AIR-SOURCE HEAT PUMP HEATING MODE MODEL FOR IMPLENTATION IN HOT3000

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1) SPECIFICATION OF AN AIR SOURCE HEAT PUMP IN H2K

The H2K user first specifies an air-source heat pump system from the Type 2 list. Type 1 list contains different sources for the backup heat source. This can be either from a Furnace, Boiler, Baseboard, Hydronic system, or Plenum Heaters. In the air-source heat pump input screen, it can be specified whether the heat pump is used for heating only or for both heating and cooling. In this case, the cooling type can be either Conventional, Economizer Control, or Ventilation control. The user is also required to specify the unit Capacity and the COP_r under rating conditions in the heating and the cooling modes.

In the heating mode, there are three types of Temperature Cut-off Control. These are Balanced Point, Restricted, and Unrestricted. In the Balance Point mode, the heat pump turns off when unable to meet the whole space heating load. The Restricted mode is based on the heat pump turning off at a specific user specified outdoor temperature. The backup heat source is used whenever the heat pump shuts off in both the Balance Point and the Restricted control options. In the Unrestricted control mode, the heat pump operates continuously with or without the space backup heat source to meet the load.

In addition to the previous inputs, the user also specifies the Crankcase Heater power, the Sensible Heat Ratio, and the Openable Window Area. The Crankshaft is a heater that keeps the oil in the compressor warm. The Openable Window Area is used to estimate the free cooling that can be achieved when the outside temperature falls below the space temperature.

In the input screen for Baseboard, Hydronic, and Plenum Heaters, the user can specify whether the capacity of the backup heater is specified or calculated by H2K. The efficiency of the backup heat source can also be specified.

2) HEAT PUMP CAPACITY AND *C.O.P.* CORRELATIONS

The model presented here is for electric heat pumps with a backup heat source. The backup can be either from a furnace or a boiler. The H2K user can also specify the backup heat source as baseboard, hydronic, or plenum heaters.

The available steady-state heating capacity of an air-source heat pump is given by (4)

$$ss\_heat\_pump\_cap = ss\_heat\_pump\_cap\_r \times (0.766836 + 0.027487 \times T_o + 0.00028936 \times T_o^2 - 1.4658 \times 10^{-5} \times T_o^3 - 5.65296 \times 10^{-7} \times T_o^4) \quad (1)$$

where:

ss_heat_pump_cap	heat pump heating capacity at current conditions (W). This is the heat delivered to the air stream on the condenser side.
ss_heat_pump_cap_r	heat pump capacity at rating conditions (W)
T_o	outdoor temperature (^{o}C)

The Coefficient of Performance $C.O.P._{HP}$ is given by (4)

$$C.O.P._{HP} = C.O.P._r \times (0.846394 + 0.018819 \times T_o - 6.37288 \times 10^{-5} \times T_o^2 - 9.165897 \times 10^{-6} \times T_o^3 - 1.99907 \times 10^{-8} \times T_o^4) \quad (2)$$

where:

$C.O.P._{HP}$	Coefficient Of Performance at actual conditions
$C.O.P._r$	Coefficient Of Performance at rated conditions

3) INITIAL ESTIMATE OF THE PART-LOAD RATIO L_{HP}

Once the space heat load is known, an initial estimate for the part-load ratio can be obtained. The Part-Load Ratio is defined in this case the same way it is defined for furnaces. If the fan of the air handler is in auto mode, then the Part-Load Ratio L_{HP} is given by

$$L_{HP} = \frac{heating\_load}{ss\_heat\_pump\_cap + fan\_capacity} \quad (3)$$

In case the fan is on continuously, the fan heat input should be included as part of the internal gains of the space. The heating load in this case would account for the contribution of the fan toward the space energy balance. In this case, the Part-Load Ratio is

$$L_{HP} = \frac{heating\_load}{ss\_heat\_pump\_cap} \quad (4)$$

If L_{HP} is greater than 1, then the heat pump does not have enough capacity to meet the space heat load. In this case backup heat is needed. For balance-point control, the heat pump turns off and the whole heat load is provided by the backup heat source. For unrestricted operation, the heat pump and the backup source both operate to supply the load. For restricted cut-off control, the heat load is provided by the backup heat if the outdoor temperature is below the cut-off point. Otherwise, the heat pump and the backup heat source operate alternatively to meet the load.

4) PART-LOAD PERFORMANCE

The performance of the heat pump at part-load conditions is dependent on the part-load factor P_{HP}. This factor is the normalized efficiency degradation given by

$$P_{HP} = \frac{Part\ Load\ Efficiency}{Steady\ State\ Efficiency} \tag{5}$$

When the heat pump is operating at part load, the performance of the unit is degraded. This effect is accounted for by the function *HEAT_EIR_FPLR* (2). Henderson (3) presents correlations for the function *HEAT_EIR_FPLR* for three different types of heat pumps. This correlation is given by

$$HEAT\_EIR\_FPLR = a + b \times L_{HP} + c \times L_{HP}^{2} + d \times L_{HP}^{3} \tag{6}$$

where L_{HP} is the part-load ratio. Values for *a, b, c,* and *d* are given for three types of heat pumps as indicated in the following Table.

Table 1: Correlation coefficients for the *HEAT_EIR_FPLR* function

Heat Pump Type	***a***	***b***	***c***	***d***
Typical Heat Pump (N_{max}=2.5; *pr*=0.01)	0.0101858	1.18131	-0.246748	0.0555745
Good Heat Pump (N_{max}=2.5;*pr*=0.01)	0.00988125	1.08033	-0.105267	0.0151403
Poor Heat Pump (N_{max}=3;*pr*=0.03)	0.0300924	1.20211	-0.311465	0.0798283

Presently, H2K has a single part-load performance curve for all types of heat pumps. The H2K interface should be changed to allow the user to choose between a “Typical”, “Good”, and “Poor” heat pump.

The Part-Load Factor is then given by

$$P_{HP} = \frac{L_{HP}}{HEAT\_EIR\_FPLR} \tag{7}$$

According to Henderson (3), a new part-load factor P'_{HP} can be defined in order to account for off-cycle power use. The off-cycle power use is due to crankcase heaters, controls, fans or other factors. The modified part-load factor is given by

$$P'_{HP} = \frac{L_{HP}}{\left(\frac{L_{HP}}{P_{HP}} + (1 - \frac{L_{HP}}{P_{HP}})pr\right)} \tag{8}$$

where pr is given in Table 1 for the different equipment types.

Interface Modification: Since the new Part-Load Factor P'_{HP} accounts for any losses related to the crankcase heaters, the separate input in H2K for this quantity will not be needed anymore.

Currently the correlation between P_{HP}, associated with part-load performance, and L_{HP} in H2K is

$$P_{HP} = 0.9 + 0.1 L_{HP} \tag{9}$$

Equations 6 through 9 are applicable when $L_{HP} \leq 1$.

Figure 1 shows the variation of the heat pump Part-Load Factor with the Part-Load Ratio based on equations 6 and 7. Figure 1 also shows the variation of P_{HP} based on equation 9 currently implemented in H2K. It is clear that the correlation currently implemented in H2K leads to a very different part-load performance than that based on the LBL report by Henderson (2).

Interface Modification: It is recommended that the part-load performance based on equations 6 and 7 be implemented in H3K. Most of the users will most likely not know whether they have a “Good”, “Typical”, or “Poor” heat pump. It is then recommended that the default H2K heat pump be of the “Typical” type.

5) INTERACTION OF THE HEAT PUMP AND THE BACKUP HEAT SOURCE

First if the outdoor temperature is below the minimum below which the heat pump is turned off, then the backup heat source is used. This value should be set to –12.22 ^{o}C based on the default value in DOE-2 (2).

If the outdoor temperature is above the minimum value, the heat pump and the backup heat energy consumption depend on the initial estimate of part-load ratio of the heat pump, equations 3 and 4, and the control method employed. The part-load ratio and the part-load factor for the backup heat source are designated by L_b and P_b respectively.

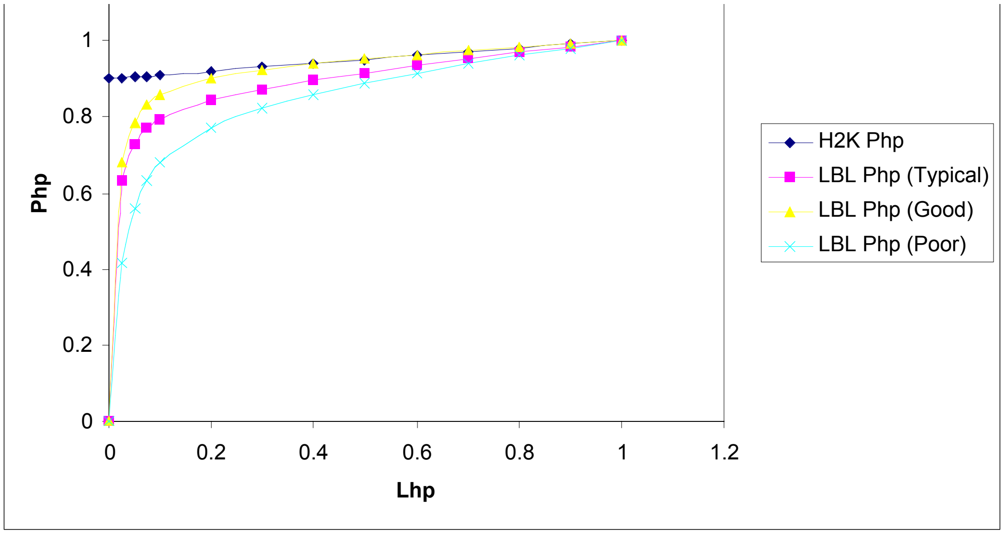

Figure 1: Comparison of the part-load performance based on the H2K correlation and that based on the LBL study by Henderson (3)

a) Balance point control; $L_{HP} \leq 1$

The full load is satisfied by the heat pump. L_{HP} is that given by either equation 3 or 4 and

$$L_b = 0$$

b) Balance point control; $L_{HP} > 1$

The full load is satisfied by the backup heat source.

$$L_{HP} = 0$$

If the backup source is a furnace or a boiler:

Fan in Auto-Mode

$$L_b = \frac{heating\_load}{ss\_backup\_capacity + fan\_capacity}$$

Fan in Continuous Mode

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$

where *heating_load* accounts for the effect of the fan heat on the load.

For baseboard, hydronic, or plenum heater backup sources, which don't employ a circulation fan:

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$

$P_b = 1$

c) Restricted cut-off ($T_{outdoor} > T_{cut\text{-}off}$); $L_{HP} \leq 1$

The full load is satisfied by the heat pump. L_{HP} is that given by either equation 3 or 4 and

$L_b = 0$

d) Restricted cut-off ($T_{outdoor} < T_{cut\text{-}off}$); $L_{HP} \leq 1$

The full load is satisfied by the backup heat source.

$L_{HP} = 0$

If the backup source is a furnace or a boiler:

Fan in Auto Mode

$$L_b = \frac{heating\_load}{ss\_backup\_capacity + fan\_capacity}$$

Fan in Continuous Mode

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$

where *heating_load* accounts for the effect of the fan heat on the load.

If the backup source is baseboard, hydronic, or plenum heaters, which don't employ a circulation fan:

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$

$P_b = 1$

e) Restricted cut-off ($T_{outdoor} > T_{cut\text{-}off}$); $L_{HP} > 1$

The heat pump and the backup heat source operate together for the whole time step to satisfy the load. In case the backup heat source is a furnace or a boiler, it can be shown that the following relationship holds (4):

$$P_{HP} \times \frac{ss\_heat\_pump\_cap}{heating\_load} \times t_f + P_b \frac{ss\_backup\_capacity}{heating\_load} \times (1 - t_f) - 1 = 0 \qquad (10)$$

where t_f is the fractional on-time of the heat pump. If t_1 is the actual time the heat pump is on in seconds and Δt is the simulation time step in seconds, then

$$t_f = \frac{t_1}{\Delta t} \tag{11}$$

We also have

$$L_{HP} = P_{HP} \times t_f \tag{12}$$
$$L_b = P_b \times (1 - t_f) \tag{13}$$

Equations 6, 7, 10, 12, and 13 form a system of five non-linear equations with six unknowns P_{HP}, $HEAT\_EIR\_FPLR$, P_b, L_{HP}, L_b, and t. An additional equation relating P_b and L_b can be obtained from the part-load performance characteristics of the furnace/boiler. The system of seven equations in seven unknowns can then be solved using Newton's Method.

In case the backup heat source is baseboard, hydronic, or plenum heater, the heat pump is on continuously. The remaining heat load is satisfied by the backup source. In this case, we have

$$L_{HP} = P_{HP} = 1$$
$$L_b = \frac{heating\_load - ss\_heat\_pump\_cap}{ss\_backup\_cap}$$
$$P_b = 1$$

f) Restricted cut-off ($T_{outdoor} < T_{cut\text{-}off}$); $L_{HP} > 1$

The full load is satisfied by the backup heat source.

$$L_{HP} = 0$$

Fan in Auto Mode:

$$L_b = \frac{heating\_load}{ss\_backup\_capacity + fan\_capacity}$$

Fan in Continuous Mode:

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$

where *heating_load* accounts for the effect of the fan heat on the load.

If the backup source is baseboard, hydronic, or plenum heaters, which don't employ a circulation fan:

$$L_b = \frac{heating\_load}{ss\_backup\_capacity}$$
$$P_b = 1$$

g) Unrestricted control; $L_{HP} \leq 1$

The full load is satisfied by the heat pump. L_{HP} is that given by either equation 3 or 4 and

$$L_b = 0$$

h) Unrestricted control; $L_{HP} > 1$

The heat pump and the backup heat source operate together to satisfy the load. The calculation procedure outlined for case (e) above is applied in this case.

6) MINIMUM ON-TIME OF THE HEAT PUMP

The term N_{max} in Table 1 is used to determine the minimum on-time of the heat pump based on

$$(t_{HP}^{on})_{\min} = \frac{3600}{4N_{\max}} \text{ minutes} \qquad (14)$$

The actual run-time of the heat pump is given by

$$t_{HP}^{on} = \frac{L_{HP}}{P_{HP}} \times \Delta t \qquad (15)$$

a) Heat Pump only Operation

If the predicted actual on-time of the heat pump is less than the minimum recommended in equation 15, then the actual on-time is set to the minimum possible time. Then we have

$$t_{HP}^{on} = (t_{HP}^{on})_{\min} = \frac{L_{HP}}{P_{HP}} \times \Delta t \qquad (16)$$

where Δt is the simulation time step. Equations 6, 7, and 16 can then be solved for P_{HP}, *HEAT_EIR_FPLR*, and L_{HP} using Newton's Method.

b) Heat Pump and Fossil Fuel Backup Heat Operation

The on-time of the backup heat and the heat pump are related by

$$P_{HP} \times ss\_heat\_pump\_cap \times t_{HP}^{on} + P_b \times ss\_backup\_cap \times t_b^{on} = heating\_load \times \Delta t \tag{17}$$

If the predicted on-time of the heat pump is less then the recommended minimum, then the heat pump on-time is modified according to equation 16. Equations 6, 7 and 16 can then be solved for P_{HP}, *HEAT_EIR_FPLR*, and L_{HP}.

The backup system part-load ratio and factor are related to the system on-time through

$$t_b^{on} = \frac{L_b}{P_b} \times \Delta t \tag{18}$$

Equations 17 and 18 can be combined with part-load performance equations for the backup system, similar to equations 6 and 7 for the heat pump, and solved for backup system part-load ratio and factor. In order for the new solution to feasible, we must have

$$t_{HP}^{on} + t_b^{on} \le \Delta t \tag{19}$$

In case the new backup heat and heat pump on-times do not satisfy this inequality, then it is assumed that the heat pump is off and the backup heat provides the total heating load. It is assumed here that the backup heat has enough capacity to satisfy the total heating load.

In case the on-time of the backup system is less then the minimum recommended for the backup system, the backup system on-time is set to the minimum possible. The new part-load ratio and factor of the backup system are then determined. Equation 6, 7,15, and 17 are then solved for P_{HP}, *HEAT_EIR_FPLR*, and L_{HP}, and $t^{on}{}_{HP}$. The new estimates for the heat pump and backup system on-times have to also satisfy equation 19. Otherwise, it is assumed that the backup system is off and only the heat pump is operational.

7) EFFECT OF THE CONDENSER AIR FLOW RATE

The performance of the heat pump is also a function of the air-flow rate on the condenser side. In DOE-2 (2), this effect is accounted for by the function *RATED_HEIR_FCFM* given by

$$RATED\_HEIR\_FCFM = 1.3824 - 0.4336 \times PLRCFM + 0.0512 \times PLRCFM^2 \tag{20}$$

where

$$PLRCFM = \frac{SUPPLY\_CFM}{RATED\_CFM} \qquad (21)$$

Interface Modification: Currently, when the H2K user specifies an air-source heat pump in the cooling mode, the indoor fan flow rate and power are part of the input. For the air-source heat pump in the heating mode, only the indoor fan power is part of the input. It is suggested then that the H2K interface be modified so that the indoor fan flow rate is also part of the input for an air-source heat pump in the heating mode. If the user does not specify the fan flow rate and power, they should be calculated internally.

8) ENERGY CONSUMPTION

Using the part-load ratio and factor set previously, the heat pump power consumption is then given by

$$heat\_pump\_power = \frac{ss\_heat\_pump\_cap}{COP_{HP}} \times \frac{L_{HP}}{P'_{HP}} \times RATED\_HEIR\_FCFM \qquad (22)$$

In this case, the heat pump energy consumption during the time step Δt is

$$heat\_pump\_energy = heat\_pump\_power \times \Delta t \qquad (23)$$

The backup heat energy consumption is given by

$$backup\_power\_input = \frac{ss\_backup\_capacity}{steady\_state\_efficiency} \times \frac{L_b}{P_b} \qquad (24)$$

The backup heat energy consumption is

$$backup\_energy = backup\_power\_input \times \Delta t \qquad (25)$$

The circulation fan power is based on the report of Barringer (1). If the fan is sized based on the furnace capacity, then

$$fan\_power = 0.0194 \times ss\_furnace\_cap \qquad (26)$$

If the fan is sized based on the heat pump capacity, then

$$fan\_power = 0.0467 \times ss\_heat\_pump\_cap\_r \qquad (27)$$

If the backup system of the heat pump does not employ a circulation fan, then the indoor fan of the air distribution system is sized based on equation 27. In case the backup system requires an indoor fan, the size of the fan is chosen equal to the maximum of the sizes predicted by equations 26 and 27.

Fan in Auto mode:
If the backup system does not employ a circulation fan

$$fan\_energy = fan\_power \times L_{HP} \times \Delta t \tag{28}$$

If the backup system employs a circulation fan

$$fan\_energy = fan\_power \times (L_b + L_{HP}) \times \Delta t \tag{29}$$

Fan in Continuous mode:

$$fan\_energy = fan\_power \times \Delta t \tag{30}$$

References

1) Barringer, C., Further Improvements to the HOT2000 Subroutine – Part B: Furnace and Heat Pump Models*,* NRCan Report No. ET-91-045

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4) HOT2000 Technical Manual, Version 6, Canadian Home Builders Association, August 1991

5) McBride, M.F., "Measurement of Residential Thermostat Dynamics for Predicting Transient Performance", ASHRAE Paper PH-79-7A, No. 3.