SIMULATION OF RESIDENTIAL SOLAR DHW SYSTEMS IN HOT3000 SOFTWARE

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ABSTRACT

The CANMET Energy Technology Centre (CETC) is currently developing the next-generation residential building energy analysis software - HOT3000 -, which uses the ESP-r simulation engine. Part of the development of this simulation tool is the addition of interface support and ESP-r models for four commonly used residential solar DHW (SDHW) systems.

This paper presents the simulation models incorporated into ESP-r to model three of the SDHW systems. These include models for a solar collector, a storage tank with an immersed heat exchanger, and mains-water temperature. The simulated solar fraction for a well-characterized SDHW is found to be within 5% of the test day data for the system. The paper also describes the HOT3000 interface design for specifying SDHW systems.

INTRODUCTION

CETC's original residential building energy analysis software - HOT2000 (2003) - of CETC is based on the bin method, which limits the capability to model advanced HVAC systems. To overcome this limitation, the simulation engine of HOT2000 was replaced with ESP-r (ESRU 2000) engine. The Graphical-User Interface (GUI) for the new ESP-r-based software is called HOT3000.

The addition of the capability to model commonly found SDHW systems in HOT3000 is intended to encourage the residential building industry to install more of these systems in the houses they build. The availability of reliable simulation models in HOT3000 will give consumers and designers the opportunity to assess the energy saving potential of residential SDHW systems, which in turn will contribute to an increased uptake of these systems.

Furthermore, the availability of the simulation models in HOT3000 coincides with the recent update to the Canadian Standard Association CSA F379 Standard for the rating of solar DHW systems. The updated standard is the basis for a new certification program offered by CSA International. The availability of certified systems should increase consumer confidence in the technology. At the same time the HOT3000 SDHW models can help stimulate further interest.

In the present study, the ESP-r plant domain is used to model three of the four residential solar DHW systems planned for inclusion in HOT3000. Component models for solar collector, storage tank with immersed coil, and mains-water temperature have been incorporated into the ESP-r plant domain. It is found that the solar fraction predicted by the simulation models for one system type, under well-characterized conditions, is within 5% of the experimental rating data for this system.

SDHW SYSTEMS DESCRIPTION

The four SDHW systems are shown in Figure 1. System 1 consists of solar collector connected to a natural convection heat exchanger, which is in turn connected to a stratified storage tank. System 2 is the same as System 1 except that a forced convection heat exchanger replaces the natural convection heat exchanger. For System 3 the collector fluid is circulated directly in a spiral heat exchanger inside the solar tank. System 4 is the same as System 3 except that the collector fluid is introduced directly inside the solar tank and mains water is heated inside the spiral heat exchanger. The circulation pumps for the systems are turned on when the temperature difference between the solar collector and the solar tank exceeds a certain high limit. They are then tuned off when this temperature difference reaches a low threshold.

SIMULATION MODELS

The component models needed to assemble the plant networks for Systems 2 through 4 are all available in ESP-r with the exception of a solar collector model based on inputs for collector efficiency equation, a solar tank with immersed coil, and mains-water temperature and draw profile. In addition, the capabilities to control a plant component based on sensed temperature difference between two plant components, and to use of a mixture of water and glycol as the working fluid are both added to ESP-r.

Solar Collector Model

As the model for the solar collector is described in detail by Thevenard et al. (2004), only a brief overview is given here. The main objective for the development of this model is a collector model that accepts as inputs coefficients for the collector efficiency equation derived from a rating test. This is important, because this information is readily available for solar collectors available on the market. The model supports inputs for efficiency equations based on inlet fluid temperature, for products rated in North America, or on mean fluid temperature, for products rated in Europe.

The collector model is a one-node plant component with one inlet and one exit stream. The efficiency of the collector is corrected for any deviation from the rated mass flow rate or fluid type. The efficiency is also corrected for the effect of angle of incidence of solar radiation. The solar gain derived from the efficiency is used in an energy balance on the collector to determine the fluid exit temperature.

An important input to the model is the fraction of propylene glycol in the working fluid. This same fraction is maintained for all the components in the collector loop. This is further explored in the section "Water-Propylene Glycol Mixtures", later in the paper.

Tank with Immersed Coil

This model is developed to simulate SDHW Systems 3 and 4. One node, *s* in Figure 2, is used to represent the tank (fluid + walls). The assumption that the tank is fully mixed is deemed appropriate, because the HX at the bottom of the tank tends to stir the water inside the tank. A second node, *c* in Figure 2, is used to represent the immersed spiral heat exchanger (fluid + tubes). Each of the nodes has one incoming flow - usually from the collector or the mains for make up water. An energy balance on tank node *s* gives:

$$(MCp)_s \frac{dT_s}{dt} = (\dot{m}Cp)_{s-1}(T_{s-1} - T_s) + (UA)_s(T_e - T_s) + \dot{Q} \quad (1)$$

An energy balance for the heat exchanger node *c* gives:

$$(MCp)_c \frac{dT_c}{dt} = (\dot{m}Cp)_{c-1}(T_{c-1} - T_c) - \dot{Q} \quad (2)$$

Note that in the ESP-r formulation, the temperatures T_c, T_{c-1}, T_s, and T_{s-1} are assumed to be at the exit of the heat exchanger node *c*, the HX incoming flow node *c-1*, the tank node *s*, and the tank incoming flow node *s-1*, respectively. The heat transfer $\dot{Q}$ is positive when it is transferred from the HX to the tank fluid. The mass, *M*, and the specific heat, *Cp*, of the tank and HX nodes and the overall heat loss coefficient, *UA*, of the tank are all inputs to the model. Next, a method to estimate the heat transfer between the HX and the tank is required.

Figure 3 shows a small segment of the heat exchanger with a constant overall heat transfer coefficient $U_{c,i}$. If transient effects are neglected, the differential heat transfer between the HX section and the tank fluid is given by,

$$d\dot{Q} = (U_c P)_i (T_{c,x} - T_s)dx = -(\dot{m}CpdT)_c \quad (3)$$

In this equation, a distinction is made between the temperature at the exit of the HX coil T_c used in equation 2 and the HX temperature $T_{c,x}$ at a location *x* along the length of the HX. Integrating equation 3 over the whole length of the coil gives the following expression for the total heat transfer:

$$\dot{Q} = (\dot{m}Cp)_c (T_{c-1} - T_s)\left[\exp\left(\frac{-(U_c P)_i L}{(\dot{m}Cp)_c}\right) - 1\right] \quad (4)$$

The temperature difference between the inlet to the HX T_{c-1} and the tank T_s is the maximum temperature difference between the two fluids. Therefore the effectiveness of the HX coil is:

$$e = \left[\exp\left(\frac{-(U_c P)_i L}{(\dot{m}Cp)_c}\right) - 1\right] \quad (5)$$

The average temperature of the coil based on equation 3 is given by,

$$T_{c,avg} = T_s - \frac{(\dot{m}Cp)_c (T_{c-1} - T_s)}{(U_c P)_i L}\left[\exp\left(\frac{-(U_c P)_i L}{(\dot{m}Cp)_c}\right) - 1\right] \quad (6)$$

The overall heat transfer coefficient based on the coil inside heat transfer area is given by:

$$\frac{1}{(U_c P)_i} = \frac{1}{(hP)_i} + \frac{\ln(r_o / r_i)}{2pk_w} + \frac{1}{(hP)_o} \quad (7)$$

The current model implementation assumes laminar flow inside the tube and the Nusselt Number is calculated using (Manlapaz and Churchill 1981):

$$Nu_{d,i} = \left[\left(4.364 + \frac{4.636}{X_3} \right)^3 + 1.816 \left(\frac{De}{X_4} \right)^{2/3} \right]^{1/3}$$

$$X_3 = \left(1 + \frac{1342}{De^2 \ \mathrm{Pr}} \right)^2 \qquad (8)$$

$$X_4 = 1 + \frac{1.15}{\mathrm{Pr}}$$

The Nusselt Number for the natural convection on the outside of the helical coil is based on a correlation by Taherian and Allen (1998) and is given by

$$Nu_{Dhx,o} = 0.182 \left(Ra_{Dhx} \frac{H}{L} \right)^{0.394} \qquad (9)$$

The procedure for determining the hydraulic diameter of the coil-shell combination, *Dhx*, can be found in Ajele's thesis (1995).

In ESP-r the component subroutine for the model for the tank with immersed coil is called every plant time step. In addition, within each plant time step, the component subroutine is called iteratively until the solution to the plant network converges for the time step. When the component subroutine is called, the temperatures of the nodes and those of the incoming flows are known from the previous iteration. In addition, the mass flow rates of the incoming flows to the nodes are also known.

The implementation in ESP-r of the model for the tank with immersed coil is based on the following algorithm:

1. Initialize all relevant physical properties of the tank and HX fluids. Coil properties are evaluated at the average fluid temperature based on equation 6. The total U-value of the coil in equation 6 is initially based on an estimate from the previous iteration. Also the fraction of glycol is used to set the appropriate physical properties.
2. Evaluate Nusselt Number Nu_i for flow inside the coil based on equation 8 and then deduce inside heat transfer coefficient h_i.
3. Evaluate Nusselt Number Nu_o for free convection outside the coil based on equation 9 and then deduce outside heat transfer coefficient h_o. The temperature difference used in the evaluation of Ra_{Dhx} is equal to the absolute value of the difference between T_{avg} from equation 6 and the tank fluid temperature T_s.
4. Evaluate new value for coil overall heat transfer coefficient $U_{c,i}$ from equation 7.
5. Use equation 4 to find total heat transfer between coil and tank fluid.
6. Set ESP-r matrix coefficients, for plant network solver, based on forms of equations 1 and 2.
7. Save relevant quantities for next iteration.
8. Save output variables.

The formulation of the model uses the average temperature for the whole coil T_{avg} to evaluate the fluid properties and the Nusselt Numbers. A further refinement of the model is to apply the procedure described previously, to find the total heat transfer, on smaller sections of the coil. Then add the heat transfer rates for all the sections to find the total heat transfer for the coil. A version of the model with this refinement is implemented and compared to the approach outlined previously. The results obtained from the refined model, using a System 3 input file, show very minor differences in the simulation results. Therefore, the simpler formulation of the model is adopted.

Mains-Water Temperature: Moore Model

The Moore Method is a soil temperature estimation model, originally developed for implementation in HOT2000 (Moore 1986). Using average monthly ambient dry air temperature and annual heating degree days, the Moore Method is a series of steps used to estimate the temperature of the soil at any depth at any time of year.

Calculating the temperature of the soil for hour *n* of the year is the first step of the Moore Method, and can be closely approximated by the following function (Kusuda and Achenbach, 1965) and the curve shown in Figure 4:

$$T_{soil} = A_{soil} + B_{soil} \cdot \cos\left(2 \cdot p \cdot \frac{n}{8766} - P_{soil} \right) \qquad (10)$$

The remaining steps of the Moore Method, and the variables used in equation 10, are defined in the following section.

Incorporating the Moore Method into ESP-r

The ground temperature calculation – and consequently the mains water temperature – is used in several different models within ESP-r; in the BASESIMP (Beausoleil-Morrison and Mitalas, 1997) basement heat loss calculation, in the simulation of the residential domestic hot water (DHW) tanks, in the simulation of cogeneration tanks, as well in the simulation of ground-source heat pumps (GSHP).

The following steps were followed to calculate the ground temperature profile in ESP-r:

1. Determine the number of heating degree days (DD) from the weather files

The heating degree days calculation for a certain location is performed in at the beginning of the simulation, as it needs to parse each CWEC (Canadian Weather for Energy Calculation, Numerical Logics. 1999) weather file for the maximum and minimum daily ambient temperatures.

The annual heating degree day calculations use a base of 18.2°C. The average ambient temperature for any given day is calculated by $T_{a,avg} = \frac{T_{a,\max} + T_{a,\min}}{2}$.

If this average is greater than 18.2°C, then the number of degree days for that day is 0. If this average is less than 18.2°C, then the number of degree days are: $DD = 18.2 - T_{a,avg}$.[1]

2. Calculate the ground temperature parameters based on Moore's Model

For implementation in ESP-r, the variables required to calculate the ground temperature were being read in from multiple input files. This was modified to a single input file and the calculation of applicable variables.

Average Ground Temperature for the year

$$A_{soil} = T_{annual,avg} - 1.438 + \left(9.189 \times 10^{-4}\right) DD \quad (11)$$

Where: $$T_{annual,avg} = \frac{\sum_{j=1}^{12} T_{a,j}}{12} \quad (12)$$

Ground Temperature Amplitude

$$B_{soil} = B_a - 7.875 + \left(1.97 \times 10^{-3}\right) DD \quad (13)$$

Where: $$B_a = \frac{-\sqrt{S_1^2 + C_1^2}}{6} \quad (14)$$

$$S_1 = \sum_{j=1}^{12} \left\{ T_{a,j} \cdot \sin\left[\frac{2\pi}{12}(j - 0.5)\right]\right\} \quad (15)$$

$$C_1 = \sum_{j=1}^{12} \left\{ T_{a,j} \cdot \cos\left[\frac{2\pi}{12}(j - 0.5)\right]\right\} \quad (16)$$

Phase Shift (P_{soil})

$$P_{soil} = P_a - 0.0756 + \left(2.128 \times 10^{-5}\right) DD \quad (17)$$

Where: $$P_a = \tan^{-1}\left\{\frac{S_1}{C_1}\right\} \quad (18)$$

3. Calculate the mains water temperature based on the ground temperature parameters

The mains water temperature for the month j ($T_{cold\ mains}$) is then calculated based on a modified equation from Cooper (1991):

$$T_{cold\ mains} = T_{LimitT_{avg\ ground}} + 3.0 + A_{\mathrm{mod}} \cdot B_{soil} \cdot \sin\left(\frac{p}{6} \cdot j \cdot T_{ground\ offset}\right) \quad (19)$$

Where the depth amplitude modifier is:

$$A_{\mathrm{mod}} = 0.2 + 0.04 \cdot \left(T_{LimitT_{avg\ ground}} - 5.0\right) \quad (20)$$

And $T_{LimitT_{avg\ ground}}$ limits the value of A_{soil} to be within 5°C and 20°C.

An ESP-r plant component is generated to specify mains-water monthly temperature and hourly draw profile over the course of the day. One option in the component data is to specify values for mains-water temperature for each month. The other option is to specify that mains-water temperatures are to be based on Moore model.

Water-Propylene Glycol Mixtures

Two working fluids that can be specified in ESP-r: moist air and water. A component, declared in the plant databases as air-based, can only be connected to other air-based components to form a plant network. The same applies for water-based components. The plant solver generates solutions for node temperatures and total flow rate leaving the node. The ESP-r formulation can accommodate up to two fluid types, through the same node, to properly model moist air systems.

The spot in the plant matrix solver, reserved for water-vapor for air systems, is left empty when modeling water-based systems. Fortunately this place holder can be used to model water-propylene glycol mixtures. The mass fraction of propylene glycol in the fluid is an input to the solar collector model. This fraction is used to set appropriate physical properties used in the solar collector energy balance. In addition, the plant solver now solves for the water and glycol mass flow rates through the collector.

In order to complete the implementation of the capability to model water-glycol mixtures, other plant components in the same plant loop as the solar collector need to determine the proper fraction of glycol in the working fluid, and then use this information to

[1] Note: $T_{a,avg} = \frac{T_{a,\max} + T_{a,\min}}{2} \neq \frac{\sum_{l=1}^{24} T_{a,l}}{24}$

determine the proper physical properties to use in the energy balance. The mass balance of these components also needs to account for the presence of glycol in the flow. This has been implemented in the model for the circulation pump and the tank with immersed coil as described earlier in this paper. The same modifications can be implemented in the future in other plant components to support water-propylene glycol mixtures.

COMPARISON OF RATING DATA WITH SIMULATION RESULTS

Rating data for a Type 3 commercial SDHW system is compared against simulation results. All of the relevant characteristics of this system are shown in Table 1. The rating test is carried for a whole day. The radiation on the collector and its angle of incidence, the mains water temperature, and DHW draws are all recorded for each hour of the test day. The mains-water temperature is maintained very close to 15 °C and the DHW draws total 300 L/day. The surrounding temperature of the collector and the solar tank during the test are 15.3 °C and 20 °C, respectively. All of these measured parameters are used to generate the ESP-r results.

The auxiliary tank is in the same environment as the solar tank. However, no data is available on the insulation around the auxiliary tank. The simulation results are obtained with negligible heat loss from the auxiliary tank.

During the rating test the energy supplied at the auxiliary tank is measured and the contribution of solar energy toward the DHW load is deduced for the rating day. This solar contribution is then extrapolated to the whole year. The reported solar contribution for the rated system considered is 9.1 GJ.

To generate the solar contribution from simulation, two annual runs are performed. In the first run the circulation pump to the collector is always off to find the electricity consumption of the auxilairy tank with no solar contribution $E_{nosolar}$. In the second run the collector pump is turned on and off based on the ΔT_{on} and ΔT_{off} values in Table 1 and the electricity consumption of the auxiliary tank in this case is designated E_{solar}. The solar contribution Q_{solar} toward DHW load is given by,

$$\begin{aligned} Q_{solar} &= E_{nosolar} - E_{solar} - Q_{pump} \\ &= 18.09GJ - 9.19GJ - 0.269GJ \\ &= 8.63GJ \end{aligned} \tag{21}$$

Where Q_{pump} is the heat gain from the collector circulation pump. It is to be noted here that the ESP-r pump model presently assumes that only the portion (1 - h_{pump}), 30% in this case, of the total pump electricity consumption goes toward heating the fluid. This seems to be a bug in ESP-r as a more appropriate portion is the pump efficiency itself or an assumption that all the pump electricity is gained by the fluid. If we assume that all the pump energy heats the operating fluid, this would result in a temperature rise of 0.64 °C using a specific heat of 3500 J/kg-°C for a 50% water-50% glycol mixture. If only 30% of the pump energy is gained by the fluid, then the temperature rise is only 0.19 °C. The difference between the two values for the temperature rise through the pump is so small to alter the performance of the collector. As a result, the solar contribution predicted in equation 21 would still hold.

HOT3000 INTERFACE FOR SDHW SYSTEMS

Figure 5 shows the HOT3000 graphical interface for defining SDHW systems. The user is able to choose between each of the four systems described earlier in the paper. If the system is not rated system, then the user needs to specify values, or use the defaults, for all inputs listed in the interface menu. These include specific inputs for the solar collector, solar tank, auxiliary tank, heat exchanger if applicable, and circulation pumps on the collector side and load side if applicable. Additional inputs for the solar and auxiliary tanks are under the input screens titled “Solar Tank” and “Auxiliary Tank” in Figure 4.

If the user specifies that the system is rated, a drop down menu is activated to provide a list of choices. At this point only the rated Type 3 System - described earlier - is available. As more systems are rated and data becomes available, the list in the drop down menu will be expanded. In this case, all of the input fields in shown in Figure 5 are greyed except for the collector slope and azimuth. The greyed fields are defaulted based on the characteristics of the rated system chosen.

When the system is rated, the ESP-r predicted solar contribution is corrected by a factor that accounts for the difference in the rating results and the simulation results. For example for the rated Type 3 System described earlier, the annual solar contribution based on rating test is 9.1 GJ and that from simulation is 8.63 GJ. So for this system, the ESP-r predicted solar contribution is multiplied by a factor of 1.0544 to get a better estimate of the performance of the system. As more rated systems data is added to HOT3000, an appropriate correction factor will be derived for each of the systems.

CONCLUSIONS

A simulation model is added into ESP-r/HOT3000 to model a solar collector based on inputs for collector efficiency equation. Models are also added for a storage tank with an immersed coil, and for predicting mains water temperature. The capability to model water-propylene glycol mixture is also implemented.

These models and new features are used to support capability to model three commonly available solar DHW systems in HOT3000 software. It is found that the simulation predicted solar contribution is within 5% of the value from a rating test for a well-charaterized SDHW system. Additional work is planned in the future to simulate the performance of another Type of SDHW system and to add more performance data for rated systems to HOT3000.

Table 1: Charateristics of rated Type 3 SDHW System

COMPONENT	**INPUT**	**VALUE**
Solar collector	h_0; h_1; h_2	0.694; -4.85; 0.
	Slope	30°
	Area	5.76 m^2
	(q, k) pairs	(0°,1.); (30°,0.994); (45°,0.964); (60°,0.828); (70°,0.74)
	Fluid	50% water-50% propylene glycol
	Mass	100 kg
	Specific heat	322 J/kg-°C
Circulation pump	Power	85 W
	h_{pump}	70%
	Flow rate	0.038 kg/s
	ΔT_{on}; ΔT_{off}	5.55 °C; 1. °C
Solar Tank	Volume	227 L
	$(UA)_s$	1.54 W/m^2-K
	L	9.14 m
	r_i	0.0127 m
	r_o	0.0137 m
	R_c	0.2 m
	H	0.4 m
	R_s	0.25 m
Auxiliary tank	Volume	189.3 L
	Set point	55 ± 1 °C

NOMENCLATURE

A — Area (m^2)
A_{soil} — Mean ground temperature (°C)
A_{mod} — Depth amplitude modifier
B_{soil} — Ground temperature amplitude (°C)
Cp — Specific heat (J/kg-°C)
d — Coil tube diameter (m)
De — Coil internal flow Dean Number ($\mathrm{Re}_d \sqrt{\frac{r}{R_c}}$)
$d\dot{Q}$ — Heat transfer associated with small section of coil (W)
dT — Temperature change associated with small section of coil (°C)
dx — Length of small section of coil (m)
Dhx — Hydraulic diameter of coil-shell system (m)
$E_{nosolar}$ — Electricity consumption of auxiliary tank with no solar contribution (GJ)
E_{solar} — Electricity consumption of auxiliary tank with solar contribution (GJ)
H — Coil height (m)
j — Month of the year
L — Coil length (m)
$\dot{m}$ — Mass flow rate (kg/s)
M — Mass (kg)
n — Number of hours into year (note: there are 8766 hours/year)
Nu — Nusselt Number
P — Coil tube perimeter (m)
P_{soil} — Soil temperature phase shift
Pr — Prandtl Number
Q_{pump} — Heat gain from pump (GJ)
Q_{solar} — Solar contribution toward DHW load (GJ)
$\dot{Q}$ — Heat transfer from coil to tank fluid (W)
r — Coil tube radius (m)
Ra_{Dhx} — Rayleigh Number ($\frac{gb(T_{c,avg} - T_s)Dhx^3}{na}$)
R_c — Radius of curvature of coil helix (m)
R_s — Radius of tank shell (m)
Re_d — Reynolds Number ($\frac{4\dot{m}}{pdm}$)
t — Time (sec)
T — Temperature (°C)
$T_{cold\ Mains}$ — Mains water temperature for month (°C)

$T_{ground\ offset}$

Ground temperature offset (Cooper) (°C)

T_{soil} Soil temperature (°C)

U Overall heat transfer coefficient (W/m^2-°C)

Greek Symbols

e Coil heat exchanger effectiveness

h Collector efficiency

$$(h = h_0 - h_1 \frac{\Delta T}{G} - h_2 \left(\frac{\Delta T}{G} \right)^2)$$

h_{pump} Pump efficiency

q Angle of incidence (°)

k Incidence angle correction factor

Subscripts

a Ambient variable

annual Annual value

avg Average value

c Coil node variable

c-1 Coil incoming flow node variable

e Surrounding variable

i Variable associated with inside of the coil

j Monthly index

k Daily index

l Hourly index

s Tank node variable

s-1 Tank incoming flow node variable

x Arbitrary distance along the coil length

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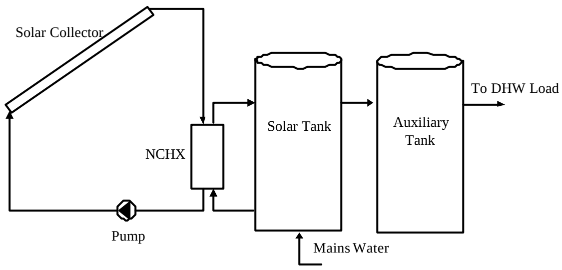
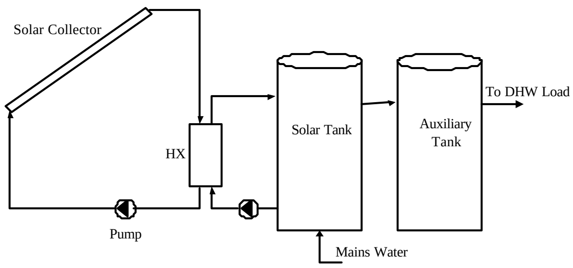
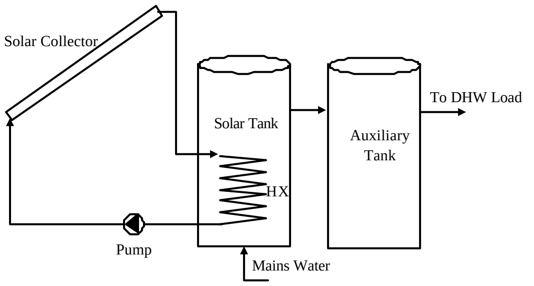


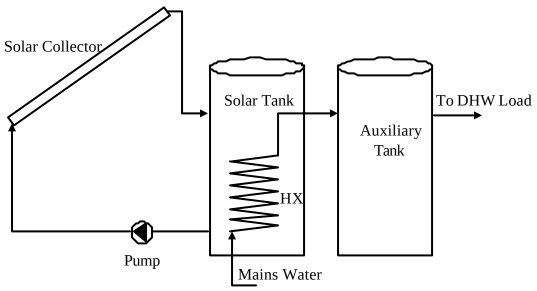
(a) System 1



(b) System 2



(c) System 3



(d) System 4

Figure 1: Details of SDHW systems

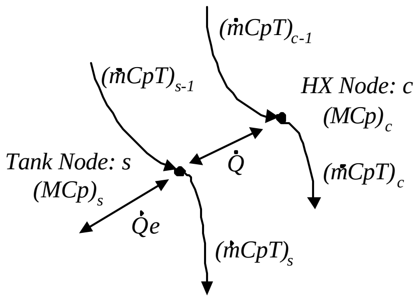


Figure 2: Nodal representation of tank with immersed coil for ESP-r plant model

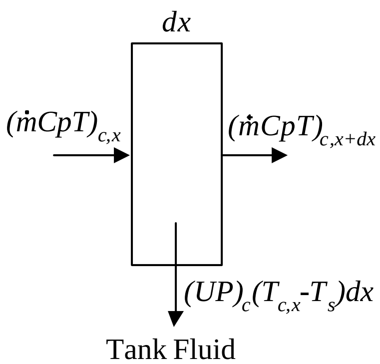


Figure 3: Details of heat transfer between HX coil segment and tank fluid

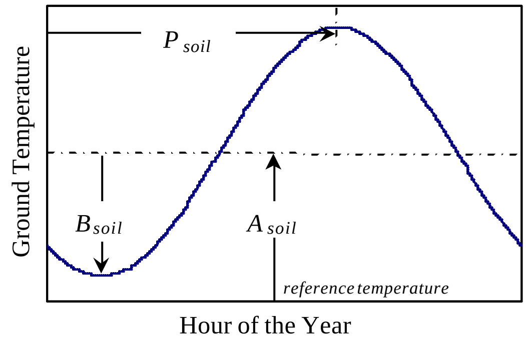


Figure 4: Ground temperature fluctuations over a year

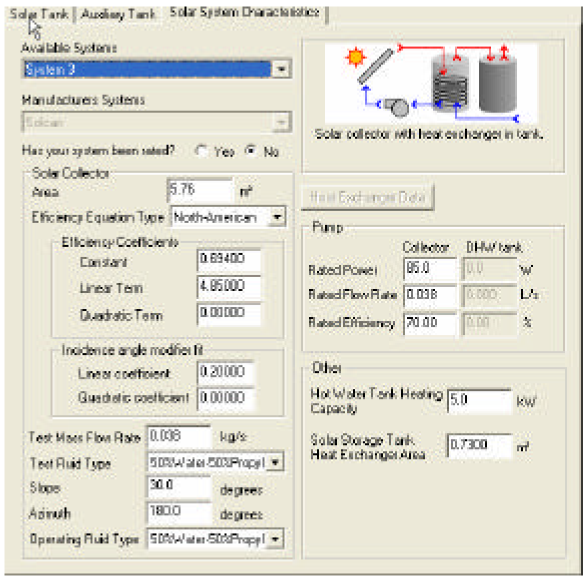


Figure 5: HOT3000 interface for specifying SDHW systems