AIR-SOURCE HEAT PUMP COOLING MODE MODEL FOR IMPLEMENTATION 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 HVAC systems list. 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. When the heat pump is used in the cooling mode, the cooling type can be either Conventional, Economizer, or Ventilation. The user is also required to specify the heating capacity and COP_r in the cooling mode under rating conditions.

In addition to the previous inputs, the user also specifies the Cooling Type, Crankcase Heater power, the Sensible Heat Ratio, and the Openable Window Area. The Openable Window Area is used to estimate the free cooling that can be achieved when the outside temperature falls below the space temperature. There are three choices for Cooling Type: Conventional, Economizer, and Ventilation. When Conventional is chosen, space cooling is always satisfied by the heat pump regardless of the outdoor temperature. In ventilation control, a fixed amount for outdoor air is supplied until the cooling load is satisfied. The heat pump is employed whenever the ventilation air alone can not satisfy the load.

Several local HVAC systems dealers were contacted and they all agree that they are not aware of an economizer control option for residential heat pump systems. It is therefore recommended that this option be removed from the HOT3000 interface.

2) HEAT PUMP COOLING CAPACITY

The steady-state cooling capacity is given by

$$ss\_cooling\_cap = ss\_cooling\_cap\_r \times CAP' \tag{1}$$

where *ss_cooling_cap_r* is the steady-state capacity at ARI rating conditions. The capacities are assumed to reflect the total amount of cooling that occurs through the evaporator of the heat pump.

Currently, HOT2000 has the following correlation for the correction function *CAP'*

$$CAP'(e\_enthalpy, odb\_temp) = 1.1208 + 1.40772 \times 10^{-7} \times e\_enthalpy - 0.00927 \times odb\_temp \tag{2}$$

with the temperatures in ^oC and the enthalpy in J/kg

The suggested correlation in the Barringer (1987) report is

$$CAP'(ewb\_temp, odb\_temp) = 0.85931 + 0.02394 \times ewb\_temp - 0.00927 \times odb\_temp \tag{3}$$

with the temperatures in ^{o}C

The correlation in Henderson et al. (2000) is

$$CAP'(ewb\_temp, odb\_temp) = 0.418934 + 0.017421 \times ewb\_temp - 0.00617 \times odb\_temp \tag{4}$$

with the temperatures in ^{o}F

The correlation used in system RESYS in DOE-2.1E (1994) is

$$\begin{aligned} CAP'(ewb\_temp, odb\_temp) = {} & 0.6003404 + 0.0022873 \times ewb\_temp - 0.0000128 \times odb\_temp^2 + \\ & 0.0013898 \times odb\_temp - 0.0000806 \times odb\_temp^2 + \\ & 0.0001412 \times ewb\_temp \times odb\_temp \end{aligned} \tag{5}$$

with the temperatures in ^{o}F

ewb_temp	coil entering wet-bulb temperature
odb_temp	outdoor dry-bulb temperature
e_enthalpy	coil entering enthalpy

Table 1 lists values for the capacity correction factor based on the four different correlations. The dependence of the correlation currently in HOT2000 on the indoor wet-bulb temperature is very weak compared to the other three correlations. The best agreement is between the Barringer correlation and the DOE-2.1 E.

The DOE-2.1 E correlation was compared against some actual manufacturers data, contained in the IEA Task 22 document on HVAC BESTEST (2000). The percentage difference between the correlation predictions and the data varies from 0 to 3% depending on the outdoor/indoor temperature combination. The DOE-2.1E correlation will then be implemented in HOT3000.

Table 1: Comparison of the three correlations for the cooling capacity correction factor

Outdoor Dry Bulb *Odb_temp*	Indoor Wet-Bulb *iwb_temp*	*CAP'* HOT2000	*CAP'* Barringer	*CAP'* (Henderson)	*CAP'* RESYS DOE-2.1E
35 °C	10	0.80057316	0.77426	0.703834	0.758021
	12	0.801164402	0.82214	0.7665496	0.809772
	14	0.801854185	0.87002	0.8292652	0.861191
	16	0.80268474	0.9179	0.8919808	0.912278
	18	0.803529372	0.96578	0.9546964	0.963034
	20	0.80444439	1.01366	1.017412	1.013458
30 °C	10	0.84692316	0.82061	0.759364	0.813271
	12	0.847514402	0.86849	0.8220796	0.860447
	14	0.848204185	0.91637	0.8847952	0.907291
	16	0.84903474	0.96425	0.9475108	0.953803
	18	0.849879372	1.01213	1.0102264	0.999984
	20	0.85079439	1.06001	1.072942	1.045832

3) HEAT PUMP COOLING COP

The COP in the cooling mode is

$$COP_{HP} = COP_r \times COP' \tag{6}$$

Currently HOT2000 has the following correlation for *COP'*

$$COP'(e\_enthalpy, idb\_temp) = \frac{1}{0.44618 \ - \ 8.1029 \times 10^{-8} \ \times \ e\_enthalpy \ + \ 0.01926 \ \times \ odb\_temp} \tag{7}$$

where temperature is in °C and enthalpy is in J/kg

A correlation based on Barringer's report is

$$COP'(ewb\_temp, odb\_temp) = \frac{1}{0.5967 - 0.01378 \times ewb\_temp + 0.01926 \times odb\_temp} \tag{8}$$

where temperatures are in °C

A correlation by Henderson et al. (2000) is

$$COP'(ewb\_temp, odb\_temp) = \frac{1}{0.282094 - 0.005832 \times ewb\_temp + 0.01167 \times odb\_temp} \tag{8}$$

where temperatures are in °F

A correlation used in system RESYS in DOE-2.1E (1994) is

$$COP'(ewb\_temp, odb\_temp) = 1 / (-0.9617787 + 0.0481775 \times ewb\_temp - 0.0002311 \times odb\_temp^2 + 0.0032439 \times odb\_temp + 0.0001488 \times odb\_temp^2 - 0.0002952 \times ewb\_temp \times odb\_temp) \quad (9)$$

where temperatures are in ^oF

Table 2 lists COP' values from the four correlations. The correlation currently in HOT2000 does not account properly for the effect of the indoor conditions. The effect is obvious when the other three correlations are used.

The DOE-2.1 E correlation was compared to the manufacturer's data in the HVAC BESTEST (2000). The percentage difference between the correlation predictions and the manufacturer's data varies from 0 to 3% depending on the indoor/outdoor temperature combination. The DOE-2.1E correlation will then be used in HOT3000.

4) EFFECT OF FLOW RATE ON THE COOLING CAPACITY AND COP

The heat pump cooling capacity and COP are a function of the mass flow rate over the cooling coil. The correction factors for the flow rate effect are based on the correlation employed in the DOE-2.1E routine RESYS.

$$cooling\_cap\_flow\_corr = 0.8 + 0.2 \times flow\_ratio \quad (10)$$

$$cooling\_cop\_flow\_corr = \frac{1}{1.156 - 0.1816 \times flow\_ratio + 0.0256 \times flow\_ratio^2} \quad (11)$$

Table 2: Comparison of the three correlations for the cooling COP correction factor

Outdoor Dry Bulb *Odb_temp*	Indoor Wet-Bulb *iwb_temp*	*COP'* HOT2000	*COP'* Barringer	*COP'* Henderson	*COP'* RESYS DOE2.1E
35 ^oC	10	0.894575126	0.882613	0.9097989	0.894265
	12	0.89484756	0.904617	0.9275157	0.905365
	14	0.89516561	0.927747	0.9459363	0.921807
	16	0.895548867	0.952091	0.9651034	0.944167
	18	0.895938957	0.977746	0.9850632	0.973279
	20	0.896361938	1.004823	1.0058662	1.010322
30 ^oC	10	0.978905468	0.964599	1.0059208	1.020943
	12	0.979231696	0.990943	1.0276237	1.025283
	14	0.979612571	1.018766	1.0502838	1.03605
	16	0.980071568	1.048196	1.0739657	1.053654
	18	0.980538786	1.079377	1.0987402	1.078793
	20	0.981045442	1.112471	1.1246848	1.112526

$$flow\_ratio = \frac{volume\_flow}{volume\_flow\_r} \quad (12)$$

flow_ratio	ratio of operating flow rate to flow rate at rating conditions

The reference volume flow rate for air conditioners is 450 cfm/ton (6.037 x 10^{-5} (m^3/s)/W).

5) PART-LOAD PERFORMANCE

The part-load performance in cooling mode is the same as that for heating mode for heat pumps documented by Haddad (2000). This is in agreement with the findings in a recent report by Henderson (2000). The degradation associated with part-load performance is accounted for through the use of the Part-Load Factor P_{HP} given as a function of the Part-Load Ratio L_{HP}.

6) CONTROL STRATEGIES

Figure 1 shows all the relevant states for an air conditioning process through the cooling coil of an air-source heat pump. Process 1-2 is through the supply fan, 2-4 is through the cooling coil, and 4-5 is to represent the sensible cooling process through the coil. Sate 3 is also known as the Apparatus-Dew Point. It is assumed that the space conditions are known at the end of a time step in ESP-r.

Conventional
The airflow through the cooling coil is 100% return air. The heat pump is on until the sensible load of the space is satisfied.

Part-Load Ratio L_{HP}

Without a circulation fan or fan in continuous mode:

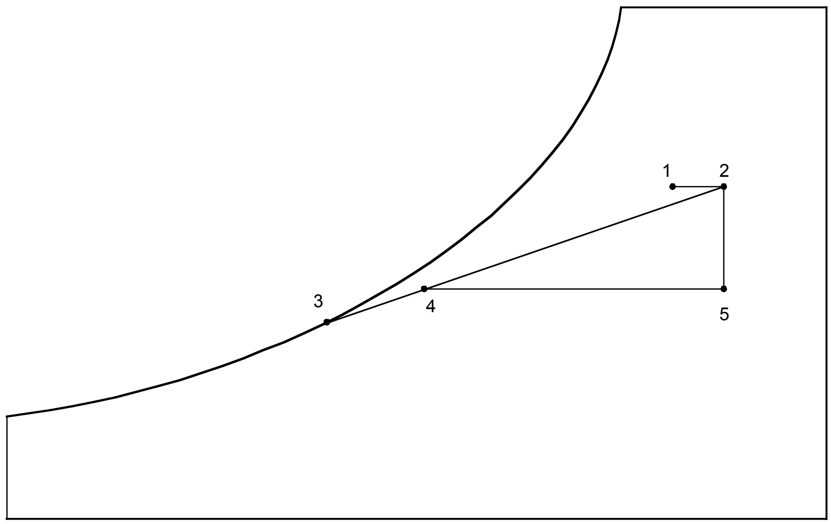

Figure 1: Air-conditioning process

$$L_{HP} = \frac{sensible\_cooling\_load}{sensible\_cooling\_cap} \tag{13}$$

In this case the fan heat input is accounted for as part of the internal gains of the space.

Circulation Fan in Auto-Mode:

$$L_{HP} = \frac{sensible\_cooling\_load}{sensible\_cooling\_cap - fan\_cap} \tag{14}$$

Ventilation

In this case, a specified amount of outdoor air is brought inside the space when the outdoor temperature is less than that indoors until the sensible cooling load is satisfied. If the load is not satisfied with the ventilation flow, then the heat pump is employed.

Total sensible cooling capacity from ventilation air

$$vent\_sensible\_cooling\_cap = vent\_mass\_flow \times specific\_heat \times (T_1 - odb\_temp) \tag{15}$$

If the heat pump has to be employed, L_{HP} is given by

Without a circulation fan or fan in continuous mode:

$$L_{HP} = \frac{sensible\_cooling\_load - vent\_sensible\_cooling\_cap}{sensible\_cooling\_cap} \tag{16}$$

In this case the fan heat input is accounted for as part of the internal gains of the space.

Circulation Fan in Auto-Mode:

$$L_{HP} = \frac{sensible\_cooling\_load - vent\_sensible\_cooling\_cap}{sensible\_cooling\_cap - fan\_cap} \tag{17}$$

7) COOLING COIL INLET CONDITIONS

$$w_2 = w_1 \tag{18}$$

With circulation fan:

$$T_2 = T_1 + \frac{fan\_cap}{mass\_flow \times specific\_heat} \tag{19}$$

Without circulation fan:

$$T_2 = T_1 \tag{20}$$

$$specific\_heat = (1006 + 1805 w_2)\ J/kg{-}^{o}C \tag{21}$$

8) SENSIBLE HEAT RATIO

The sensible heat ratio is the fraction of the total heat transfer at the cooling coil that is sensible. The calculation procedure for the sensible heat ratio *SHR* currently implemented in HOT2000 is based in most part on the Barringer's report (1987). The same procedure is shown in this section with few modifications. The procedure in HOT2000 always employs the bypass factor at rating conditions *BFr*. In the current procedure, the bypass factor *BF* corrected for the actual flow rate is used. The bypass factor is the fraction of total airflow through the coil that exits the coil at the same temperature as that at the inlet. The other portion of the airflow is at the coil surface temperature. It is assumed that the indoor space conditions, state 1, are known at the end of the calculation for the time step in question.

$$SHR = \frac{h_5 - h_4}{h_2 - h_4} \tag{22}$$

$$h_2 = h_1 + \frac{fan\_cap}{mass\_flow} \tag{23}$$

$$h_4 = h_2 - \frac{ss\_cooling\_cap}{mass\_flow} \tag{24}$$

$$h_3 = h_2 - \frac{h_2 - h_4}{1 - BF} \tag{25}$$

$$T_3 = -5.80119 + 6.64782 \times 10^{-1} \times h_3 - 5.01455 \times 10^{-3} \times h_3^2 + 2.49725 \times 10^{-5} \times h_3^3 - 5.50151 \times 10^{-8} \times h_3^4 \tag{26}$$

$$w_3 = \frac{h_3 - 1006 \times T_3}{2501000 + 1805 \times T_3} \tag{27}$$

$$T_4 = T_3 + (T_2 - T_3) \times BF \tag{28}$$

$$w_4 = w_3 + BF \times (w_1 - w_3) \tag{29}$$

$$h_5 = 1006 \times T_2 + w_4 \times (2501000 + 1805 \times T_2) \tag{30}$$

where

BF coil bypass factor

Once the sensible heat ratio is known, it is then possible to find the available sensible cooling capacity of the heat pump

$$sensible\_cooling\_cap = SHR \times ss\_cooling\_cap \tag{31}$$

9) APPARATUS BYPASS FACTOR

The following procedure is based on Henderson et al. 2000

For an air-to-refrigerant heat exchanger $C_{\min} / C_{\max} \approx 0$

The effectiveness of the heat exchanger is then

$$\varepsilon = 1 - \exp\left(-\frac{hA}{flow\_rate \times specific\_heat}\right) \tag{32}$$

Definition of effectiveness

$$\varepsilon = \frac{T_2 - T_4}{T_2 - T_{cold,i}} \approx \frac{T_2 - T_4}{T_2 - T_3} = 1 - BF \tag{33}$$

Therefore,

$$BF = \exp\left(-\frac{hA}{flow\_rate \times specific\_heat}\right) \tag{34}$$

Using the bypass factor at rating conditions, it is possible to estimate the ratio *hA/specific_heat* of the heat exchanger. This ratio is then used to find *BF* at the new flow rate.

10) APPARATUS DEW-POINT AND BYPASS FACTOR AT RATING CONDITIONS

The following procedure is based on the Barringer report 1987

Rating conditions are:

Outdoor dry-bulb temperature 35 ^{o}C

Indoor dry-bulb temperature	26.7 ^{o}C
Indoor wet-bulb temperature	19.4 ^{o}C
Indoor air humidity ratio	0.0112
Indoor dry-air density	1.1565 kg/m^3
Indoor moist air density	1.1695 kg/m^3
Volume flow rate	450 cfm/ton (6.037 x 10^{-5} (m^3/s)/W)

A line is defined for the process line 2 – 3 through the cooling coil for the rating conditions

$$w = m \times T + b \tag{35}$$

State 2 is at the exit of the supply fan. It is assumed that the power of the fan is 0.773 W/(L/s). The flow rate through the fan is

$$vol\_flow\_rate\_r = 6.037 \times 10^{-5} \times ss\_cooling\_cap\_r \tag{36}$$

The fan power is then

$$fan\_cap\_r = 0.773 \times 1000 \times vol\_flow\_rate\_r \tag{37}$$

The temperature at the exit of the supply fan

$$T_{2r} = 26.7 + \frac{fan\_cap\_r}{1.1565 \times vol\_flow\_rate\_r \times 1015} \tag{38}$$

Given the sensible heat ratio at rating conditions, we can find h_{4r} and T_{4r}

$$h_{4r} = h_{2r} - \frac{ss\_cooling\_cap\_r}{1.156 \times vol\_flow\_rate\_r} \tag{39}$$

$$T_{4r} = T_{2r} - \frac{SHRr \times ss\_cooling\_cap\_r}{1.156 \times vol\_flow\_rate\_r \times 1015} \tag{40}$$

$$w_{4r} = \frac{h_{4r} - 1006 \times T_{4r}}{2501000 + 1805 \times T_{4r}} \tag{41}$$

Then

$$m = \frac{w_{1r} - w_{4r}}{T_{1r} - T_{4r}} \tag{42}$$

$$b = w_{1r} - m \times T_{1r} \tag{43}$$

Using an appropriate relationship between temperature and humidity ratio at saturation, it is possible to solve for T_{3r}

$$T_{3r} = \frac{(-B + (B^2 - 4 \times A \times C)^{0.5})}{2 \times A} \tag{44}$$

$$A = 2.1539 \times 10^{-5}$$
$$B = 1.0776 \times 10^{-4} - m$$
$$C = 4.2065 \times 10^{-3} - b$$

Bypass Factor

$$BFr = \frac{T_{4r} - T_{3r}}{T_{1r} - T_{3r}} \tag{45}$$

This section for the determination of the bypass factor will be placed at the interface level. Given the user inputs, it is then possible to estimate the bypass factor and determine whether the inputs are acceptable. The bypass factor can not be negative and it can not be greater than unity. If it is, then the user is prompted to modify the value of the sensible heat factor.

11) ENERGY CONSUMPTION

The heat pump power consumption in the cooling mode is

$$heat\_pump\_power = \frac{ss\_cooling\_cap \times cooling\_cap\_flow\_corr}{COP_{HP} \times cooling\_cop\_flow\_corr} \times \frac{L_{HP}}{P'_{HP}} \tag{46}$$

The heat pump energy consumption during time step Δt is

$$heat\_pump\_energy = heat\_pump\_power \times \Delta t \tag{47}$$

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