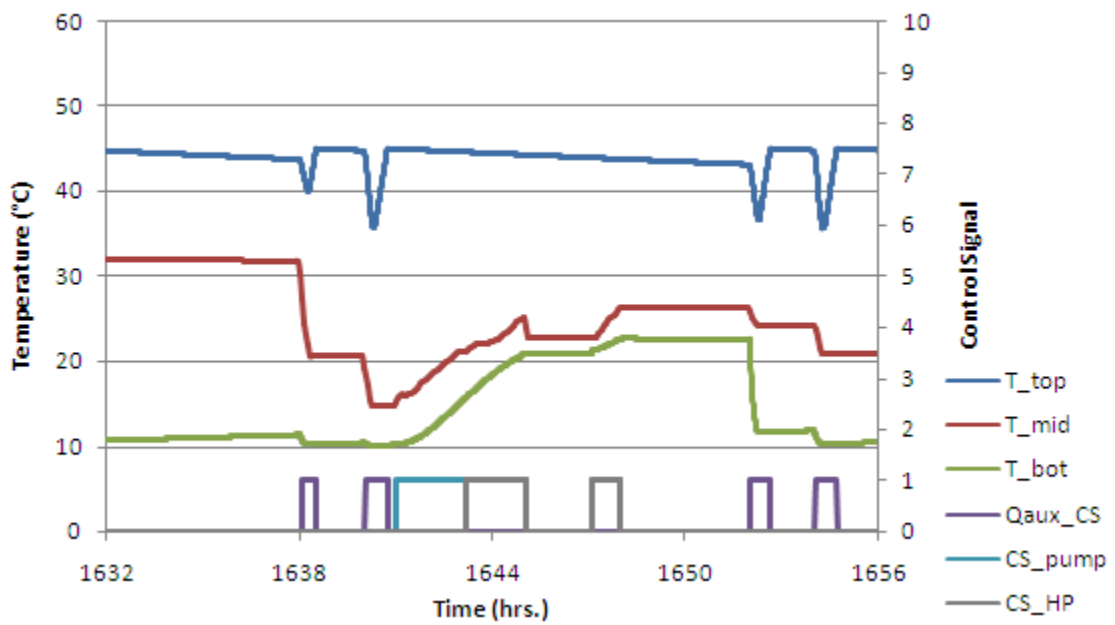
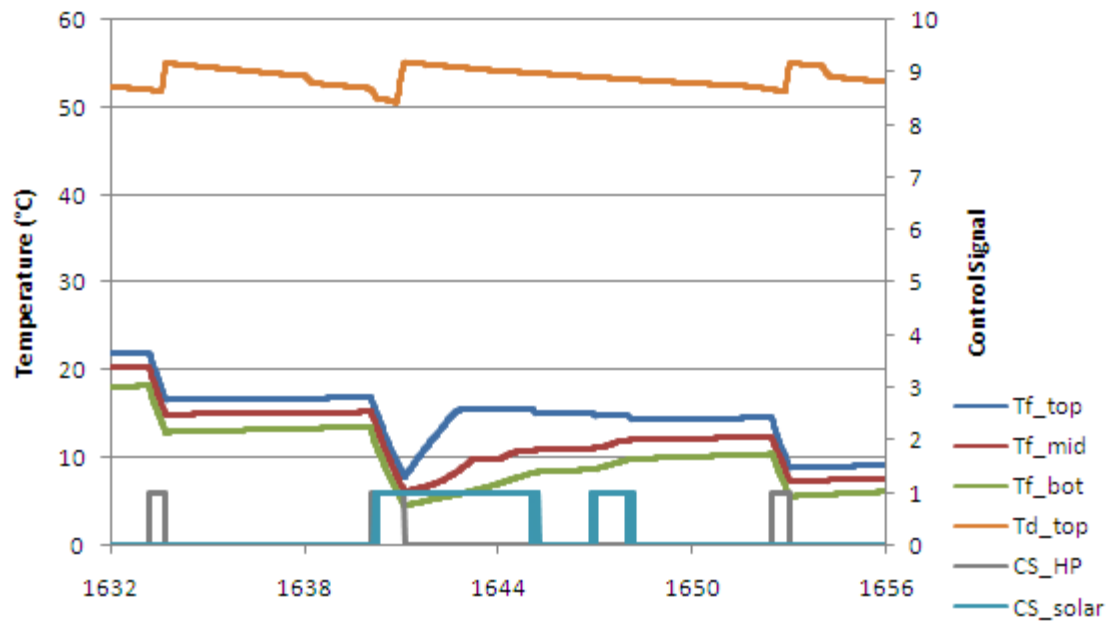


FIGURE 4.21 - OPERATION OF DUAL TANK (TOP) AND SOLAR-SIDE (BOTTOM) I-HPASDHW SYSTEMS ON A CLOUDY MARCH DAY

The solar loop run times on this day for the Dual tank and Solar-side i-HPASDHW systems were approximately six hours and four hours and fifty-four minutes, respectively. Similar to the day in December, the colder fluid in the float tank allowed the Dual tank i-HPASDHW system to collect more energy compared to the Solar-side i-HPASDHW system.

Due to the configurations of the two systems, the Solar-side i-HPASDHW system, in general, was able to collect more solar energy in the summer but the Dual tank i-HPASDHW system had the advantage in the winter. In the summer, the cold replacement water introduced to the bottom of the domestic tank in the Solar-side i-HPASDHW system, which was connected to the solar loop, decreased the bottom tank temperature during a water draw. However, the float tank in the Dual tank i-HPASDHW system was charged in the summer and did not have the cold replacement water reducing the temperatures at the bottom of the tank. Therefore, after each water draw, the bottom tank temperature in the float tank was, in general, higher compared to the domestic tank of the Solar-side i-HPASDHW system. This allowed the Solar-side i-HPASDHW system to send colder fluid to the inlet of the collector, which increased the run times of the solar loop (see Figure 4.19). In the winter, however, the float tank was generally at very low temperatures and allowed the Dual tank i-HPASDHW system to send colder fluid to the collector inlet (see Figure 4.20).

4.4 OVERALL ENERGY CONSUMPTION AND COST COMPARISON

The total electric consumption, solar energy collected, and solar fraction for each system are summarized in Table 4.10. Notice how the solar fraction improved for the two i-HPASDHW systems compared to the traditional SDHW system.

The percentage of the overall energy into and out of each system from the various sources is shown in Figure 4.22. The energy into the system included the useful solar energy collected and the electric loads for the pumps, heat pump (if applicable), and auxiliary heaters. The energy out of the system consisted of the

delivery water at 55°C during the water draws, and losses from the tank to the surrounding environment. For the draw profiles simulated, all of the systems delivered approximately 2.0×10^7 kJ of energy, while the energy into the system and losses to the surroundings varied from case to case. It should be noted that all of the systems did not deliver the exact same amount of energy over the year. There were times on cold days that the solar assisted systems were unable to reach the set delivery temperature due to the low temperature at the top of the tank and the limited capacity of the top-up heater. However, using a simple energy balance, the total energy into a system must equal the energy out.

TABLE 4.10 - SYSTEM PERFORMANCE COMPARISONS

System	E_T (MJ)	Q_{coll} (MJ)	SF
Electric DHW	20 070	N/A	N/A
Traditional SDHW	8 714	12 077	0.58
Dual tank i-HPASDHW	7 387	14 805	0.67
Solar-side i-HPASDHW	6 524	12 824	0.66

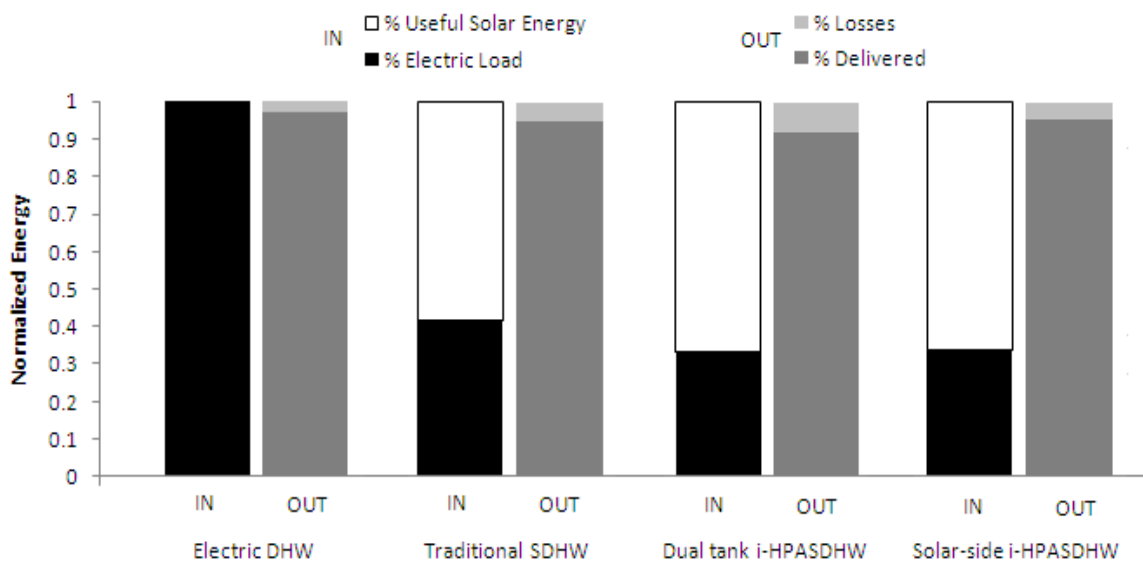


FIGURE 4.22 - NORMALIZED ENERGY INTO AND OUT OF EACH SYSTEM

The overall electrical usage (E_T) of each system directly correlated to the annual projected operating cost. According to Ontario Hydro, the electricity rate in 2009 was approximately \$0.075 per kilowatt-hour (Ontario Hydro, website). Using this value and converting the total electrical energy consumption to kilowatt-hours for each system, the annual operating costs were projected for the four systems and are shown in Figure 4.23.

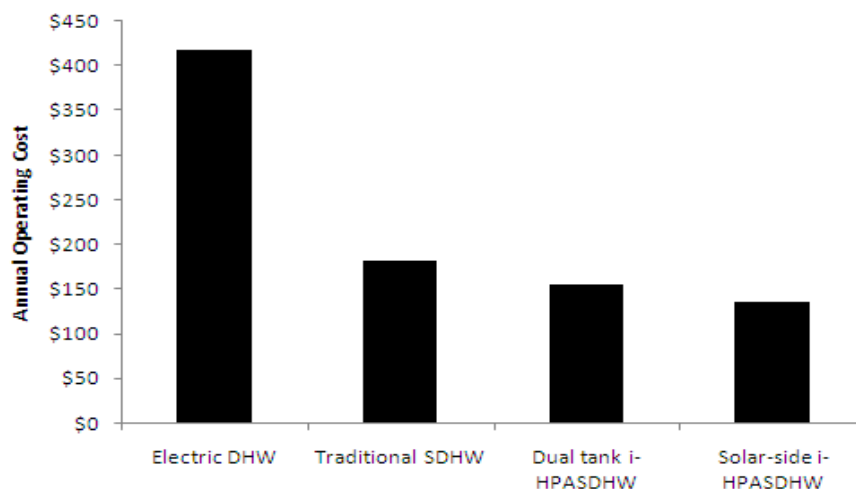


FIGURE 4.23 - ANNUAL OPERATING COSTS

The calculated annual operating costs for each system are also summarized in Table 4.11.

TABLE 4.11 - ANNUAL OPERATING COSTS

System	Annual Operating Cost
Electric DHW	\$418.13
Traditional SDHW	\$181.55
Dual tank i-HPASDHW	\$153.89
Solar-side i-HPASDHW	\$135.91

The Solar-side i-HPASDHW system had the lowest operating cost, followed by the Dual tank i-HPASDHW system. Therefore, for these two i-HPASDHW systems, implementing a heat pump into the design helped to

reduce the overall electrical consumption, increase the solar fraction, and thus, decrease the annual operating cost. The heat pump allowed the two systems to collect more solar energy by increasing the run times and efficiencies experienced by the solar loop, while reducing the overall electrical consumption. This was true because the increased amount of solar energy collected by the two i-HPASDHW systems greatly reduced the energy required from the auxiliary heaters. Also, redirecting some of the power from the auxiliary heaters to operate a heat pump was a much more efficient use of the power. This was reflected in the solar fractions (SF) calculated for each system (see Table 4.10). It should be noted that the traditional SDHW system alone was able to reduce the annual operating costs by approximately 56% compared to the electric DHW system. Compared to the traditional SDHW system, the Dual tank and Solar-side i-HPASDHW systems reduced the operating costs further by 15% and 25% respectively (see Table 4.11).

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The potential and feasibility of the two i-HPASDHW configurations examined were shown with the analysis of the simulation results. Out of the four systems modeled, the two heat pump assisted configurations proved to be the most energy efficient under the conditions considered. The Solar-side i-HPASDHW system had the lowest annual operating cost followed by the Dual tank i-HPASDHW system. Even with the additional components added to the configurations, the overall energy consumption of the two i-HPASDHW systems was considerably less than the two base systems.

Introducing a heat pump to the design allowed the system to circulate colder fluid through the collector which helped to increase the amount of energy collected, both daily and for the entire year. The Solar-side system used a small capacity heat pump directly to assist the solar loop, whereas the Dual tank system used a larger heat pump to transfer energy from the float tank to charge the domestic tank. Therefore, the Dual tank and Solar-side i-HPASDHW systems operated very differently from each other and this difference was reflected in their performances throughout the simulation period. The Dual tank i-HPASDHW system generally had longer solar loop run times in the winter and the Solar-side i-HPASDHW system had longer run times in the summer. This was true because of the difference in the performance of the two configurations under the seasonal weather conditions discussed in Chapter 4. The Dual tank i-HPASDHW system collected the most solar energy over the simulation period, but also had the highest tank losses to the surroundings and consumed more electric energy than the Solar-side system.

5.2 RECOMMENDATIONS

There are many places in the system configuration that the heat pump can be introduced and deciding where to put it and what capacity to use are not trivial decisions. Depending on the location, the weather that the system will experience will have a huge impact on the way that the system will function and what is required. There are also many other factors that will influence the performance of these heat pump assisted systems such as the water draw profile, collector size, tank size, and more. Therefore, it is important to understand that the results presented here were for the simulated conditions considered only and that the performance of these systems depended on many variables. That is why computer simulation is very important in the continuing development of implementing these i-HPASDHW systems.

It is also very important to understand that the results presented here were only for the simulated models. While the potential has been shown, prototype systems must be built, with properly sized equipment, and tested to get an accurate idea of the practical performance of each configuration considered. Once that stage is completed, detailed payback period calculations need to be performed for each configuration for the specific design conditions considered (location, water draw profile, etc.).

To further investigate the feasibility of the two i-HPASDHW systems presented in this work, there are many other things to consider. The next step is to examine their performance in different locations. For example, it would be beneficial to compare all of the systems operating in different cities all across Canada to potentially see which configuration will perform better in the various climates. Also, more realistic water draws for specific applications should be applied to observe the effects on the systems' performance. Finally, more configurations should be analyzed in order to get a better knowledge of how a heat pump can be used to assist in enhancing the overall performance of the system.

Appendix A

External Heat Pump Files

A.1 DUAL TANK I-HPASDHW SYSTEM

10.00 35.00 55.00 ! Values of Entering Load Temperatures in °C
-10.00 10.00 30.00 50.00 55.00 55.10 70.00 ! Values of Entering Source
Temperatures in °C

5.600	1.802	!Total Cooling(kW)and Power(kW) at 10.00/-10.00	HP
7.690	2.012	!Total Cooling(kW)and Power(kW) at 10.00/10.00	HP
9.747	2.232	!Total Cooling(kW)and Power(kW) at 10.00/30.00	HP
11.804	2.462	!Total Cooling(kW)and Power(kW) at 10.00/50.00	HP
12.833	2.676	!Total Cooling(kW)and Power(kW) at 10.00/55.00	HP
5.000	0.200	!Total Cooling(kW)and Power(kW) at 10.00/55.10	HE
7.000	0.200	!Total Cooling(kW)and Power(kW) at 10.00/70.00	HE
5.480	1.952	!Total Cooling(kW)and Power(kW) at 35.00/-10.00	****
7.496	2.192	!Total Cooling(kW)and Power(kW) at 35.00/10.00	
9.530	2.418	!Total Cooling(kW)and Power(kW) at 35.00/30.00	
11.558	2.656	!Total Cooling(kW)and Power(kW) at 35.00/50.00	
12.572	2.898	!Total Cooling(kW)and Power(kW) at 35.00/55.00	
2.500	0.200	!Total Cooling(kW)and Power(kW) at 35.00/55.01	
4.500	0.200	!Total Cooling(kW)and Power(kW) at 35.00/70.00	
5.375	2.092	!Total Cooling(kW)and Power(kW) at 55.00/-10.00	
7.385	2.330	!Total Cooling(kW)and Power(kW) at 55.00/10.00	
9.360	2.588	!Total Cooling(kW)and Power(kW) at 55.00/30.00	
11.341	2.847	!Total Cooling(kW)and Power(kW) at 55.00/50.00	
11.684	3.118	!Total Cooling(kW)and Power(kW) at 55.00/55.00	
0.000	0.200	!Total Cooling(kW)and Power(kW) at 55.00/55.01	
2.000	0.200	!Total Cooling(kW)and Power(kW) at 55.00/70.00	

A.2 SOLAR-SIDE I-HPASDHW SYSTEM

10.00 35.00 80.00 ! Values of Entering Load Temperatures in °C

-10.00 10.00 30.00 50.00 60.00 80.00 ! Values of Entering Source
Temperatures in °C

0.933	0.300	!Total Cooling(kW)and Power(kW) at 10.00/-10.00	HP
1.282	0.335	!Total Cooling(kW)and Power(kW) at 10.00/10.00	HP
1.625	0.372	!Total Cooling(kW)and Power(kW) at 10.00/30.00	HP
1.967	0.411	!Total Cooling(kW)and Power(kW) at 10.00/50.00	HP
2.311	0.446	!Total Cooling(kW)and Power(kW) at 10.00/60.00	HP
2.667	0.480	!Total Cooling(kW)and Power(kW) at 10.00/80.00	HP
0.913	0.325	!Total Cooling(kW)and Power(kW) at 35.00/-10.00	*****
1.249	0.365	!Total Cooling(kW)and Power(kW) at 35.00/10.00	
1.589	0.403	!Total Cooling(kW)and Power(kW) at 35.00/30.00	
1.926	0.443	!Total Cooling(kW)and Power(kW) at 35.00/50.00	
2.265	0.483	!Total Cooling(kW)and Power(kW) at 35.00/60.00	
2.633	0.523	!Total Cooling(kW)and Power(kW) at 35.00/80.00	
0.882	0.349	!Total Cooling(kW)and Power(kW) at 80.00/-10.00	
1.217	0.389	!Total Cooling(kW)and Power(kW) at 80.00/10.00	
1.537	0.431	!Total Cooling(kW)and Power(kW) at 80.00/30.00	
1.863	0.475	!Total Cooling(kW)and Power(kW) at 80.00/50.00	
2.005	0.519	!Total Cooling(kW)and Power(kW) at 80.00/60.00	
2.167	0.567	!Total Cooling(kW)and Power(kW) at 80.00/80.00	

Appendix B

TRNSYS COMPONENTS (TRNSYS, 2006)

All of the documentation in Appendix B was taken from the following file located in the TRNSYS help menu: *TRNSYS 16 Volume 5: Mathematical Reference* (TRNSYS, 2006). The TRNSYS components included in this section include:

1. Type4: Stratified Fluid Storage Tank (pg. 117)
2. Type14: Time dependent forcing function (pg. 122)
3. Type11: Tee Piece, Flow Diverter, Flow Mixer, Tempering Valve (pg. 124)
4. Type6: Auxiliary Heater (pg. 128)
5. Type3: Variable Speed Pump (pg. 130)
6. Type1: Flat-plate Collector (pg. 132)
7. Type109: Combined Data Reader and Solar Radiation Processor (pg. 138)
8. Type5: Heat Exchanger (pg. 144)
9. Type2: Differential Controller (pg. 149)
10. Type62: Calling Excel (pg. 151)
11. Type65: Online Plotter (pg. 152)
12. Type25: Printer (pg. 156)
13. Type24: Quantity Integrator (pg. 158)

5.12.12 Type 4: Stratified Fluid Storage Tank

The thermal performance of a fluid-filled sensible energy storage tank, subject to thermal stratification, can be modeled by assuming that the tank consists of N ($N \leq 15$) fully-mixed equal volume segments, as shown in Figure 5.12.12-1. The degree of stratification is determined by the value of N . If N is equal to 1, the storage tank is modeled as a fully-mixed tank and no stratification effects are possible. Options of fixed or variable inlets, unequal size nodes, temperature deadband on heater thermostats, incremental loss coefficients, and losses to gas flue of auxiliary heater are all available.

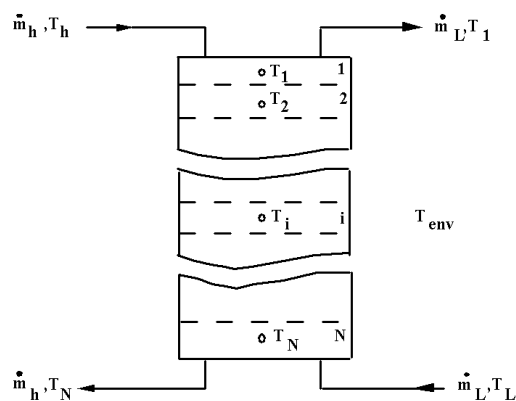


Figure 5.12.12-1: Stratified Fluid Storage Tank

5.12.12.1 Nomenclature

A_i	surface area of the i th tank segment
C_{pf}	specific heat of the tank fluid
H_i	height of i th segment
i	tank segment with the top (hottest) segment having $i = 1$
I_1	number of the tank segment in which the first heater is located $1 \leq I_1 \leq N$
I_2	number of the tank segment in which the second heater is located $1 \leq I_2 \leq N$
$I_{T,1}$	node position of entering flow from heat source $1 \leq I_{T,1} \leq N$
$I_{T,2}$	node position of return flow from load $1 \leq I_{T,2} \leq N$
$I_{T,1}$	number of the tank segment in which the thermostat of the first heater is located $1 \leq I_{T,1} \leq N$
$I_{T,2}$	number of the tank segment in which the second heater thermostat is located $1 \leq I_{T,2} \leq N$
M_i	mass of fluid in the i th section
\dot{m}_L	fluid mass flow rate to the load and/or of the makeup fluid
\dot{m}_h	fluid mass flow rate to tank from the heat source
N	number of fully mixed (uniform temperature) tank segments ($N \leq 15$)

\dot{Q}_{aux}	total rate of energy input by the heater
$\dot{Q}_{aux,1}$	rate of energy input by the first auxiliary heater
$\dot{Q}_{aux,2}$	rate of energy input by the second auxiliary heater
\dot{Q}_{env}	rate of energy loss from the tank to the surroundings, including boiling effects if applicable
$\dot{Q}_{HE,1}$	maximum rate of energy input by the first heater
$\dot{Q}_{HE,2}$	maximum rate of energy input by the second heater
\dot{Q}_i	rate of energy input by the heating element to the i th segment
\dot{Q}_{in}	rate of energy input to tank from hot fluid stream
\dot{Q}_{rec}	the rate of energy input by the heater necessary for all segments $i \leq l$ to be raised to the set temperature
\dot{Q}_s	rate at which sensible energy is removed from the tank to supply the load
S_h	number of the tank segment to which the fluid from the heat source enters $1 \leq S_h \leq N$
S_L	number of the tank segment to which the fluid replacing that extracted to supply the load enters $1 \leq S_L \leq N$
t	time
\bar{T}	average storage temperature
T_{env}	temperature of the environment surrounding the tank
T_i	temperature of the i th tank segment
T_f	average temperature of exhaust flue when heater is not operating
T_h	temperature of the fluid entering the storage tank from the heat source
T_L	temperature of the fluid replacing that extracted to supply the load
$T_{set,1}$	set temperature of the first heater thermostat
$T_{set,2}$	set temperature of the second heater thermostat
U_t	loss coefficient between the tank and its environment (per unit area)
ΔU_j	incremental loss coefficient between the i th tank node and its environment (per unit area)
$(UA)_f$	total conductance for heat loss to gas flue when auxiliary heater is not operating
$(UA)_{f,i}$	conductance for heat loss to gas flue for node i
V_t	tank volume
ΔE	internal energy change of the tank
$\Delta T_{db,1}$	first thermostat temperature deadband. Heater turns on when $T_{ T1} = (T_{set,1} - \Delta T_{db,1})$ and stays on until $T_{ T1} = T_{set,1}$
$\Delta T_{db,2}$	second thermostat temperature deadband. Heater turns on when $T_{ T2} = (T_{set,2} - \Delta T_{db,2})$ and stays on until $T_{ T2} = T_{set,2}$
α_i	a control function defined by $\alpha_i = 1$ if $i = S_h$; 0 otherwise
β_j	a control function defined by $\beta_j = 1$ if $j = S_L$; 0 otherwise
γ_i	a control function defined by $\gamma_i = \dot{m}_h \sum_{j=1}^{i-1} \alpha_j - \dot{m}_L \sum_{j=i+1}^N \beta_j$

γ_f	a control function that defines if the auxiliary heater is off or on. 1 is off, 0 is on
γ_{htr}	an optional control function input (0 or 1) that disables or enables the internal auxiliary heater
ρ_f	fluid density

5.12.12.2 Mathematical description

OPERATION MODES

In **mode 1**, flow streams enter the tank at fixed positions. The load flow enters at the bottom of the tank and the hot source stream enters just below the auxiliary, if present, or at the top of the tank if no auxiliary is specified. At the end of each time interval, any temperature inversions that exist are eliminated by total mixing of the appropriate adjacent nodes.

In **mode 2**, the flowstream enters the node that is closest to it in temperature. With sufficient nodes, this permits a maximum degree of stratification.

In **mode 3**, the user must specify the nodes containing the load flow and source flow inlet locations.

The user may specify the height of each node using parameters 6 through 5+N. Optionally, equal size nodes may be specified most simply by setting parameter 6 to a negative number such that the total tank height is the absolute value of parameter 6. In this case, no additional node size specifications are required.

INTERNAL AUXILIARY HEATERS

The model optionally includes two electric resistance heating elements, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during selected periods of each day (e.g., off-peak hours). The electric resistance heaters may operate in one of two modes. The first mode, a master/slave relationship, allows the bottom heating element to be enabled only when the top element is satisfied. In this control mode, it is impossible for both electric heaters to be on simultaneously. However, it is possible for both heaters to be on during the same timestep (upper heater may be on during first half of the timestep and lower heater may be on during the second half of the timestep). Mode 1 is common to most domestic hot water applications. In mode 2, both heaters may be on simultaneously. This allows for quicker heating of the storage tank, but at a significantly higher electric demand. If no electric heating elements are present in the tank to be modeled, set the maximum auxiliary heating rate to zero (do not set the node locations to zero).

The auxiliary heaters employ a temperature deadband. The heater is enabled if the temperature of the node containing the thermostat is less than $(T_{set} - \Delta T_{db})$ or if it was on for the previous interval and the thermostat temperature is less than T_{set} . If the lower heater meets these criteria and the master/slave relationship is employed, a check will be made to see if the upper electric heater is on before enabling the second heating element.

THERMAL LOSSES

In many circumstances, the tank may not be uniformly insulated or users may wish to account for pipe entrances on the storage tank. With version 14, it became possible for users to incrementally insulate certain nodes of stratified storage tanks by the specification of additional parameters. To utilize the incremental loss coefficients, users must set the fifth parameter less than zero and specify the incremental loss coefficients. The loss coefficient for the *i*th node is then:

$$U_i = |\text{PAR } 5| + \Delta U_i$$

A pressure relief valve has been added to the storage tank to account for boiling effects. The user must specify the boiling temperature of the fluid; venting will release sufficient energy to keep the tank at the boiling temperature. The loss of mass due to venting has been neglected.

The model allows for losses to the exhaust flue of an in-tank gas auxiliary heater. The overall loss from any node above and including the auxiliary heater occurs from the exterior and interior of the tank. The user specifies the overall conductance for heat loss to the flue when the heater is not operating, $(UA)_f$, based upon an environmental temperature of T_{env} . This conductance is divided among the nodes above and including the heater.

FLOW STREAMS

An assumption, employed in this model, is to assume that the fluid streams flowing up and down from each node are fully mixed before they enter each segment. In terms of Figure 5.12.12–2, this implies that \dot{m}_1 is added to \dot{m}_4 , \dot{m}_2 is added to \dot{m}_3 , and a resultant flow, either up or down, is determined. An energy balance on the *i*th segment (neglecting losses) is then:

$$M_i C_{pf} \frac{dT_i}{dt} = \begin{cases} (\dot{m}_1 - \dot{m}_3) C_{pf} (T_{i-1} - T_i) & \dot{m}_1 \geq \dot{m}_3 \\ (\dot{m}_3 - \dot{m}_1) C_{pf} (T_{i+1} - T_i) & \dot{m}_1 < \dot{m}_3 \end{cases} \quad \text{Eq 5.12.12-1}$$

It has been found that this latter assumption generally permits a higher degree of stratification than the former and yields results that agree well with experimental measurements (1).

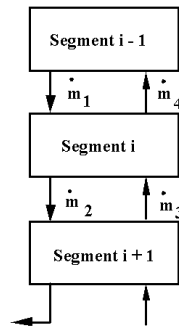


Figure 5.12.12–2: Flowstreams between Segments

The auxiliary heater is off if $\gamma_{htr} = 0$ or if it was previously off and $T_{IT} \geq (T_{set} - \Delta T_{db})$ or if $T_{IT} \geq T_{set}$. Otherwise, the rate of energy delivered to the tank from the heater is $\dot{Q}_{aux} = \min(\dot{Q}_{reg}, \dot{Q}_{max})$. If a master/slave relationship is specified between the two auxiliary heaters, the lower auxiliary heater is also off if the first auxiliary heater is on. The model assumes that energy supplied to the tank from the heater is placed in the tank segment containing the heater, until the temperature of that segment is equal to that of the segment above. Then, energy is added equally to both segments until they reach the temperature of the segment above them, etc. If both heating elements are allowed to be on simultaneously, the upper element effects are calculated first, followed by the lower element.

An energy balance written about the i th tank segment is expressed:

$$\begin{aligned}
 M_i C_{pf} \frac{dT_i}{dt} &= \alpha_i \dot{m}_h C_{pf} (T_h - T_i) + \beta_i \dot{m}_L C_{pf} (T_L - T_i) + U A_i (T_{env} - T_i) \\
 &+ \gamma_i (T_{i-1} - T_i) C_{pf} \quad \text{if } g_i > 0 \\
 &+ \gamma_i (T_i - T_{i+1}) C_{pf} \quad \text{if } g_i < 0 \\
 &+ \dot{Q}_i \quad \text{for } i = 1, N
 \end{aligned}
 \tag{Eq 5.12.12-2}$$

The temperatures of each of the N tank segments are determined by the integration of their time derivatives expressed in the above equation as outlined in Section 1.10. At the end of each timestep, temperature inversions are eliminated by mixing appropriate adjacent nodes.

Energy flows and change in internal energy are calculated as follows:

$$\dot{Q}_{env} = \sum_{i=1}^N U A_i (T_i - T_{env}) + \gamma_f \sum_{i=1}^{i=N} (U A)_{f,i} (T_i - T_f)
 \tag{Eq 5.12.12-3}$$

$$\dot{Q}_s = \dot{m}_L C_{pf} (T_1 - T_L)
 \tag{Eq 5.12.12-4}$$

$$\dot{Q}_{in} = \dot{m}_h C_{pf} (T_h - T_N)
 \tag{Eq 5.12.12-5}$$

$$\Delta E = \frac{V \rho_f C_{pf} \left[\sum_{i=1}^N T_i - \sum_{i=1}^N T_i \Big|_{t=TIME0} \right]}{N}
 \tag{Eq 5.12.12-6}$$

5.12.12.3 References

1. Klein, S.A., "A Design Procedure for Solar Heating Systems", Ph.D. Thesis, Department of Chemical Engineering, University of Wisconsin-Madison, (1976)

5.13.13 Type14: Time dependent forcing function

In a transient simulation, it is sometimes convenient to employ a time-dependent forcing function which has a behavior characterized by a repeated pattern. The purpose of this routine is to provide a means of generating a forcing function of this type. The pattern of the forcing function is established by a set of discrete data points indicating its values at various times through one cycle. Linear interpolation is provided in order to generate a continuous forcing function from this discrete data.

5.13.13.1 Nomenclature

TIME current value of time in simulation

C_T the cycle time (the time span after which the pattern repeats itself, which may be the total simulation time)

N the number of segments defining the function ($N+1$ points must be specified)

V_O the initial value of the forcing function (occurs at $TIME = 0, CT, 2CT, 3CT$ etc.)

V_i the value of the forcing function at point i

t_i the elapsed time from the start of the cycle at which point i and V_i are reached

\bar{V} the linearly interpolated average value of the function over the timestep

t_O the initial value of time. Must be zero if the function repeats itself. IF C_T is the total simulation time, t_O can be less than or equal to the initial simulation time

Δt the simulation timestep

5.13.13.2 Mathematical Description

The cycle must be completely specified requiring that t_N ($t_N = t_i$ at $i = N$) be greater than or equal to C_T .

\bar{V} , the average value of the function, is calculated as follows:

$$t_c = \text{MOD}(\text{TIME}, C_T) - \Delta t/2 \quad \text{Eq 5.13.13-1}$$

i is then found satisfying $t_{i-1} < t_c < t_i$ then

$$R = \frac{t_c - t_{i-1}}{t_i - t_{i-1}} \quad \text{Eq 5.13.13-2}$$

$$\bar{V} = V_{i-1} + R(V_i - V_{i-1}) \quad \text{Eq 5.13.13-3}$$

5.13.13.3 Special considerations

Both the instantaneous value of the forcing function are available as outputs. When step-like functions are to be defined, it is recommended to define the function by repeating each time value with two different values of V , and then use the average value (output(1)) in the simulation. This will guarantee the use of the exact same profile for any value of the time step.

E.g. to define an occupancy in a building between 8 AM and 5PM (occupancy is 0 at night, 1 during the day, and must change instantly from 0 to 1 and 1 to 0):

- Define the origin (time = 0, $V = 0$)
- Define the time at which the occupancy starts, repeating the value 0 (time = 8, $V = 0$)
- Repeat the time at which the occupancy stops with the value 1 (time = 8, $V = 1$)
- Define the time at which the occupancy stops, repeating the value 1 (time = 17, $V = 1$)
- Repeat the time at which the occupancy stops with the value 1 (time = 17, $V = 0$)
- Define the end of the period t_c (after that the cycle is repeated) (time = 24, $V = 0$)
- Use output(1) (average value over the time step)

5.6.13 Type 11: Tee Piece, Flow Diverter, Flow Mixer, Tempering Valve

The use of pipe or duct 'tee-pieces', mixers, and diverters, which are subject to external control, is often necessary in thermal systems. This component has ten modes of operation. Modes 1 through 5 are normally used for fluids with only one important property, such as temperature. Modes 6 through 10 are for fluids, such as moist air, with two important properties, such as temperature and humidity. Modes 1 and 6 simulate the function of a tee-piece that completely mixes two inlet streams of the same fluid at different temperatures and or humidities as shown in Figure 5.6.13–1. Modes 2 and 7 simulate the operation of a flow diverter with one inlet which is proportionally split between two possible outlets, depending on the value of g , an Input control function as shown in Figure 5.6.13–2. Modes 3 and 8 simulate the operation of a flow mixer whose outlet flow rate, temperature, and/or humidity is determined by mixing its two possible inlets in the proportion determined by g as shown in Figure 5.6.13–3. For modes 2, 3, 7, and 8, g must have a value between 0 and 1. Modes 4, 5, 9 and 10 are temperature controlled flow diverters that may be used to model tempering valves.

5.6.13.1 Nomenclature

m_i	mass flow rate of inlet fluid
m_o	mass flow rate of outlet fluid
m_1	mass flow rate at position 1 (See Figures)
m_2	mass flow rate at position 2 (See Figures)
T_h	heat source fluid temperature
T_i	temperature of inlet fluid
T_o	temperature of outlet fluid
T_{set}	maximum temperature of fluid supplied to load
T_1	temperature at position 1 (See Figures)
T_2	temperature at position 2 (See Figures)
γ	control function having a value between 0 and 1
ω_1	humidity ratio at position 1
ω_2	humidity ratio at position 2
ω_i	humidity ratio of inlet fluid
ω_o	humidity ratio of outlet fluid

5.6.13.2 Mathematical Description

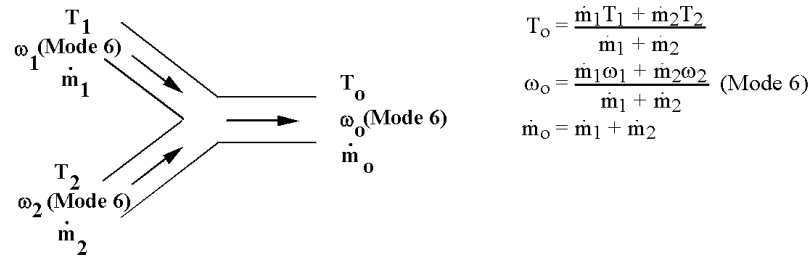


Figure 5.6.13–1: Mode 1 and 6: (Tee Piece)

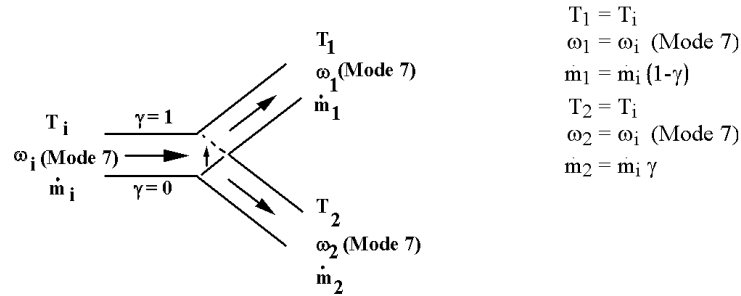


Figure 5.6.13–2: Mode 2 and 7: (Flow Diverter)

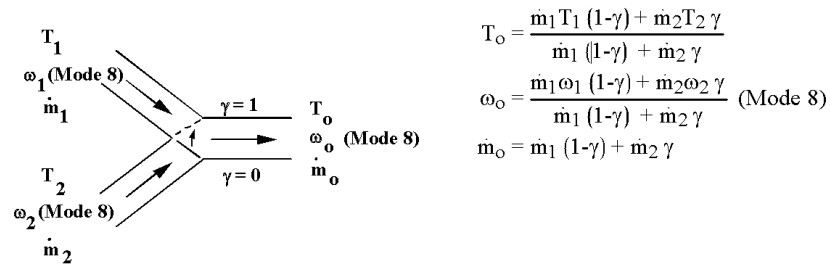


Figure 5.6.13–3: Mode 3 and 8: (Flow Mixer)

WARNING: The outlet temperatures are left unchanged from the previous call under no-flow conditions to avoid unnecessary calls to downstream components. As a result, the outlet temperatures should not be used for any control decisions.

Modes 4, 5, 9 and 10 are similar to modes 2 and 7 except that γ is calculated by the Type 11 routine. In domestic, commercial and industrial heating applications, it is common to mix heated fluid with colder supply fluid so that the flow stream to the load is no hotter than necessary. Often this is accomplished by placing a "tempering valve" in the storage outlet stream (position A on Figure 5.6.13–4 below). Such a valve relies on the supply pressure to drive fluid through the heat source and bypass lines in proportion to the valve setting.

Although thermally equivalent, it is better for simulation purposes to place a temperature controlled flow diverter at point B (in the figure below) than to place a temperature controlled mixer at point A. Modes 4 and 5 of Type 11 are designed for this purpose. The control function γ is set so that if flow stream 1 displaces fluid of temperature T_h , the mixed fluid temperature will not exceed the temperature T_{set} . Modes 4 and 9 differ from 5 and 10 in that Modes 4 and 9 send the entire flow stream through outlet 1 when $T_h < T_i$, while Modes 5 and 10 send the entire flow stream through outlet 2 when $T_h < T_i$

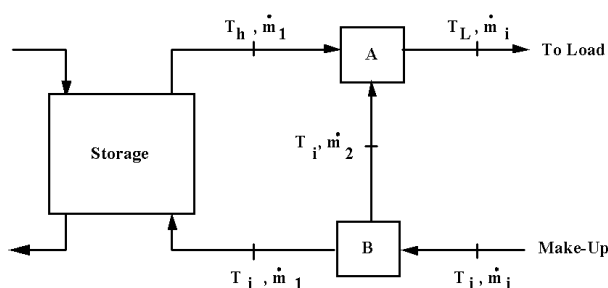


Figure 5.6.13–4: Example of Tempering Valve Use

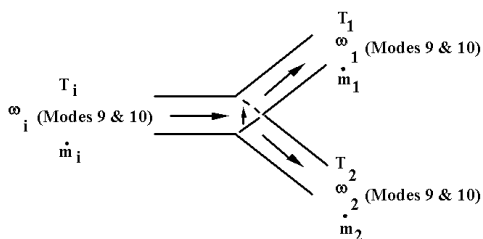


Figure 5.6.13–5: Modes 4, 5, 9, and 10 (Tempering Valve)

Table 5.6.13-1:

$T_1 = T_i$	$\gamma = (T_{\text{set}} - T_i)/(T_h - T_i)$	if $T_h > T_{\text{set}}$
$\omega_1 = \omega_i$ (Modes 9 & 10)	$\gamma = 1$	if $T_i \leq T_h \leq T_{\text{set}}$
$\dot{m}_1 = \dot{m}_i (\gamma)$	$\gamma = 1$	if $T_h < T_i$ (Modes 4 & 9)
$T_2 = T_i$	$\gamma = 0$	if $T_h < T_i$ (Modes 5 & 10)
$\omega_2 = \omega_i$ (Modes 9 & 10)	Note: The control function γ will not be changed after NSTK iterations at the same time step.	
$\dot{m}_2 = \dot{m}_1 (1 - \gamma)$	Also Note: T_{set} must be $\geq T_i$ at all times.	

5.4.12 Type 6: Auxiliary heater

An auxiliary heater is modeled to elevate the temperature of a flowstream using either internal control, external control or a combination of both. The heater is designed to add heat to the flowstream at a rate less than or equal to \dot{Q}_{\max} , which is a user determined quantity, whenever the control function γ is equal to 1 and the outlet temperature is less than the setpoint T_{set} .

By specifying a constant value of γ equal to 1 and a sufficiently large value for \dot{Q}_{\max} , Type 6 will perform like a domestic hot water auxiliary heater with internal control to maintain an outlet temperature of T_{set} .

By providing a control function of 0 or 1 and setting T_{set} to a very high value with a reasonably low value of \dot{Q}_{\max} , Type 6 will perform like an externally controlled ON/OFF heating device.

Users should be aware that the maximum thermal energy transfer to the flowstream is not \dot{Q}_{\max} but $\eta_{\text{htr}} \cdot \dot{Q}_{\max}$.

5.4.12.1 Nomenclature

Cpf	[kJ/kg.K]	fluid specific heat
\dot{m}_i	[kg/hr]	inlet fluid mass flow rate
\dot{m}_o	[kg/hr]	outlet fluid mass flow rate
\dot{Q}_{aux}	[kJ/hr]	required heating rate including efficiency effects
\dot{Q}_{fluid}	[kJ/hr]	rate of heat addition to fluid stream
\dot{Q}_{loss}	[kJ/hr]	rate of thermal losses from heater to environment
\dot{Q}_{max}	[kJ/hr]	maximum heating rate of heater
Tenv	[C]	temperature of heater surroundings for loss calculations
Ti	[C]	fluid inlet temperature
To	[C]	fluid outlet temperature
Tset	[C]	set temperature of heater internal thermostat
UA	[kJ/hr]	overall loss coefficient between the heater and its surroundings during operation
γ	[-]	external control function which has values of 0 or 1
η_{htr}	[0..1]	efficiency of auxiliary heater

5.4.12.2 Mathematical Description

If $T_i \geq T_{\text{set}}$, $\dot{m}_i \leq 0$, or $\gamma = 0$ then

$$T_o = T_i, \dot{m}_o = \dot{m}_i, \dot{Q}_{\text{loss}} = 0, \dot{Q}_{\text{fluid}} = 0, \text{ and } \dot{Q}_{\text{aux}} = 0$$

Otherwise, an energy balance on the steady-state heater reveals:

$$T_o = \frac{\dot{Q}_{\text{max}} \eta_{\text{htr}} + \dot{m} C_{\text{pf}} T_i + UA T_{\text{env}} - \frac{UA T_i}{2}}{\dot{m} C_{\text{pf}} + \frac{UA}{2}} \quad \text{Eq. 5.4-1}$$

$$\dot{m}_o = \dot{m}_i$$

$$\dot{Q}_{\text{aux}} = \dot{Q}_{\text{max}}$$

$$\dot{Q}_{\text{fluid}} = \dot{m}_o C_{\text{pf}} (T_o - T_i) \quad \text{Eq. 5.4-2}$$

$$\bar{T} = \frac{(T_o + T_{\text{in}})}{2} \quad \text{Eq. 5.4-3}$$

$$\dot{Q}_{\text{loss}} = UA (\bar{T} - T_{\text{env}}) + (1 - \eta_{\text{htr}}) \dot{Q}_{\text{max}} \quad \text{Eq. 5.4-4}$$

Unless $T_o > T_{\text{set}}$, then

$$T_o = T_{\text{set}},$$

$$\dot{m}_o = \dot{m}_i,$$

$$\dot{Q}_{\text{fluid}} = \dot{m}_o C_{\text{pf}} (T_{\text{set}} - T_i) \quad \text{Eq. 5.4-5}$$

$$\bar{T} = \frac{(T_{\text{set}} + T_{\text{in}})}{2} \quad \text{Eq. 5.4-6}$$

$$\dot{Q}_{\text{aux}} = \frac{\dot{m} C_{\text{pf}} (T_{\text{set}} - T_i) + UA (\bar{T} - T_{\text{env}})}{\eta_{\text{htr}}} \quad \text{Eq. 5.4-7}$$

where: $\dot{Q}_{\text{aux}} = \dot{Q}_{\text{loss}} + \dot{Q}_{\text{fluid}}$

5.6.12 Type 3: Variable Speed Pump or Fan without Humidity Effects

This pump or fan model computes a mass flow rate using a variable control function, which must be between 0 and 1, and a fixed (user specified) maximum flow capacity. Pump or fan power consumption may also be calculated, either as a linear function of mass flow rate or by a user-defined relationship between mass flow rate and power consumption. With the release of TRNSYS version 14, a user-specified fraction of the pump/fan power is converted to fluid thermal energy. Due to this addition, Input files written for TRNSYS versions 13.1 and earlier that call the Type 3 subroutine will have to be modified. No modifications to TRNSYS 14 or TRNSYS 15 pump descriptions will be needed to run in TRNSYS 16.

In many systems, there is no continuous flow modulation and the control function is either 0 or 1. In this case, the outlet flow rate and the power used are either both zero or both at their maximum values.

It is imperative that the user realizes that the Type 3 routine sets the fluid flow rate for components downstream of the pump. The inlet fluid flow rate Input to the Type 3 routine is used for convergence checking only.

5.6.12.1 Nomenclature

C_i	coefficient of polynomial relating P/P_{\max} to \dot{m}/\dot{m}_{\max}
C_p	specific heat of fluid
f_{par}	fraction of pump/fan power converted to fluid thermal energy
\dot{m}	pump mass flow rate
\dot{m}_{\max}	maximum flow rate (when $\gamma = 1$)
P	power consumption of pump or fan
P_{\max}	maximum power consumption (when $\gamma = 1$)
T_i	inlet fluid temperature
T_o	outlet fluid temperature
γ	control function ($0 \leq \gamma \leq 1$)

5.6.12.2 Mathematical Description

The outlet temperature is calculated as

$$T_o = T_i + \frac{P * f_{\text{par}}}{\dot{m} C_p} \quad \text{Eq. 5.6-1}$$

The outlet mass flow rate is simply

$$\dot{m}_o = \gamma \dot{m}_{\max} \quad \text{Eq. 5.6-2}$$

If only the required PARAMETERS are provided, a linear relationship between flow rate and power consumption is assumed:

$$P = \gamma P_{\max} \quad \text{Eq. 5.6-3}$$

If more than four PARAMETERS are provided, the additional parameters are used as coefficients in a polynomial relating power consumption to flow rate:

$$P = 0, \quad T_O = T_{in} \quad \text{if } \dot{m} = 0 \quad \text{Eq. 5.6-4}$$

or

$$P = P_{\max} [c_0 + c_1 \dot{\gamma} + c_2 \dot{\gamma}^2 + \dots + c_i \dot{\gamma}^i] \quad \text{if } \dot{m} > 0 \quad \text{Eq. 5.6-5}$$

where $c_0, c_1, c_2, \dots, c_i$ are entered as optional PARAMETERS 5, 6, 7, ..., $i+5$.

5.11.12 Type 1: Flat-plate collector (Quadratic efficiency)

This component models the thermal performance of a variety of collector types using theory. The total collector array may consist of collectors connected in series and in parallel. The thermal performance

of the total collector array is determined by the number of modules in series and the characteristics of each module. The user must provide results from standard tests of efficiency versus a ratio of fluid temperature minus ambient temperature to radiation ($\Delta T/l_T$). The fluid temperature may be an inlet, average, or outlet temperature. The model assumes that the efficiency vs. $\Delta T/l_T$ curve can be modeled as a quadratic equation. Corrections are applied to the slope, intercept, and curvature parameters to account for the presence of a heat exchanger, identical collectors in series, and flow rates other than those at test conditions.

There are four possibilities for considering the effects of off-normal solar incidence. Optical modes 2 and 3 require test data for single-axis incidence angle modifiers. Optical mode 4 determines modifiers from properties of the covers. In the fifth optical mode, the user must enter bi-axial incidence angle modifier data. This is useful for considering non-optically symmetric collectors such as evacuated tubes, etc. If the optical mode is set to 1, no off-normal incidence effects are considered.

5.11.12.1 Nomenclature

A	[m ²]	Total collector array aperture or gross area (consistent with $F_R(\tau\alpha)$, F_{RU_L} , $F_{RU_{L/T}}$ and G_{test})
A _a	[m ²]	Aperture area of a single collector module
A _r	[m ²]	Absorber area of a single collector module
a ₀	[-]	Intercept (maximum) of the collector efficiency (Eq 5.11.12-3)
a ₁	[kJ/h-m ² -K]	Negative of the first-order coefficient in collector efficiency equation
a ₂	[kJ/h-m ² -K ²]	Negative of the second-order coefficient in collector efficiency equation
b ₀	[-]	Negative of the 1 st -order coefficient in the Incident Angle Modifier curve fit equation (Eq 5.11.12-13)
b ₁	[-]	Negative of the 2 nd -order coefficient in the IAM curve fit equation
C _{pf}	[kJ/kg-K]	Specific heat of collector fluid
C _{min}	[kJ/h-K]	Minimum capacitance rate (mass flow times specific heat) of heat exchanger flow streams
F _R	[-]	Overall collector heat removal efficiency factor
F _{av}	[-]	Modified value of F _R when the efficiency is given in terms of T _{av} , not T _i
F _o	[-]	Modified value of F _R when the efficiency is given in terms of T _o , not T _i
I	[kJ/h-m ²]	Global (total) horizontal radiation
I _d	[kJ/h-m ²]	Diffuse horizontal radiation
I _T	[kJ/h-m ²]	Global radiation incident on the solar collector (Tilted surface)

I_{bT}	[kJ/h-m ²]	Beam radiation incident on the solar collector
\dot{m}	[kg/h]	Flowrate at use conditions
\dot{m}_{test}	[kg/h]	Flowrate in test conditions
N_S	[-]	Number of identical collectors in series
T_a	[°C]	Ambient (air) temperature
T_{av}	[°C]	Average collector fluid temperature
T_i	[°C]	Inlet temperature of fluid to collector
T_o	[°C]	Outlet temperature of fluid from collector
U_L	[kJ/h-m ² -K]	Overall thermal loss coefficient of the collector per unit area
$U_{L/T}$	[kJ/h-m ² -K ²]	Thermal loss coefficient dependency on T (see Eq 5.11.12-5)
α	[-]	Short-wave absorptance of the absorber plate
β	[°]	Collector slope above the horizontal plane
θ	[°]	Incidence angle for beam radiation
ρ_g	[-]	Ground reflectance
τ	[-]	Short-wave transmittance of the collector cover(s)
$(\tau\alpha)$	[-]	Product of the cover transmittance and the absorber absorptance
$(\tau\alpha)_b$	[-]	$(\tau\alpha)$ for beam radiation (depends on the incidence angle θ)
$(\tau\alpha)_n$	[-]	$(\tau\alpha)$ at normal incidence
$(\tau\alpha)_s$	[-]	$(\tau\alpha)$ for sky diffuse radiation
$(\tau\alpha)_g$	[-]	$(\tau\alpha)$ for ground reflected radiation

5.11.12.2 Mathematical Description

A general equation for solar thermal collector efficiency can be obtained from the Hottel-Whillier equation (Duffie and Beckman, 1991) as:

$$\eta = \frac{Q_u}{A I_T} = \frac{\dot{m} C_{pf}(T_o - T_i)}{A I_T} = F_R (\tau\alpha)_h - F_R U_L \frac{(T_i - T_a)}{I_T} \quad \text{Eq 5.11.12-1}$$

The loss coefficient U_L is not exactly constant, so a better expression is obtained by taking into account a linear dependency of U_L versus $(T_i - T_a)$:

$$\eta = \frac{Q_u}{A I_T} = F_R (\tau\alpha)_h - F_R U_L \frac{(T_i - T_a)}{I_T} - F_R U_{L/T} \frac{(T_i - T_a)^2}{I_T} \quad \text{Eq 5.11.12-2}$$

Eq 5.11.12-2 can be rewritten as:

$$\eta = a_0 - a_1 \frac{(\Delta T)}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \quad \text{Eq 5.11.12-3}$$

Which is the general solar collector thermal efficiency equation used in Type 1. The thermal efficiency is defined by 3 parameters: a_0 , a_1 and a_2 . Those 3 parameters are available for collectors tested according to ASHRAE standards and rated by SRCC (ASHRAE, 2003; SRCC, 1995), as well as for collectors tested according to the recent European Standards on solar collectors (CEN, 2001). Many examples of collector parameters can be found on the internet (e.g. SPF, 2004).

Note: It is important to make sure that collector area entered as a parameter match the area used when determining the values of a_0 , a_1 and a_2 . Typically, efficiency curves are provided for gross area in the US and aperture area in Europe

In Eq 5.11.12-3, ΔT is equal to $(T_i - T_a)$. Collector test reports sometimes provide the efficiency curve using a different temperature difference:

$$\Delta T = \begin{cases} \Delta T_i = T_i - T_a \\ \Delta T_{av} = T_{av} - T_a \\ \Delta T_o = T_o - T_a \end{cases} \quad \text{Eq 5.11.12-4}$$

The 1st formulation is usually preferred in the US, while the 2nd one is used in most European documents. Eq 5.11.12-2 can use any of those definitions of the temperature difference and the user can specify the a_0 , a_1 and a_2 coefficients using any of the definitions. If the coefficients are given in terms of the average or the outlet temperature, correction factors are applied. Those correction factors have been derived for linear efficiency curves (Eq 5.11.12-1), so Eq 5.11.12-2 must first be converted to that form by performing some manipulations. A modified first-order collector efficiency coefficient is defined:

$$U'_L = U_L + U_{L/T} (T_i - T_a) \quad \text{Eq 5.11.12-5}$$

Which gives

$$\eta = \frac{Q_u}{A I_T} = F_R (\tau\alpha)_n - F_R U'_L \frac{(T_i - T_a)}{I_T} \quad \text{Eq 5.11.12-6}$$

The correction factors are then given by (Duffie and Beckman, 1991):

$$\begin{cases} F_R (\tau\alpha) = F_{av} (\tau\alpha)_n \left(\frac{\dot{m}_{test} C_{pf}}{\dot{m}_{test} C_{pf} + \frac{F_{av} U'_L}{2}} \right) \\ F_R U'_L = F_{av} U'_L \left(\frac{\dot{m}_{test} C_{pf}}{\dot{m}_{test} C_{pf} + \frac{F_{av} U'_L}{2}} \right) \end{cases} \quad \text{Eq 5.11.12-7}$$

$$\begin{cases} F_R (\tau\alpha) = F_o (\tau\alpha)_n \left(\frac{\dot{m}_{test} C_{pf}}{\dot{m}_{test} C_{pf} + F_o U'_L} \right) \\ F_R U'_L = F_o U'_L \left(\frac{\dot{m}_{test} C_{pf}}{\dot{m}_{test} C_{pf} + F_o U'_L} \right) \end{cases} \quad \text{Eq 5.11.12-8}$$

5.11.12.3 Corrections to the ideal efficiency curve

Analytical corrections are applied to the collector parameters to account for:

- Operation at flow rates other than the value at test conditions
- N_s identical collectors mounted in series
- Non-normal solar incidence

These modifications are outlined in (Duffie and Beckman, 1991) and summarized as follows.

FLOW RATE CORRECTION

In order to account for conditions when the collector is operated at a flow rate other than the value at which it was tested, both $F_R (\tau\alpha)_n$ and $F_R U_L'$ are corrected to account for changes in F_R . The ratio, r_1 , by which they are corrected is given by:

$$r_1 = \frac{F_R U_L' |_{use}}{F_R U_L' |_{test}} = \frac{F_R (\tau\alpha)_n |_{use}}{F_R (\tau\alpha)_n |_{test}} = \frac{\frac{\dot{m} C_{pf}}{A F' U_L} \left(1 - e^{-\frac{A F' U_L}{\dot{m} C_{pf}}} \right) |_{use}}{\frac{\dot{m}_{test} C_{pf}}{A F' U_L} \left(1 - e^{-\frac{A F' U_L}{\dot{m}_{test} C_{pf}}} \right) |_{test}} \quad \text{Eq 5.11.12-9}$$

To use this equation, it is necessary to estimate $F' U_L$. That quantity can be calculated from the test conditions:

$$F' U_L = -\frac{\dot{m} C_{pf}}{A} \ln \left(1 - \frac{F_R U_L' A}{\dot{m} C_{pf}} \right) \quad \text{Eq 5.11.12-10}$$

For liquid collectors, $F' U_L$ calculated from the test conditions is approximately equal to $F' U_L$ at use conditions and can be used in both the numerator and denominator of Eq 5.11.12-9.

SERIES COLLECTORS

Both $F_R (\tau\alpha)_n$ and $F_R U_L'$ are analytically modified to account for identical collectors mounted in series. The ratio, r_2 , by which they are corrected is:

$$r_2 = \frac{1 - \left(1 - \frac{A F_R U_L'}{\dot{m} C_{pf}} \right)^{N_s}}{N_s \frac{A F_R U_L'}{\dot{m} C_{pf}}} \quad \text{Eq 5.11.12-11}$$

INCIDENCE ANGLE MODIFIER (IAM)

Collector tests are generally performed on clear days at normal incidence so that the transmittance - absorptance product $(\tau\alpha)$ is nearly the normal incidence value for beam radiation, $(\tau\alpha)_n$. The intercept efficiency, $F_R(\tau\alpha)_n$, is corrected for non-normal solar incidence by the factor $(\tau\alpha)/(\tau\alpha)_n$. By definition, $(\tau\alpha)$ is the ratio of the total absorbed radiation to the incident radiation. Thus, a general expression for $(\tau\alpha)/(\tau\alpha)_n$ is:

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT} \frac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d \left(\frac{1+\cos\beta}{2}\right) \frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho_g I \left(\frac{1-\cos\beta}{2}\right) \frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T} \quad \text{Eq 5.11.12-12}$$

For flat-plate collectors, $(\tau\alpha)_b/(\tau\alpha)_n$ can be approximated from ASHRAE test results (ASHRAE, 2003) as:

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0 \left(\frac{1}{\cos\theta} - 1\right) - b_1 \left(\frac{1}{\cos\theta} - 1\right)^2 \quad \text{Eq 5.11.12-13}$$

Note: Some collector tests only provide the IAM value at one incidence angle, typically 50°. In such case, it is recommended to use Optical Mode 2, assume that $b_1 = 0$ and calculate b_0 using Eq 5.11.12-3.

TYPE 1 OPTICAL MODES

5 optical modes can be selected to Input the IAM data:

- Optical mode 1: perfect IAM $(\tau\alpha)/(\tau\alpha)_n=1$ for any incidence angle
- Optical mode 2: the user specifies the values of b_0 and b_1 in Eq 5.11.12-13.
- Optical mode 3: values of $(\tau\alpha)_b/(\tau\alpha)_n$ versus θ are supplied in an external data file but the collector is assumed to be symmetrical so only one direction is provided in the data file (see here below).
- Optical mode 4: the function routine TAU_ALPHA (see Volume 08, Programmer's guide) is used to estimate incidence angle modifiers for beam radiation in terms of incidence angle and cover properties.
- Optical mode 5: values of $(\tau\alpha)_b/(\tau\alpha)_n$ versus θ are supplied in an external data file for both the longitudinal and transversal directions (see here below). Note that this mode is usually used to simulate evacuated collectors, for which it is recommended to use Type 71.

The incidence angle modifiers for both sky, $(\tau\alpha)_s/(\tau\alpha)_n$, and ground diffuse, $(\tau\alpha)_g/(\tau\alpha)_n$, are determined in modes 2-4 by defining equivalent incidence angles for beam radiation that give the same transmittance as for diffuse radiation (Duffie and Beckman, 1991). The effective incidence angles for sky diffuse and ground reflected radiation are:

$$\theta_{\text{sky}} = 59.68 - 0.1388 \beta + 0.001497 \beta^2 \quad (\text{in degrees}) \quad \text{Eq 5.11.12-14}$$

$$\theta_{\text{gnd}} = 90.00 - 0.5788 \beta + 0.002693 \beta^2 \quad (\text{in degrees}) \quad \text{Eq 5.11.12-15}$$

5.11.12.4 External data files

Type 1 can optionally read the incidence angle modifier (IAM) data from an external data file. These data are read and interpolated by subroutine DYNAMICDATA (See Volume 08, Programmer's Guide). The data consists of between 2 and 10 values of incidence angles and modifiers. This section will only describe the data file used in Optical Mode 3. Optical Mode 5 (bidirectional IAM's) is typically used for evacuated tube collectors, for which it is recommended to use Type 71. The data file used in Optical Mode 5 is the same as the data file used by Type 71, and is described in section 5.11.14.4, page 5–344.

DATA FILE FOR OPTICAL MODE 3

Type 1 optionally reads the IAM values from a data file. An example is provided in "Examples\Data Files". The data file format is as follows ($2 \leq N_a \leq 10$):

```
<Incidence angle 1> <Incidence angle 2> etc.      Na values [0;90]
<IAM 1>                                           IAM for angle 1
<IAM 2>                                           IAM for angle 1
...
<IAM Na>                                          IAM for angle Na
```

The principle of the data file is that the first line gives the values of the independent variable (incident angle) that will be used in the "IAM map". Then the dependent variable (IAM) is provided for all values of the independent variable. Data are read in free format.

Example

```
    0   10   20   30   40   50   60   70   80   90   ! Angle values
1.000 ! IAM for incident angle 1 ( 0)
0.997 ! IAM for incident angle 2 (10)
0.988 ! IAM for incident angle 3 (20)
...
0.644 ! IAM for incident angle 8 (70)
0.120 ! IAM for incident angle 9 (80)
0.000 ! IAM for incident angle 10 (90)
```

5.11.12.5 References

ASHRAE, 2003 - Standard 93-2003: Methods of testing to determine the performance of solar collectors, ASHRAE, Atlanta

CEN, 2001. EN 12975-2:2001. Thermal solar systems and components – Solar collectors – Part 2: Test methods. European Committee for Standardization, Brussels, Belgium. (www.cenorm.be)

Duffie J.A. and Beckman W.A., 1991. Solar Engineering of Thermal Processes – Second Edition, Wiley-Interscience, New York

Solar Rating and Certification Corporation, 1995. SRCC Standard 100. Test Methods and Minimum Standards for certifying Solar Collectors. Available on www.solar-ratings.org

SPF, 2004 - Institut für Solartechnik SPF, online collector test reports on www.spf.ch

5.14.12 Type 109: Combined data reader and solar radiation processor

This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and generating direct and diffuse radiation outputs for an arbitrary number of surfaces with arbitrary orientation and inclination.

Type 109 reads some standard weather data file formats, as well as a user-specified format according to a syntax explained here below.

5.14.12.1 Nomenclature

A_i	Anisotropy index
a_i	Addition factor for the i th value
a/c	Weighted circumsolar solid angle
f	Modulating factor for Reindl tilted surface model
F_1'	Reduced brightness coefficient (circumsolar)
F_2'	Reduced brightness coefficient (horizon brightening)
I_0	Extraterrestrial radiation
I_{0n}	Extraterrestrial radiation at normal incidence
I_b	Beam radiation on horizontal surface
I_{bn}	Beam radiation at normal incidence
I_{bT}	Beam radiation on tilted surface
I_d	Diffuse radiation on horizontal surface
I_{dn}	Direct normal beam radiation
I_{dT}	Diffuse radiation on tilted surface
I	Total radiation on a horizontal surface
I_T	Total radiation on a tilted surface
I_{gT}	Ground reflected radiation on a tilted surface
K_T	Ratio of total radiation on a horizontal surface to extraterrestrial radiation
L_{loc}	Longitude of a given location
L_{unit}	Logical unit number from which data lines are to be read
m_i	Multiplication factor for the i th value
R_b	Ratio of beam radiation on tilted surface to beam on horizontal
R_d	Ratio of diffuse radiation on tilted surface to diffuse on horizontal

R_r	Ratio of reflected radiation on tilted surface to total radiation on horizontal
rh	Relative humidity (%)
T_a	Ambient temperature
$V_i(n)$	ith value read from the nth line
$V_i'(n)$	ith value of the nth line after application of the multiplication and addition factors
Y_i	ith time interpolated value
α	Solar altitude angle ($90 - \theta_z$)
β	Slope of surface, positive when tilted in the direction of the azimuth specification
β'	Slope of tracking axis
δ	Solar declination angle
Δ_{td}	Time interval at which data is provided (e.g., $\Delta_{td} = 1$ for hourly data).
Δ	Sky brightness parameter
ε	Sky clearness parameter
γ	Azimuth angle of surface; angle between the projection of the normal to the surface into the horizontal plane and the local meridian. (facing equator = 0, west positive, east negative)
γ'	Azimuth angle of axis; angle between the projection of the axis line onto the horizontal plane and local meridian. (Same sign convention as for γ)
γ_s	Solar azimuth angle
θ	Angle of incidence of beam radiation on surface
θ_z	Solar zenith angle
ρ_g	Ground reflectance
ϕ	Latitude

5.14.12.2 Operation modes

There are four different modes of weather data format handling:

- a userdefined mode (MODE 1) for arbitrary weather data
- MODE 2 to read in TMY2-data format
- MODE 3 to read in the German TRY-data format
- VDI- MODEs 91x and 92x according to the german standard VDI 2078.

This data reader is also able to read in general data (which may be any kind of data without restriction to weather data), converting it to a desired system of units and making it available to other TRNSYS UNITS as time varying forcing functions.

TYPE 109 uses free-formatted reading for user defined data. Each value must be separated from the previous value by a blank or a comma for MODE 0 or MODE 1.

5.14.12.3 Special Considerations

- Up to 5 UNITS of TYPE 109 may be specified.
- The data from line to line must be at constant time intervals (e.g., hourly ambient temperature readings).
- In user defined data mode (MODE 0), values are output in the same sequence as they appear on the data lines, i.e. if the 3rd value on each data line is CO₂ concentration, then the 3rd OUTPUT will be the CO₂ concentration value.
In every weather data mode, the OUTPUTS have the same predefined order in order to facilitate the connection process.
- In user defined data mode (MODE 0), up to 20 comment lines may precede the data lines. Comment lines must not begin with a number.
- Outputs may or may not be interpolated between data timesteps depending upon the parameter specifications. For instance, if the number of occupants of a room were read in, these should not be interpolated.
- If Simulation ends with Weather Data containing radiation $\neq 0$ the output for radiation data is set to zero for the last hour of simulation.
- The wind direction in TRNSYS depends on the convention given in the weather data file. The standard file-formats indicated in the above table use as convention N=0°, E=90°, etc. The user must check that this convention is in accord with the specific component that will use the information later in the simulation (i.e., COMIS or CONTAM).

5.14.12.4 Mathematical Description

Type 109 uses the same algorithms as Type 16 to calculate solar radiation on tilted surfaces (with the same tilted surface radiation modes 1 to 4) and to calculate the position of one – and two-axes tracking surfaces. Please refer to section 5.10.12, page 5–285, for more details.

The Radiation data is checked for values > 0 before sunrise and after sunset and is interpolated for time steps smaller or larger than the time difference between two data lines. The internal radiation Processor generates direct and diffuse radiation outputs for an arbitrary number of surfaces with any azimuth and slope. Moreover, standard outputs are Temperature, relative humidity, wind velocity as well as wind direction. Up to four more data columns may be processed using user defined weather data in MODE 1.

HORIZONTAL RADIATION MODES

Type 109 needs two components of solar radiation (e.g. beam and diffuse horizontal) in order to calculate the radiation on a tilted surface. It can use different combinations:

- I_b and I_d
- I and I_d
- I and I_{bn}
- I , T_{amb} and RH. The diffuse radiation is estimated using Reindl's full correlation (6a)
- I . The diffuse radiation is estimated using Reindl's reduced correlation

5.14.12.5 Data file syntax in Mode 1

HEADER SYNTAX

The header contains keywords, followed by the respective values. Keywords are contained between <brackets>.

An example for the German location Würzburg is shown here below:

```

<userdefined>
<longitude> -9.9 ! East of greenwich: negative
<latitude> 49.8
<gmt> 1 !time shift from GMT, east: positive (hours)
<interval> 1 !Data file time interval between consecutive lines (hours)
<firsttime> 1 !Time corresponding to first data line (hours)
<var> IBEAM_H <col> 5 <interp> 0 <add> 0 <mult> 1 <samp> -1 !...to get radiation in W/m²
<var> IBEAM_N <col> 0 <interp> 0 <add> 0 <mult> 1 <samp> 0 !...to get radiation in W/m²
<var> IDIFF_H <col> 6 <interp> 0 <add> 0 <mult> 1 <samp> -1 !...to get radiation in W/m²
<var> IGLOBAL_H <col> 0 <interp> 0 <add> 0 <mult> 1 <samp> 0 !...to get radiation in W/m²
<var> TAMB <col> 3 <interp> 2 <add> 0 <mult> 1 <samp> 0 !...to get °C
<var> RHUM <col> 4 <interp> 1 <add> 0 <mult> 100 <samp> 0 !...to get rel. hum. in %
<var> WSPEED <col> 2 <interp> 1 <add> 0 <mult> 1 <samp> 0 !...to get wind speed in m/s
<var> WDIR <col> 1 <interp> 1 <add> 0 <mult> 1 <samp> 0 !...to get wind dir. in degr.
<var> udef1 <col> 12 <interp> 0 <add> 0 <mult> 100 <samp> 0 !...to get ... in ...
<var> test <col> 9 <interp> 1 <add> 0 <mult> 100 <samp> 0 !...to get ... in ...
<var> idefix <col> 8 <interp> 2 <add> 0 <mult> 100 <samp> 0 !...to get ... in ...
<var> udef4 <col> 11 <interp> 0 <add> 0 <mult> 100 <samp> 0 !...to get ... in ...
<data>
270 2.6 .7 .93 0 0 -10 3.2 1e3 .2 8 0 1
330 1.5 .6 .94 0 0 -11 3.2 2e3 .2 8.1 0 1
    
```

The whole header is enclosed by two keywords <userdefined> and <data>, marking the beginning and end of the header section:

```

<userdefined>
.
.
.
<data>
    
```

Inside this header, the following keywords *must* appear:

Keyword	Units	Description
<longitude>	VALUE (degrees)	east of greenwich: negative
<latitude>	VALUE (degrees)	
<gmt>	VALUE (hours)	time shift from GMT, east: positive if solar time ° write "solar"
<interval>	VALUE (hours)	data file time interval Δt_d between consecutive lines
<firsttime>	VALUE (hours)	time corresponding to first data line

It is extremely important to specify the correct values. Any difference in geographical data or time will lead to an artificial time shift. For radiation data, this results in a wrong amount of direct or diffuse radiation on tilted surfaces. This will cause warnings in the listing file:

```
***** WARNING FROM UNIT 12 TYPE 109 DATA READER
          RADIATION AT TIME 6.25 HAS A VALUE OF 23 BUT SUN IS DOWN
          IN DATA COLUMN 5 -- SUNRISE AT 6.67, SUNSET AT 17.21
```

Weather data variables are indicated by the keyword <var>, followed by specific names:

Specific Name	Description
IBEAM_H	Beam radiation on horizontal
IBEAM_N	Beam radiation at normal incidence
IDIFF_H	Sky diffuse radiation on horizontal
IGLOB_H	Global radiation on horizontal
TAMB	Ambient temperature
RHUM	Relative humidity of ambient air
WSPEED	Wind speed
WDIR	Wind direction

One or more of these variables have to appear in the user defined data header. Please use the variable names like indicated in the listing above, when the corresponding physical variable is available. There is special type of interpolation for radiation data, which can't be changed by the user, since behavior at sunrise and sunset has to be taken into account. Thus the values of the keyword <interp> are ignored for radiation data.

Up to 4 extra quantities can be read in, like "udef1" in the Würzburg example.

If the column number equals 0 inside a <var> definition line, this indicates to skip the information.

Moreover, information about the columns containing the respective values, the interpolation mode, the ability of data manipulation through addition and multiplication factors as well as the value which determines the data corresponding time interval are indicated by additional keywords. The keywords belong to a certain variable and have to appear in a one line statement and in a fixed order:

```
<var> NAME <col> VALUE <interp> VALUE <add> VALUE <mult> VALUE <samp> VALUE
```

Keyword	Value	Description
<col>		Number of the column for variable NAME. If value = 0, the variable will be skipped and the respective output set to zero
<interp>	0	No interpolation
	1	Linear interpolation
	2	Five point spline interpolation (Akima)
<add>		addition factor a_i
<mult>		multiplication factor m_i
<samp>	-1	column value is a mean value related to the time interval Δt_j ending at the time corresponding to actual data line

- 0 column value is a mean value related to the time interval $\Delta t_d/2$ before and after the time corresponding to actual data line
- 1 column value is a mean value related to the time interval Δt_d starting at the time corresponding to actual data line

Addition and multiplication factors have to be chosen in a way that values have the following units:

Variable	Unit
Radiation	[W/m ²]
Temperature	[°C]
Relative humidity	[%]
Wind speed	[m/s]
Wind direction	[degrees]

It is recommended to avoid spline interpolation for relative humidity data, because the smoothing of data may result in a relative humidity of more than 100% for data with a sudden increase from 90 to 99% for example. The same is valid for wind speed to avoid negative values. So spline interpolation is applicable in the case of temperature or additional user defined data columns.

5.14.12.6 References

1. SOLMET, Volume 2 - Final Report, "Hourly Solar Radiation Surface Meteorological Observations," TD-9724, (1979).
2. Randall, C.M. and Whitson, M.E., Final Report, "Hourly Insolation and Meteorological Data Bases Including Improved Direct Insolation Estimates," Aerospace Report No. ATR-78(7592)-I, (1977).
3. Duffie, J.A. and Beckman, W.A., Solar Energy Thermal Processes, Wiley, New York, 1974.
4. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1972.
5. Braun, J.E. and Mitchell, J.C., "Solar Geometry for Fixed and Tracking Surfaces," Solar Energy, vol. 31, No. 5, October, 1983.
6. (a) Reindl, D. T., Beckman, W. A., Duffie, J. A., "Diffuse Fraction Correlations", Solar Energy, Vol. 45, No. 1, 1990, pp. 1-7.
(b) Reindl, D. T., Beckman, W. A., Duffie, J. A., "Evaluation of Hourly Tilted Surface Radiation Models", Solar Energy, Vol. 45, No. 1, 1990, pp. 9-17.
7. Hay, J.E., Davies, J.A., "Calculation of The Solar Radiation Incident on An Inclined Surface", Proceedings First Canadian Solar Radiation Workshop, pp. 59-72, (1980).
8. Perez, R., Stewart, R., Seals, R., Guertin, T., "The Development and Verification of The Perez Diffuse Radiation Model", Sandia Report SAND88-7030, (Sandia National Laboratories, Albuquerque, New Mexico, 87185, USA) October, 1988.

5.3.12 Type 5: Heat Exchanger

A zero capacitance sensible heat exchanger is modeled in the parallel, counter, various cross flow configurations and shell and tube modes. For all modes, given the hot and cold side inlet temperatures and flow rates, the effectiveness is calculated for a given fixed value of the overall heat transfer coefficient. The cross flow modes assume one of the following.

1. That the hot (source) side fluid is unmixed while the cold (load) side is completely mixed
2. That the cold (load) side fluid is unmixed while the hot (source) side is completely mixed
3. That neither the cold nor the hot side fluids are mixed or
4. That both the hot and cold sides are mixed.

The mathematical description that follows is covered in detail in Kays and London (1). The shell and tube model and the situation in which both fluids are unmixed are covered in DeWitt and Incropera (2). Type 91 models a constant effectiveness heat exchanger in which UA is calculated instead of being provided as an Input.

5.3.12.1 Nomenclature

C_c	capacity rate of fluid on cold side, $\dot{m}_c C_{pc}$
C_h	capacity rate of fluid on hot side, $\dot{m}_h C_{ph}$
C_{max}	maximum capacity rate
C_{min}	minimum capacity rate
C_{pc}	specific heat of cold side fluid
C_{ph}	specific heat of hot side fluid
ϵ	heat exchanger effectiveness
\dot{m}_c	fluid mass flow rate on cold side
\dot{m}_h	fluid mass flow rate on hot side
\dot{Q}_T	total heat transfer rate across heat exchanger
\dot{Q}_{max}	the maximum heat transfer rate across exchanger
T_{ci}	cold side inlet temperature
T_{co}	cold side outlet temperature
T_{hi}	hot side inlet temperature
T_{ho}	hot side outlet temperature
UA	overall heat transfer coefficient of exchanger
N	number of shell passes

5.3.12.2 Mathematical Description

Type 5 relies on an effectiveness minimum capacitance approach to modeling a heat exchanger. Under this assumption, the user is asked to provide the heat exchanger's UA and inlet conditions. The model then determines whether the cold (load) or the hot (source) side is the minimum capacitance side and calculates an effectiveness based upon the specified flow configuration and on UA. The heat exchanger outlet conditions are then computed, for all flow configurations using Eq. 5.3-19 and Eq. 5.3-20. The capacitance of each side of the heat exchanger is calculated according to the following four equations.

$$C_c = \dot{m}_c C_{pc} \quad \text{Eq. 5.3-1}$$

$$C_h = \dot{m}_h C_{ph} \quad \text{Eq. 5.3-2}$$

$$C_{max} = \text{maximum value of } C_h \text{ and } C_c \quad \text{Eq. 5.3-3}$$

$$C_{min} = \text{minimum value of } C_h \text{ and } C_c \quad \text{Eq. 5.3-4}$$

A schematic of the heat exchanger is shown in Figure 5.3.12-1 below.

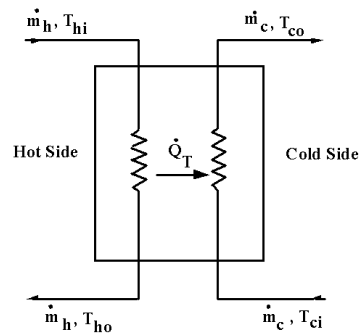


Figure 5.3.12-1: Heat Exchanger Schematic

The following indicate the expression used to calculate the heat exchanger effectiveness at each time step depending upon heat exchanger configuration.

MODE 1 - PARALLEL FLOW

$$\varepsilon = \frac{1 - \exp\left(-\frac{UA}{C_{\min}}\left(1 + \frac{C_{\min}}{C_{\max}}\right)\right)}{1 + \frac{C_{\min}}{C_{\max}}} \quad \text{Eq. 5.3-5}$$

MODE 2 – COUNTER FLOW

$$\varepsilon = \frac{1 - \exp\left(-\frac{UA}{C_{\min}}\left(1 - \frac{C_{\min}}{C_{\max}}\right)\right)}{1 - \left(\frac{C_{\min}}{C_{\max}}\right) \exp\left(-\frac{UA}{C_{\min}}\left(1 - \frac{C_{\min}}{C_{\max}}\right)\right)} \quad \text{Eq. 5.3-6}$$

MODE 3 – CROSS FLOW (HOT (SOURCE) SIDE UNMIXED, COLD (LOAD) SIDE MIXED)If $C_{\max} = C_h$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{\min}} \frac{C_{\min}}{C_{\max}}\right) \quad \text{Eq. 5.3-7}$$

$$\varepsilon = 1 - \exp\left(-\gamma \frac{C_{\max}}{C_{\min}}\right) \quad \text{Eq. 5.3-8}$$

If $C_{\min} = C_h$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{\min}}\right) \quad \text{Eq. 5.3-9}$$

$$\varepsilon = \frac{C_{\max}}{C_{\min}} \left(1 - \exp\left(-\gamma \frac{C_{\min}}{C_{\max}}\right)\right) \quad \text{Eq. 5.3-10}$$

MODE 4 – CROSS FLOW (COLD (LOAD) SIDE UNMIXED, HOT (SOURCE) SIDE MIXED)If $C_{\max} = C_c$,

$$\gamma = 1 - \exp\left(-\frac{UA}{C_{\min}}\right) \quad \text{Eq. 5.3-11}$$

$$\varepsilon = \frac{C_{\max}}{C_{\min}} \left(1 - \exp\left(-\gamma \frac{C_{\min}}{C_{\max}}\right)\right) \quad \text{Eq. 5.3-12}$$

If $C_{\min} = C_c$,

$$\gamma = 1 - \exp\left(\frac{UA}{C_{\min}} \frac{C_{\min}}{C_{\max}}\right) \quad \text{Eq. 5.3-13}$$

$$\varepsilon = 1 - \exp\left(-\gamma \frac{C_{\max}}{C_{\min}}\right) \quad \text{Eq. 5.3-14}$$

MODE 5 – CROSS FLOW: BOTH SIDES UNMIXED

$$\varepsilon = 1 - \exp\left[\left(\frac{C_{\max}}{C_{\min}}\right)\left(\frac{UA}{C_{\min}}\right)^{0.22} \left\{ \exp\left[-\frac{C_{\min}}{C_{\max}}\left(\frac{UA}{C_{\min}}\right)^{0.78}\right] - 1 \right\}\right] \quad \text{Eq. 5.3-15}$$

MODE 6 – CROSS FLOW: BOTH SIDES MIXED

$$\varepsilon = \frac{\frac{UA}{C_{\min}}}{\frac{UA}{C_{\min}} + \frac{(C_{\min}/C_{\max}) \frac{UA}{C_{\min}}}{1 - e^{-\left(\frac{UA}{C_{\min}}\right)(C_{\min}/C_{\max})}} - 1} \quad \text{Eq. 5.3-16}$$

MODE 7 – SHELL AND TUBE

$$\varepsilon_1 = 2 \left\{ 1 + \frac{C_{\min}}{C_{\max}} + \left(1 + \left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5} \frac{1 + \exp\left[-\frac{UA}{C_{\min}}\left(1 + \left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5}\right]}{1 - \exp\left[-\frac{UA}{C_{\min}}\left(1 + \left(\frac{C_{\min}}{C_{\max}}\right)^2\right)^{0.5}\right]} \right\}^{-1} \quad \text{Eq. 5.3-17}$$

$$\varepsilon = \left[\left(\frac{1 - \varepsilon_1 \frac{C_{\min}}{C_{\max}}}{1 - \varepsilon_1} \right)^N - 1 \right] \left[\left(\frac{1 - \varepsilon_1 \frac{C_{\min}}{C_{\max}}}{1 - \varepsilon_1} \right)^N - \frac{C_{\min}}{C_{\max}} \right]^{-1} \quad \text{Eq. 5.3-18}$$

ALL MODES

$$T_{ho} = T_{hi} - \varepsilon \left(\frac{C_{min}}{C_h} \right) (T_{hi} - T_{ci}) \quad \text{Eq. 5.3-19}$$

$$Q_T = \varepsilon C_{min} (T_{hi} - T_{ci}) \quad \text{Eq. 5.3-20}$$

SPECIAL CASES

Mode 3: If

$$\left| \frac{C_{min}}{C_{max}} - 1.0 \right| < 0.01 \quad \text{Eq. 5.3-21}$$

then

$$\varepsilon = \frac{\frac{UA}{C_{min}}}{\frac{UA}{C_{min}} + 1.0} \quad \text{Eq. 5.3-22}$$

All Modes: If

$$\frac{C_{min}}{C_{max}} \leq 0.01 \quad \text{Eq. 5.3-23}$$

then

$$\varepsilon = 1.0 - \exp \left(- \frac{UA}{C_{min}} \right) \quad \text{Eq. 5.3-24}$$

5.1.1. Type 2: Differential Controller

This controller generates a control function γ_o that can have values of 0 or 1. The value of γ_o is chosen as a function of the difference between upper and lower temperatures, T_H and T_L , compared with two dead band temperature differences, ΔT_H and ΔT_L . The new value of γ_o is dependent on whether $\gamma_i = 0$ or 1. The controller is normally used with γ_o connected to γ_i giving a hysteresis effect. For safety considerations, a high limit cut-out is included with the TYPE 2 controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded. Note that this controller is not restricted to sensing temperatures, even though temperature notation is used throughout the documentation.

5.1.1.1. Nomenclature

ΔT_H	[C]	upper dead band temperature difference
ΔT_L	[C]	lower dead band temperature difference
T_H	[C]	upper Input temperature
T_{IN}	[C]	temperature for high limit monitoring
T_L	[C]	lower Input temperature
T_{MAX}	[C]	maximum Input temperature
γ_i	[0..1]	Input control function
γ_o	[0..1]	output control function

5.1.1.2. Mathematical Description

Mathematically, the control function is expressed as follows:

IF THE CONTROLLER WAS PREVIOUSLY ON

$$\text{If } \gamma_i = 1 \text{ and } \Delta T_L \leq (T_H - T_L), \gamma_o = 1 \quad \text{Eq. 5.1-1}$$

$$\text{If } \gamma_i = 1 \text{ and } \Delta T_L > (T_H - T_L), \gamma_o = 0 \quad \text{Eq. 5.1-2}$$

IF THE CONTROLLER WAS PREVIOUSLY OFF

$$\text{If } \gamma_i = 0 \text{ and } \Delta T_H \leq (T_H - T_L), \gamma_o = 1 \quad \text{Eq. 5.1-3}$$

$$\text{If } \gamma_i = 0 \text{ and } \Delta T_H > (T_H - T_L), \gamma_o = 0 \quad \text{Eq. 5.1-4}$$

However, the control function is set to zero, regardless of the upper and lower dead band conditions, if $T_{IN} > T_{MAX}$. This situation is often encountered in domestic hot water systems where the pump is not allowed to run if the tank temperature is above some prescribed limit.

The controller function is shown graphically as follows.

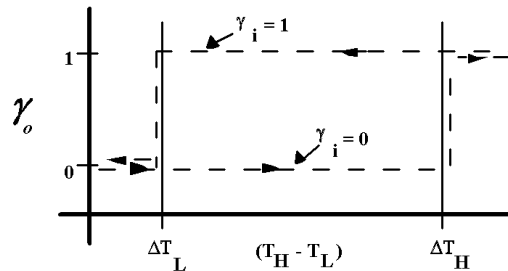


Figure 5.1.1-1: Controller Function

5.1.1.3. Special considerations

TYPE 2 INTERACTION WITH THE TRNSYS SOLVER

With the default TRNSYS solver (SOLVER 0, successive substitution), when $(T_H - T_L)$ nears the upper or lower dead band in the normal mode of operation, γ_o may sometimes oscillate between 1 and 0 for successive iterations at a given time step. This happens because T_H and T_L change slightly during each iteration, alternately satisfying and not satisfying the conditions for switching the controller. The value of PARAMETER 1, NSTK, is the number of oscillations permitted within a time step before the control function, γ_o , ceases to change. In general, it is recommended that NSTK be set to an odd number, typically five in order to encourage the controller to come to rest at a state different than at the previous time step.

With the release of TRNSYS version 14.1, an additional controller mode was added for use with the Powell's Method Solver. The Powell's Method control strategy is more robust in certain situations than the previous control strategy, solving the system of equations by not permitting the control variable to change during the iteration process. Upon convergence, the controller state is compared to the desired controller state at the converged solution and the calculations repeated if necessary. Please refer to section 5.1 of this document and see Volume 07 – "TRNEdit: Editing the Input File and Creating TRNSED Applications" for more information on the Powell's Method control strategy. It is important to note that if you use the Powell's Method control strategy, you must also use SOLVER 1 in your system.

For most simulations, use of the two control strategies will yield similar results. However, in short term simulations with unstable control behavior, the Successive Substitution (SOLVER 0) control strategy with an odd value of NSTK may yield quite different results from the Powell's Method control strategy.

5.13.18 *Type 62: Calling Excel*

5.13.18.1 *Acknowledgement*

Type 62 (Calling external programs - Excel) was originally programmed by Jochen Wriske and Markus Oertker at the Lehrstuhl für Technische Thermodynamik, RWTH Aachen. It was part of the TRNSYS 15 library of free components TRNLIB, and it was integrated to the standard library for TRNSYS 16.

5.13.18.2 *Description*

Type 62 implements a link with Excel. The Fortran routine communicates with Excel through a Component Object Model (COM) interface for fast data transfer.

Up to 10 inputs are sent to Excel. Those inputs are transferred to cells in the Excel worksheet that are named Inp1, Inp2, ... , Inp10. You must define those cells in your Excel file (use CTRL-F3 for a shortcut).

In Excel, Outputs are calculated from the inputs using standard functions or advanced VBA macros. Please see the examples provided in "%TRNSYS16%\Examples\Calling Excel".

Up to 10 Outputs can be assigned to cells for which the names Out1 to Out10 have been defined.

Up to 20 Type 62 units can be used in one simulation.

5.13.18.3 *Component configuration*

Parameter 1 is a Mode reserved for future use.

The number of inputs and outputs are set by Parameter 2 and 3

Parameter 4 (Show Excel) will decided if Excel runs completely in the background (in invisible mode) or if it is visible (In which case TRNSYS is sent to the background).

The path and filename of your Excel file are provided in a LABEL statement. Type 62 will understand the following kind of pathnames:

- Relative to the deck (default if no path is specified)
E.g. "My Excel File.xls"
- Absolute (if the path starts with "/" or if the second character is ".")
E.g. "C:\Program Files\Examples\Data Files\Type62-CallingExcel.xls"
- Relative to the TRNSYS root directory (if the path starts with ".\")
E.g. ".\Examples\Data Files\Type62-CallingExcel.xls", which is equivalent to the second example here above if TRNSYS is installed in "C:\Program Files\Trnsys16"

5.9.16 Type 65: Online plotter

The online graphics component is used to display selected system variables at specified intervals of time while the simulation is progressing. This component is highly recommended and widely used since it provides valuable variable information and allows users to immediately see if the system is not performing as desired. The selected variables will be displayed in a separate plot window on the screen.

If Parameter 10 is positive, a file containing the values of all the printed variables will be created during the simulation. Like Types 25, 27, 28 and 29, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type. Note however that the Fortran code only passes the variables to be plotted to the calling executable program (TRNExe.exe), which handles graphical output.

The online plotter can be disabled without removing the Type declaration from the input file by setting parameter 9 to -1. If all online plotters in a simulation are disabled, the default progress bar will be displayed instead. Note that if the online plotter is configured to produce an output file at the same time, that output file will still be generated if the online plotter is disabled.

5.9.16.1 Special Considerations

The following points should be noted carefully because a Type 65 component differs from most other component types in several ways.

- There can now be up to 5 TYPE65s included in a simulation.
- A TYPE 65 component may have between 1 and 20 inputs. (up to 10 on left axis and up to 10 on right axis)
- The 2nd data card following the INPUTS control card must contain an identifying label for each of the INPUTS rather than initial values as for most other components. Each label consists of up to maxDescripLength (25) characters. Labels must be separated from one another by a comma or one or more blanks.
- A LABELS card is required in order to supply the variable units for the two plots as well as the plot titles. Type 65 always requires 3 labels in TRNSYS 16. The first line beneath the LABELS card must contain the title for the left y-axis. The second line is the title for the right y-axis. The third line below the LABELS card must contain the text that will appear in the online plot identifying tab ("plot title").
- The number of inputs is equal to the sum of the first two parameters.

5.9.16.2 Quick overview of some Online plotter capabilities

If at least one "online plotter" component is present in the simulation, an online plot will be displayed during the simulation. The online plotter offers several features that will help you analyze the simulation results while it is running and after it is done.

STOP/RESUME THE SIMULATION

You can interrupt / resume the simulation while it is running by right-clicking anywhere in the plot, by using the "F7" and "F8" keys, or using the "Calculation/Stop" and "Calculation/Resume" menu entries. The "Pause at..." command is also very useful when you want to diagnose some problems occurring at a given time in a simulation.

CHANGING SOME PLOT OPTIONS

When the simulation is stopped, you can use the "Plot options" menu to change the plot background or line thickness. You can also change the left and right Y-axis limits by clicking on the axes themselves, which will display a dialog box (see Figure 5.9.16-1). Please note that changes to those limits will be lost if you re-run the simulation. You should change the online plotter parameters in the input file or Studio project if you want changes to be permanent.

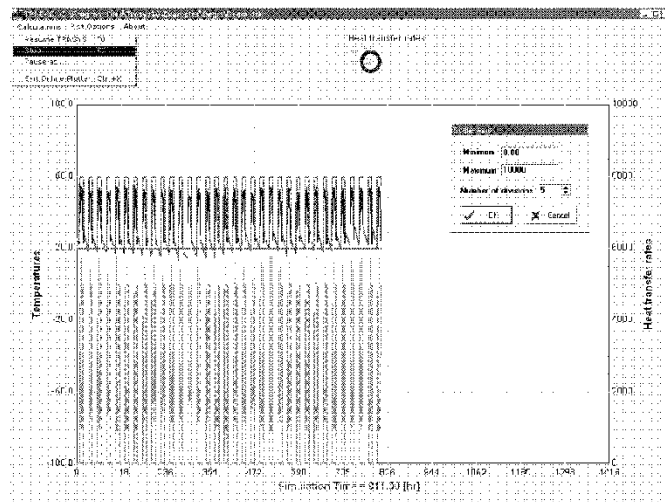


Figure 5.9.16-1: The online plotter window

You can hide or show any variable in the plot by clicking on its name in the legend fields. For example clicking in the red circle in Figure 5.9.16-1 would hide/show the QAux plot.

ANALYZING THE SIMULATION: ZOOMING AND DISPLAYING NUMERICAL VALUES

You can zoom on part of the plot to have a more detailed view of a shorter time interval. Just click on the upper-left corner of the area you want to zoom in and drag the mouse pointer to the lower-right corner, then release the mouse button. In the zoom window, you can adjust the Y-axis limits **but also the X-axis (time) limits** by clicking on the axes. This is very useful when you want to study such a short period of time that it is hard to zoom on that period right away.

You can display the numerical value of any variable at any point in time in both the "normal" and the "zoom" windows. Press the SHIFT key and move the mouse over the graph. The variable labels will be replaced with their value (and "time" will be replaced with the simulation time). This is shown in Figure 5.9.16–2 for the zoom window.

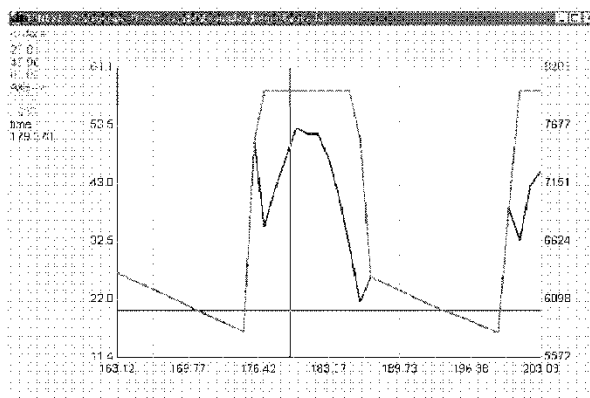


Figure 5.9.16–2: Displaying numerical values in the online plotter

Note: By pressing SHIFT and moving the mouse over the plot, you will display the values plotted by the online plotter, which are interpolated between TRNSYS time steps. If you want to see only the actual simulation time steps, press CTRL-SHIFT when moving the mouse. This can be useful to study control signal switching from 0 to 1, for example, since the online plotter will draw a continuous line between those 2 states and it will show interpolated values that do not correspond to any simulated values.

END OF THE SIMULATION

At the end of the simulation, TRNSYS will display a dialog box asking if you want to leave the online plotter open.

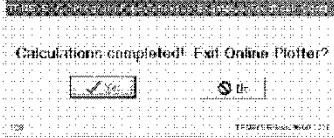


Figure 5.9.16–3: Dialog box at the end of the simulation

You can click "No" if you want to keep analyzing the simulation results. It is important to realize that if you do that, the TRNSYS simulation is actually not completed. The very last call (identified by INFO(8)=-1, see Volume 08 Programmer's Guide) only occurs after you close the online plotter. This means that some files might be locked (including the TRNSYS DLL, TRNDll.dll).

RUNNING TRNSYS IN BATCH MODE

You can run TRNSYS in batch mode by adding a "/n" switch to the command line, e.g. (on one line):

```
"C:\Program Files\Trnsys16\Exe\TRNExe.exe"  
"C:\Program Files\Trnsys16\Examples\SDHW\SDHW.dck" /n
```

In TRNSYS 16, the behavior of the /n switch was changed so that it also skips the dialog box that informs you about errors in the simulation. Note that this is only true for actual TRNSYS errors, not for exceptions generated by the code such as floating point overflows, etc.

RUNNING TRNSYS IN HIDDEN MODE

You can run TRNSYS in hidden batch mode by adding a "/h" switch to the command line, e.g. (on one line):

```
"C:\Program Files\Trnsys16\Exe\TRNExe.exe"  
"C:\Program Files\Trnsys16\Examples\SDHW\SDHW.dck" /h
```

The "/h" switch implies the "/n" switch and makes TRNSYS completely invisible (you can check that it is running by launching Windows' task manager and look for a process called TRNExe). **Please note that this switch is only applicable to simulations that do not use the online plotter or for which all online plotters are disabled** (by setting parameter 9 to -1).

5.9.12 Type 25: Printer

The printer component is used to output (or print) selected system variables at specified intervals of time. Like Types 27, 28, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

The maximum number of variables per Type 25 has been increased to 500 and there is no specific limit on the number of Type 25 units that can be used in a simulation. It is important to remember that the number of variables per printer is also limited by the maximum line length (or file width) in TRNSYS (See Volume 08, Programmer's Guide, for a reference on TRNSYS global constants).

5.9.12.1 Nomenclature

L_{unit}	-	the logical unit number on which printer output is to occur
Δt	-	the TRNSYS simulation time step
Δt_p	-	the time interval at which the INPUTS to the printer are to be printed out
t_{on}	-	the time in the simulation at which the printer is to begin printing
t_{off}	-	the time at which the printer is to stop printing
TIME	-	the current value of time in the simulation
X_i	-	the value of the i th INPUT to be printed

5.9.12.2 Mathematical Description

- if $\Delta t_p = 0$ or not specified, printing occurs only at the end of the simulation.
- if $0 < \Delta t_p \leq \Delta t$, printing will occur at intervals of Δt (every time step).
- if $\Delta t_p > \Delta t$, printing will occur every N time steps where N must be a positive integer and $N = \Delta t_p / \Delta t$.
- if t_{on} is ≤ 0 , printing begins at the start of the simulation. Otherwise, printing begins when $TIME \geq t_{on}$.
- if t_{off} is $\geq t_{end}$, printing stops at the end of the simulation. Otherwise, printing stops when $TIME > t_{off}$.
- if $L_{unit} \leq 0$ or not specified, the standard logical unit number for the Listing File (6) is used. If $L_{unit} > 0$, the number is used as the logical unit number for printer output. This allows the output of the printer to be written onto a separate file.
- if $UNITS = 1$, user-supplied units are printed to the supplied logical unit. If $UNITS = 2$, TRNSYS-supplied units are printed to the designated logical unit

5.9.12.3 *Special Considerations*

- Type 25 has one parameter that controls whether the print intervals are relative or absolute: for example, if the simulation start time is 0.5, the simulation time step is 0.25 and the printing time step is 1: if this parameter is set to 0, printing will occur at 0.5, 1.5, 2.5, etc. If this parameter is set to 1, printing will occur at 1, 2, 3, etc.
- Type 25 is also capable to append to the output file instead of re-creating it, which can be very useful for parametric runs (all parametric runs can write to the same file).
- The 2nd data card following the INPUTS control card must contain an identifying label, or variable descriptor, for each of the INPUTS rather than initial values as for most other components. (The INPUTS are printed beneath their identifying labels.) Each descriptor consists of up to maxDescripLength (25) characters. Labels must be separated from one another by a comma or one or more blanks.
- If the 5th parameter is specified as 1, the user must supply the entire set of variable units in a manner similar to the identifying labels previously described. The units are printed below the identifying labels. Each unit consists of up to maxVarUnitLength (20) characters. Variable units must be separated from one another by a comma or one or more blanks.

5.13.14 Type 24: Quantity integrator

This component model is analogous to a piece of equipment in a physical system that integrates a quantity over a period of time; for example, a kWh meter that continuously totals the amount of electrical energy consumed. Whenever a quantity in a system simulation requires integration over the period of simulation, the use of this component will perform the required function.

Like Types 25, 27, 28, 29 and 65, this component used to be implemented as a kernel routine but in TRNSYS 16 it is implemented as a standard Type.

Type 24 can integrate up to 250 variables and there is no specific limit on the number of Type 24 units that can be used in a simulation.

5.13.14.1 Nomenclature

X_i the i th quantity or rate to be integrated

Y_i the time integral of X_i

5.13.14.2 Mathematical Description

$$Y_i = \int_{\text{time}} X_i dt$$

Eq 5.13.14-1

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