Design of Domestic Hot Water Model for Hot3000

References

Bradley B. (1995), DHW Model for Hot2000 7.01, Unies Ltd, 5 pages, Feb 3, 1995

Cooper K. (1991), DHW Simulation Algorithms, SAR Engineering, 10 pages, October 21, 1991

1.Introduction

A domestic hot water (DHW) tank model will be incorporated into the ESP-r/Hot3000 program. The basis of the design will be a re-tooling of the existing model created in the Hot2000 software developed by Brian Bradley and Debra Haltrech

2.DHW basic model

The DHW model attempts to account for the losses to the room and to the flue gasses, for the variation in cold main temperature and the ambient air temperature of the room in which the tank resides as well as piping gains and losses.

The approach used in this model is to use the energy factor of the tank (EF) with the DOE test conditions to assign percentages to each of the factors contributing to the losses in the DHW system. These methods are dependant on type of fuel and tank design.

The purchased energy consumption rate is defined as:

$$q_P = \frac{q_L}{F_E} \qquad \textbf{(Watts)}(1)$$

q_L is the heat addition rate to the water in the tank**(Watts)**.

F_E is the energy factor of the tank system.

This is the basis for all the systems types regardless of the fuel or tank type.

3.Electric Tank Systems

Electric tank systems have only one source of loss attributed to the inefficiency. This is the loss of energy from the tank skin to the room sometime called standby tank losses or parasitic losses.

The relationship to the purchased energy is:

$$q_P = q_L + q_T$$ **(Watts)** (2)

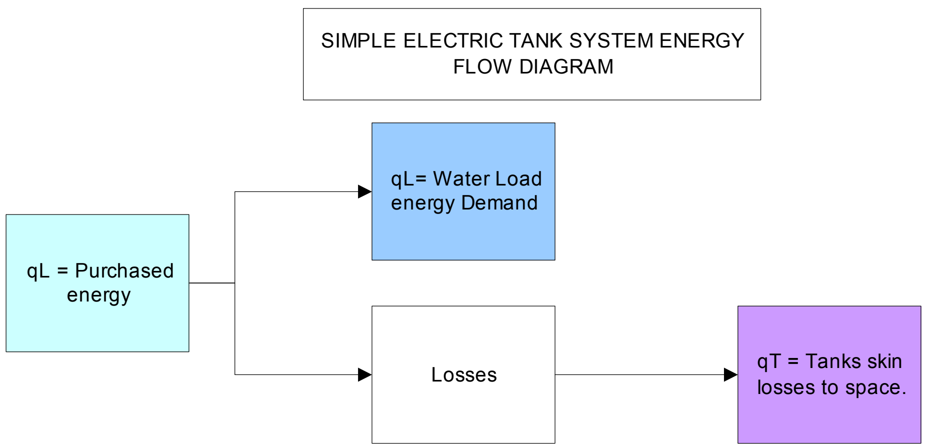

Figure 1: Simple Electric Tank System Energy Flow Diagram

Where the value q_T is the tank loss rate from the water to the surroundings.

By substituting Eq(1) into Eq(2) gives us the tank heat loss rate as the function of the tank efficiency.

$$q_T = q_L * (\frac{1}{F_E} - 1)$$ **(Watts)** (3)

This is easily translated in to a loss rate per unit temperature or "UA" value.

$$UA = \frac{q_L}{\text{delta T}} * (\frac{1}{F_E} - 1)$$ **(Watts)** (4)

The Delta T term is the difference in temperature of the surroundings in which the tank resides to the tank water temperature. So UA is a function of delta T and the EF factor of the tank.

To simplify obtaining a UA factor for any tank, the DOE standard test conditions will be applied to this equation to obtain a constant UA factor based only on the tanks energy factor. The DOE standard for testing tanks keeps the following constant.

Hot Water Demand Rate	243.4 L/Day
Cold Water Temperature	14.3 oC
Hot Water Temperature	57.2 oC
Room Temperature	20.0 oC

By the above factors we can obtain the heat addition rate to be:

$$q_L = \left(\frac{243.4\,\frac{Litres}{Day}}{86400\,\frac{Seconds}{Day}}\right) * (57.2DegC - 14.3DegC) * 4190\,\frac{J}{Litres/DegC} = 506.382Watts \tag{5}$$

Using Eq(4) with Eq(5) the and the above DOE Test standards we obtain UA as a function of the tanks energy factor.

$$UA = \frac{506.382watts}{(57.2 - 20.0)\mathrm{DegC}} * \left(\frac{1}{F_E} - 1\right) \tag{6}$$

$$UA = 13.612\,\frac{watt}{DegC} * \left(\frac{1}{F_E} - 1\right) \tag{7}$$

NOTE: for tankless electrical DHW equations (3) and (4) hold true as well, but it will account for conduction losses from the element to the room.

4.Fossil Fuel no-pilot Tank Systems

Fossil fuel systems are similar to electric systems but they have additional flue gas losses (q_G) to account for.

Thus equation (2) has to be rewritten as

$$q_P = q_L + q_T + q_G \qquad \textbf{(Watts)}\ (8)$$

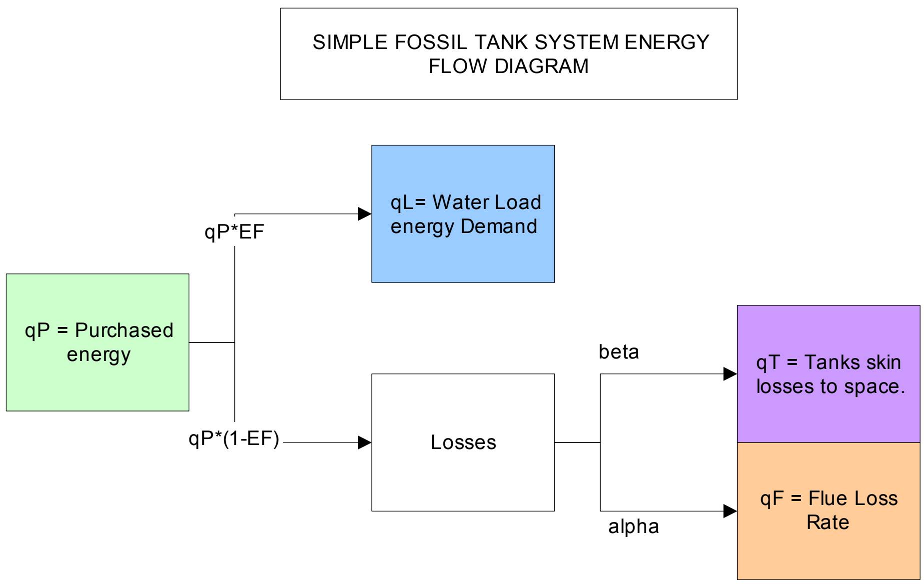

Figure 2 : Simple Fossil Tank System Energy Flow Diagram

q_G is the rate of energy lost to the flue. By dividing the equation by q_P and Eq(1) we obtain the coefficients factor for energy use.

$$1 = F_E + F_T + F_G \qquad (9)$$

The losses can be grouped by rearranging the last equation to:

$$1 - F_E = F_T + F_G \qquad (10)$$

While the Energy Factor of the tank is easily obtained, the Flue Loss Factor and the Tank Loss Factor is cannot be obtained normally by tank manufacturers. So a value must be assumed for the ratio of tank skin losses to flue losses. This also must be a function of the tank energy factor Fe. Hence the following equations must hold true.

$$F_G = \alpha * (1 - F_E) \tag{11}$$

$$F_T = \beta * (1 - F_E) \tag{12}$$

as long as

$$\alpha + \beta = 1 \tag{13}$$

Where α is the flue gas loss portion of the inefficiency $(1 - F_E)$, and β is the tank loss to room portion of the inefficiency $(1 - F_E)$. Estimated alpha and beta values have been compiled by Debra Haltrech and Brian Bradley for H2K. These are contained in appendix B.

The heat loss of the tank can be written now as:

$$q_T = F_T * q_P$$ **(Watts)** (14)

Using Eq (2)

$$q_T = F_T * \frac{q_L}{F_E}$$ **(Watts)**(15)

Using Eq (5) and DOE Test Values to solve for the UA of the tank.

$$UA = \frac{q_L}{(57.2 - 20.0)\mathrm{DegC}} * \left(\frac{F_T}{F_E}\right) = 13.612 \tfrac{Watt}{DegC} * \frac{F_T}{F_E}$$ **(W/DeltaT)** (16)

The energy loss to the flue is:

$$q_T = F_G * \frac{q_L}{F_E}$$ **(Watts)**(17)

NOTE: For tankless fossil fuel systems the losses are completely represented by flue loss. So beta will be zero in this case and alpha will be 1.0

5.Fossil Systems with Pilot

The DHW with a pilot is very similar to a burner, however it is always on and whether the tank has a demand or not, energy is always consumed and absorbed by the water. The pilot sub system is similar to the simple fossil fuel model.

$$q_B = q_{BW} + q_{BS} + q_{BF} \qquad \textbf{(Watts)}\ (18)$$

Where $\mathbf{q_{bw}}$ is the water gain form the pilot light, $\mathbf{q_{BS}}$ is the pilot to space losses and $\mathbf{q_{BF}}$ is the losses to the flue.

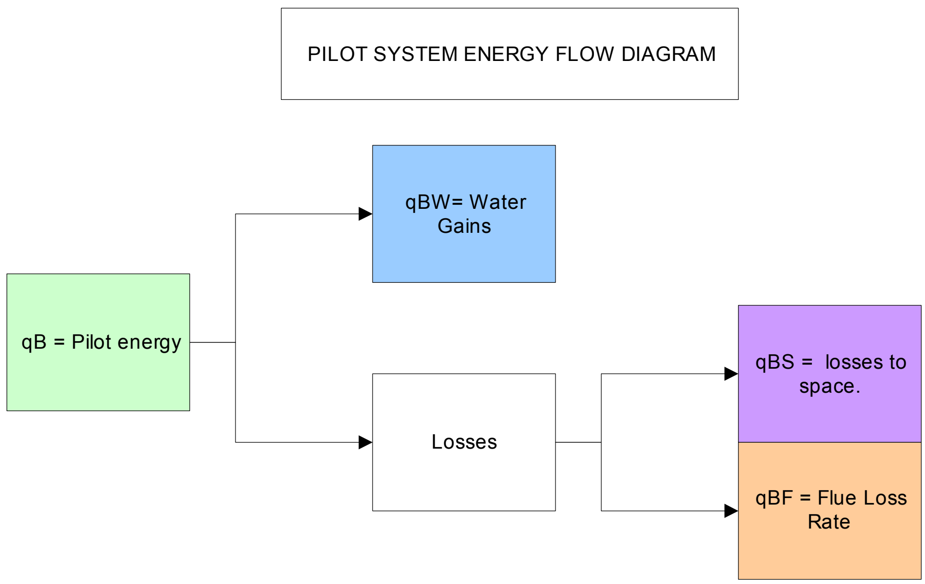

Figure 3: Pilot System Energy Flow Diagram

The energy flow balance equation for this DHW system is as follows.

$$q_P = (q_L - q_{BW}) + q_T + q_G + q_B \qquad \textbf{(Watts)}\ (19)$$

So the fossil diagram is now changed with the addition of a pilot light to the following.

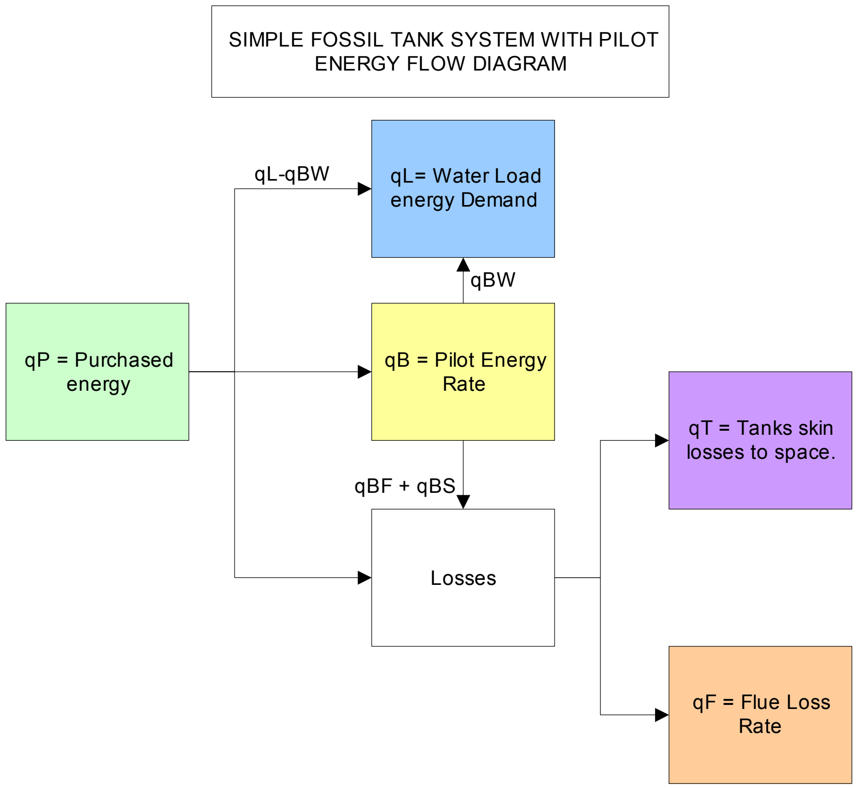

Figure 4:Simple Fossil Tank System with Pilot Energy Flow

Dividing by q_P we obtain the energy factors for the water, tank and flue gas losses.

$$1 = F_E + F_T + F_G + \frac{q_B - q_{BW}}{q_P} \tag{20}$$

Rearranging for Tank and Flue gas Losses and factoring out q_B

$$F_T + F_G = 1 - F_E - (1 - \frac{q_{BW}}{q_B}) * \frac{q_B}{q_P} \tag{21}$$

Using Eq(1) to substitute for q_P

$$F_T + F_G = 1 - F_E - (1 - \frac{q_{BW}}{q_B}) * \frac{F_E}{q_L} * q_B \tag{22}$$

As done in the simple system in Eq (11) and (12) the Fg and Ft factors are calculated but this time includes the pilot energy loss fractions within them.

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$$F_G = \alpha\left[1 - F_E - (1 - \frac{q_{BW}}{q_B}) * \frac{F_E}{q_L} * q_B\right] \tag{23}$$

$$F_T = \beta\left[1 - F_E - (1 - \frac{q_{BW}}{q_B}) * \frac{F_E}{q_L} * q_B\right] \tag{24}$$

'Through a wild calculation' (B.Bradley, 1995) the portion of energy gain from the pilot to the water is considered to be 60% of the pilots energy consumption.

In Hot2000 the standard consumption rate for the pilot $\mathbf{q_B}$ is 204.861Watts. Using the DOE testing standard values Eq (5) for $\mathbf{q_L}$ the above equations can be rewritten for generic use as:

$$F_G = \alpha\left[1 - F_E - (1 - 0.60) * \frac{F_E}{506.382} * 204.861\right] = \alpha\left[1 - F_E - 0.161823 * F_E\right] \tag{25}$$

$$F_T = \beta\left[1 - F_E - (1 - 0.60) * \frac{F_E}{506.382} * 204.861\right] = \beta\left[1 - F_E - 0.161823 * F_E\right] \tag{26}$$

Estimated alpha and beta values have been compiled by Debra Haltrech and Brian Bradley for H2K. These are contained in appendix B.

6.Water Draws

The amount of water used per day is calculated from the following formula

The daily water draw is calculated from the number of occupants (Cooper).

$$W_{Daily} = 85.0 + (35 * NumOccs) \qquad \textbf{(Litres)} \qquad (27)$$

This value must be adjusted for changes in cold main water temperatures. Some uses require a constant usage temperature over the year. Showers and personal washing are an example of this. Some uses are not dependant on temperature like laundry or dishwashing.

A value of 75% of temperature sensitive draws was used in H2K.
(This is from B.Bradley's H2KDHW model referenced in H2KDHW.F line 254.)

$$W_{NormalisedDaily} = 0.75 * \left[W_{DAILY} \frac{(T_{USAGE} - T_{COLDMAIN})}{(T_{HOTSUPPLYTEMP} - T_{COLDMAINTEMP})} \right] + 0.25 * W_{DAILY} \qquad (28)$$

$W_{NormalisedDaily}$ = Water Draw normalized to Cold Main Temperature **(Litres)**
T_{USAGE} = Average temperature at which users prefer water.**(Celsius)**
$T_{COLDMAIN}$ = Cold main water temperature. **(Celsius)**
T_{USAGE} = Temperature at which hot water tank is set at (note this is a fixed value in the model)**(Celsius)**

The cold main temperature is calculated as follows (Cooper 1991).

$$T_{COLDMAIN} = T_{MeanGround} + 3 + Amp_{GroundTempVar} * SIN[PI / 6 * (Month + GroundOffset)]$$

(Celsius) (27)

$T_{MeanGround}$ = Average Annual Deep Ground Temperature **(Celsius)**
$Amp_{GroundTempVar}$ = Amplitude of ground Temp Variance.**(Celsius)**

GroundOffset =	IF	($T_{MeanGround}$.lt.5.0)	THEN	GroundOffset = 6
	ELSEIF	($T_{MeanGround}$.gt.15.0)	THEN	GroundOffset = 8
	ELSE			GroundOffset = 7

The Demand for the model is not constant. It models real use on a house. So it is modeled after a actual varying demand per hour. The water draw curve used was taken from the CSA f379.1-88 Solar Domestic Hot Water System (Appendix C)

7. Overview of Time Step Procedure in H3K

This is an overview of the processes that are involved in the DHW model. For a complete coding refer to the source code DHW_Module.F and the Visio flowchart in the appendix.

Initialization

Before the simulation starts the temperature of the water within the tank is set to the hot supply temp.

Simulation Loop

Water Draw

First the hourly water draw for the time step is calculated. The method used in Section (3) is used. The number of time steps per hour divides that value.

Start Temperature

The start Temperature is determined by the following

1. The energy contained in the tank at the end of the last time step.
2. The Standby tank losses to the room during the last time step.
3. The energy lost due to the water draw in the present time step.

To simplify the formulas below I will define the following functions.

TVtoE(Temperature, Volume) is a function that determines the energy in joules for a volume of water at a given temperature.
EVtoT(Energy, Volume) is a functions that determine the temperature of water in degrees Celsius at a given energy and volume.

If water draw is Greater then the tank size:

$$T_{TankStartTemp} = T_{ColdMain}$$

If the water draw is less than the volume of the tank[1] then

$$EnergyInTank_{Start} = TVtoE(T_{ColdMain}, V_{WaterDraw}) + TVtoE(T_{FinalWaterLastTimeStep}, V_{Tank} - V_{WaterDraw}) - STL_{LastTimeSte}$$

Where STL is the standby tank losses from the last time step.

$$T_{TankStartTemp} = EVtoT(EnergyInTank_{Start}, V_{Tank})$$

1

Determine energy required by water during time step.
The energy gained by the water in the attempt of the system to maintain the hot supply temperature is given by. $EnergyInTank_{AtHotSupply}$ is the energy in the tank when the temperature is at the Hot Supply temperature.

$$Energy_{\text{Re}quired} = EnergyInTank_{AtHotSupplyTemp} - EnergyInTank_{Start}$$

where

$EnergyInTank_{Start} = TVtoE(T_{StartTemp}, V_{Tank})$ at the beginning of the timestep

$EnergyInTank_{AtHotSupply} = TVtoE(T_{hotSupply}, V_{Tank})$ is the energy in the tank when the temperature is at the Hot Supply temperature.

The above equation will work if the draws are less that the tank volume. If the draw is greater than the tank volume the following formula would have to be used.

$$Energy_{\text{Re}quired} = TVtoE(T_{hotSupply} - T_{ColdMainTemp}, V_{Tank}) + TVtoE(T_{HotSupply} - T_{ColdMainTemp}, (V_{WaterDraw} - V_{Tank}))$$

Determine Energy Delivered to Water.
While the energy required by the tank to heat the water up to the hot supply temperature, this does not guarantee that the burner can meet this load. The energy required over the time step is compared to the burner capacity. Whichever is less is used.

$$q_{LNet} = Min(Energy_{\text{Re}quired}, BurnerOutput_{PerTimestep})$$

Determine final temperature
The final temperature is the temperature at the end of the current time step. This is obtained by summing the energy present in the tank with the energy input to the water $\mathbf{q_{LNET}}$.

$$T_{TankFinal} = EVtoT(EnergyInTank_{Start} + q_{LNET}, V_{Tank})$$

if the draw is greater than the volume of the tank then the following formula is used.

$$T_{TankFinal} = EVtoT(EnergyInTank_{Start} + q_{LNET}, V_{WaterDraw})$$

Average tank temperature
The average temperature is not simply the average of the start and final temperature. Rather it is also dependant on the burner power and how long it takes for it to heat the water up to the set point (hot supply) temperature.

Determine the amount of energy that can be transferred to the water by the burner in one time step.

$$E_{BurnerOutputperTimestep} = BurnerPower(watts) * SecondsPerTimestep(s)$$

The average then is calculation of the fraction of the time step it takes the burner to deliver the energy to the water. The fraction of the time step is simply

$$\frac{q_{LNET}}{E_{BurnerOutputPerTimeStep}}.$$

So the average temperature over the time step is found to be.

$$T_{Average} = \frac{(T_{Start} + T_{Final})}{2} * \frac{q_{LNET}}{E_{BurnerOutputPerTimeStep}} + T_{Final} * (1.0 - \frac{q_{LNET}}{E_{BurnerOutputPerTimeStep}})$$

Determination of losses.
F_T and F_G are determined using **Eq (23)** and **Eq (24)** and appendix B
Tank losses are solved using the following equations:

$$q_T = UA * (T_{Average} - T_{Room}) * Seconds_{InTimeStep}$$

$$q_G = F_G * \frac{q_{LNET}}{F_E}$$

Determinations of Purchased Energy Required for Time step
The tanks losses are considered a part of the water energy demand. So
$q_{LNet} = q_L + q_T$
So Eq(19) can be rewritten as follows to obtain the purchased energy required for the current time step.

$$q_P = q_{LNet} + q_G + (1 - \frac{q_{BW}}{q_B}) * q_B$$

Store Values
Store the Final temperature and skin tank loss values for use in the next time step.

APPENDIX A

KEN COOPERS ORIGINAL DHW MODEL REPORT

KenCooperDHWRepo
rt.doc

APPENDIX B

ALPHA VALUES FOR TANK AND FLUE LOSSES

LISTING OF ALPHA VALUES

Conventional_tank	= 0.314113
Conventional_tank_pilot	= 0.393235
Tankless	= 1.000000
Instantaneous	= 0.588235
Instantaneous_pilot	= 0.708805
Induced_draft_fan	= 0.489625
Induced_draft_fan_pilot	= 0.624103
Direct_vent	= 0.494467
Direct_vent_pilot	= 0.633287
Condensing	= 0.000000
Oil_Conventional_tank	= 0.468284
Oil_Tankless	= 1.000000

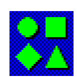
APPENDIX C

Hourly Water Demand Percentage

Hour	%of Daily Draw	Hour	%of Daily Draw
1	3.765690377	13	5.857740586
2	2.928870293	14	5.439330544
3	0	15	5.020920502
4	0	16	4.184100418
5	0	17	3.765690377
6	0	18	4.184100418
7	0	19	5.020920502
8	3.347280335	20	6.694560669
9	7.531380753	21	7.112970711
10	6.276150628	22	5.857740586
11	6.694560669	23	5.020920502
12	6.694560669	24	4.60251046

CSA f379.1-88 Solar Domestic Hot Water System

APPENDIX D
Visio Flowchart of DHW



H3KDHW.vsd

APPENDIX E
Fortran Source Code Nov 15, 2001

DHW_module.F90