SimView: HVAC

Finn Aakre Haugen, TechTeach. (finn@techteach.no)

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1 System description

The SimView simulator is available at

https://techteach.no/simview/hvac

Figure 1 shows a P&I diagram of the HVAC system which is simulated with the SimView HVAC simulator.

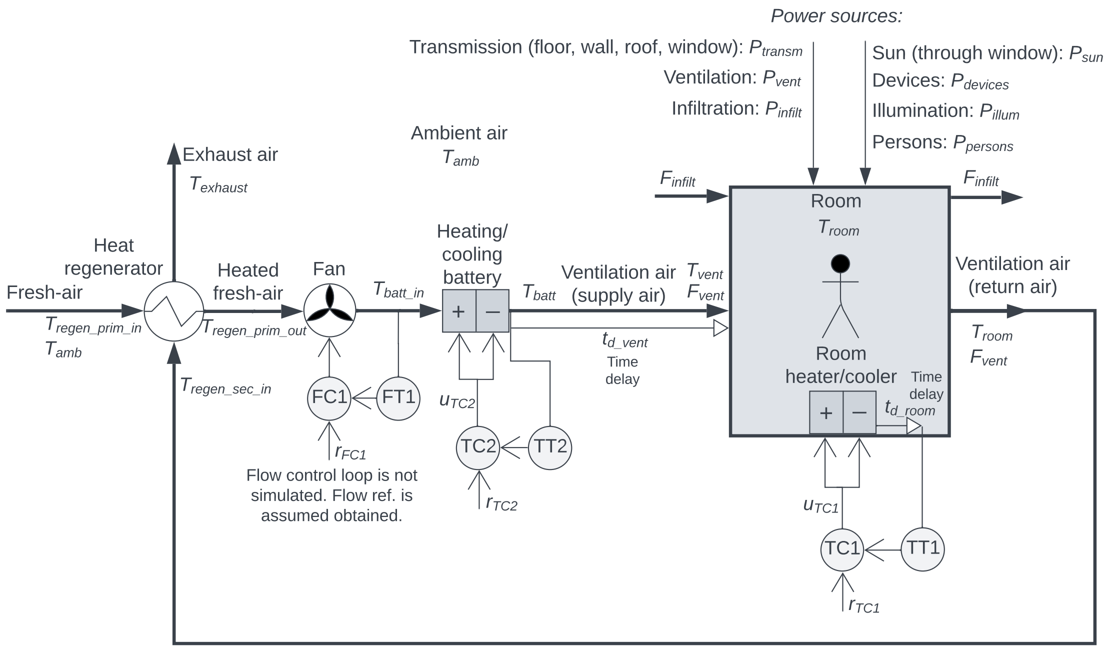

Figure 1: P&I diagram of simulated HVAC system.

- TC1 controls the room temperature so that it stays close to – ideally at – its reference, which is normally 22 °C. Sensor for room temperature: TT1. Actuator: The room heater and cooler, which provide heating/cooling as demanded by TC1. TC1 uses split range control manipulate the heater and the cooler.
- TC2 controls the supply air temperature so that it stays close to – ideally at – its reference. Sensor: TT2. Actuator: Heater and cooler battery, which provide heating and cooling as demanded by TC2. TC2 uses split range control manipulate the heater and the cooler. The temperature reference is normally 22 ° C, as for reference of the room temperature reference (to provide pleasant supply air to the room).
- The ventilation air flow is assumed "perfectly" controlled by the flow controller FC1. The simulator does not contain this control loop. Instead, the airflow is an adjustable parameter as if it were a flow reference to FC1.
- The room temperature is influenced by several power sources, see Figure 1.
- Energy regeneration is achieved by heat exchange between the return air and the fresh air.

2 Mathematical model

2.1 Modeling principle

The mathematical model which is the basis of the simulator is based on an energy balance of the air in the room and an energy balance of the air in the heating/cooling battery, assuming homogeneous temperature conditions. The model is presented in Section 2.3.

2.2 Model parameters

Table 1 shows room dimensions

Table 2 shows heat conductance parameters.

Table 3 shows air and air flow parameters.

Table 4 shows heat (power) and energy parameters.

Table 5 shows temperature variables and settings.

2.3 Energy balances

2.3.1 Energy balance of the air in the room

$$(c_{\mathrm{air}}\rho_{\mathrm{air}}V_{\mathrm{room}}T_{\mathrm{room}})' = u_{\mathrm{TC1,delayed}} + P_{\mathrm{transm}} + P_{\mathrm{infilt}} + P_{\mathrm{sun}} + P_{\mathrm{devices}} + P_{\mathrm{illum}} + P_{\mathrm{persons}} + P_{\mathrm{vent}} \quad (1)$$

Table 1: Room dimensions.

Symbol	Value (default)	Unit	Description
L_{floor}	10	m	Length of floor
W_{floor}	5	m	Width of floor
H_{wall}	2.4	m	Height of wall
W_{window}	1.0	m	Width of window
H_{window}	1.0	m	Height of window
W_{door}	1.0	m	Width of door
H_{door}	2.1	m	Height of door
n_{windows}	1	-	Number of windows
n_{doors}	1	-	Number of doors
A_{floor}	$L_{\text{floor}} \cdot W_{\text{floor}}$	m^2	Area of floor
A_{windows}	$n_{\text{windows}} \cdot L_{\text{floor}} \cdot W_{\text{floor}}$	m^2	Area of windows
A_{doors}	$n_{\text{doors}} \cdot H_{\text{door}} \cdot W_{\text{door}}$	m^2	Area of doors
$A_{\text{outer\_walls}}$	$2 \cdot A_{\text{floor}} \cdot H_{\text{wall}} - A_{\text{doors}} - A_{\text{windows}}$	m^2	Area of outer walls

or

$$T'_{\text{room}} = \left(u_{\text{TC1,delayed}} + P_{\text{transm}} + P_{\text{infilt}} + P_{\text{sun}} + P_{\text{devices}} + P_{\text{illum}} + P_{\text{persons}} + P_{\text{vent}}\right) / \left(c_{\text{air}}\rho_{\text{air}}V_{\text{room}}\right) \tag{2}$$

In the following is detailed information about the power terms on the right side of (2).

$u_{\text{TC1,delayed}}$ [W] is power supply demanded by the temperature controller TC1. It is assumed that the actual power is equal to this power demand. The supplied power is assumed time delayed with time delay $t_{d,\text{room}}$ which represents an assumed time delay from the room heater/cooler to the room temperature sensor. Thus,

$$u_{\text{TC1,delayed}}(t) = u_{\text{TC1}}\left(t - t_{d,\text{room}}\right) \tag{3}$$

P_{transm} in (2) is the net transmission heat supplied to the air in the room:

$$\begin{aligned} P_{\text{transm}} &= UA_{\text{outer\_walls}}\left(T_{\text{amb}} - T_{\text{room}}\right) \\ &\quad + UA_{\text{ceiling}}\left(T_{\text{attic}} - T_{\text{room}}\right) \\ &\quad + UA_{\text{floor}}\left(T_{\text{basement}} - T_{\text{room}}\right) \\ &\quad + UA_{\text{doors}}\left(T_{\text{amb}} - T_{\text{room}}\right) \\ &\quad + UA_{\text{windows}}\left(T_{\text{amb}} - T_{\text{room}}\right) \end{aligned} \tag{4}$$

P_{infilt} in (2) is the heat by infiltration of ambient air:

$$P_{\text{infilt}} = c_{\text{air}}\rho_{\text{air}}F_{\text{infilt}}\left(T_{\text{amb}} - T_{\text{room}}\right) \tag{5}$$

where

$$F_{\text{infilt}} = k_{\text{air\_leak\_50pa}}V_{\text{room}}/3600 \tag{6}$$

Table 2: Heat conductance parameters.

Symbol	Value (default)	Unit	Description
$U_{\text{outer wall}}$	0.22	W/(K·m^2)	Specific heat conductance of outer wall. Ref: (Tek17 2017), §14-3.
U_{ceiling}	0.18	W/(K·m^2)	Specific heat conductance of ceiling. Ref: (Tek17 2017), §14-3.
U_{floor}	0.18	W/(K·m^2)	Specific heat conductance of floor. Ref: (Tek17 2017), §14-3.
U_{door}	1.2	W/(K·m^2)	Specific heat conductance of door. Ref: (Tek17 2017), §14-3.
U_{window}	1.2	W/(K·m^2)	Specific heat conductance of window. Ref: (Tek17 2017), §14-3.
$UA_{\text{outer walls}}$	$U_{\text{outer wall}} \cdot A_{\text{outer\_walls}}$	W/K	Heat conductance of outer walls
UA_{ceiling}	$U_{\text{ceiling}} \cdot A_{\text{ceiling}}$	W/K	Heat conductance of ceiling
UA_{floor}	$U_{\text{floor}} \cdot A_{\text{floor}}$	W/K	Heat conductance of floor
UA_{door}	$U_{\text{door}} \cdot A_{\text{door}}$	W/K	Heat conductance of door

P_{sun} in (2) is the heat by the sun shining through the windows, taking into account that the sun shines from angle a_{sun} above the horizontal plane:

$$P_{\text{sun}} = n_{\text{windows}} \cdot A_{\text{windows}} \cdot P_{\text{sun\_vertical\_per\_m2}} \cdot \cos\left(\pi \cdot a_{\text{sun}}/180\right) \tag{7}$$

P_{devices} in (2) is the heat from various devices in the room:

$$P_{\text{devices}} = A_{\text{floor}} P_{\text{devices\_per\_m2}} \tag{8}$$

P_{illum} in (2) is the heat from illumination (lights):

$$P_{\text{illum}} = A_{\text{floor}} P_{\text{illum\_per\_m2}} \tag{9}$$

P_{persons} in (2) is heat from the persons in the room:

$$P_{\text{persons}} = n_{\text{persons}} \cdot P_{\text{persons\_heat\_per\_pers}} \tag{10}$$

P_{vent} in (2) is the net heat supplied to the room by the air ventilation:

$$P_{\text{vent}} = c_{\text{air}} \rho_{\text{air}} F_{\text{vent}} \left(T_{\text{amb}} - T_{\text{room}}\right) \tag{11}$$

Table 3: Air and flow parameters.

Symbol	Value (default)	Unit	Description
c	1005	J/(kg·K)	Specific heat capacity of air
ρ	1.2	kg/m^3	Density of air
F_{vent}	-	m^3/s	Flow rate of ventilation air
F_{infilt}	-	m^3/s	Flow rate of infiltration air
k_{vent}	1.2	(m^3/h)/m^2	Ventilation constant (specification). Ref: (Tek17 2017), §13-2.
$k_{\text{air\_leak\_50\_pa}}$	1.5	h^{-1}	Air leakage constant (specified maximum). Ref: (Tek17 2017), §14-3.
V_{batt}	0.1	m^3	Volume of air in heating/cooling battery
$t_{d,\text{room}}$	60	s	Time delay from room heater/cooler to room temperature sensor
$t_{d,\text{batt}}$	5	s	Time delay from heater/cooling battery to temperature in ventilation air entering room

2.3.2 Energy balance of the air in the heating/cooling battery

It is assumed that the heating/cooling battery consists of a volume (vessel) of air with air volume $V_{\text{heat\_cool\_batt}}$ heated or cooled with power as demanded by temperature controller TC2. Energy balance of the air in the battery is

$$(c_{\text{air}}\rho_{\text{air}}V_{\text{batt}}T_{\text{batt}})' = u_{\text{TC2}} + c_{\text{air}}\rho_{\text{air}}F_{\text{vent}}\left(T_{\text{regen\_primary\_out}} - T_{\text{batt}}\right) \tag{12}$$

or

$$T'_{\text{batt}} = [u_{\text{TC2}} + c_{\text{air}}\rho_{\text{air}}F_{\text{vent}}\left(T_{\text{regen\_primary\_out}} - T_{\text{batt}}\right)]/(c_{\text{air}}\rho_{\text{air}}V_{\text{batt}}) \tag{13}$$

In (13), $T_{\text{regen_primary_out}}$is calculated with

$$T_{\text{regen\_primary\_out}} = T_{\text{regen\_primary\_in}} + k_{\text{effic\_regen\_of\_heat\_regenerator}} \cdot (T_{\text{regen\_secondary\_in}} - T_{\text{regen\_primary\_in}}) \tag{14}$$

where

$$T_{\text{regen\_primary\_in}} = T_{\text{amb}} \tag{15}$$

and

$$T_{\text{regen\_secondary\_in}} = T_{\text{room}} \tag{16}$$

It is assumed that there is a time delay, $t_{d,\text{batt}}$, from $T_{\text{batt}}(t)$ to $T_{\text{vent}}(t)$ which is the temperature of the ventilation air entering the room:

$$T_{\text{vent}}(t) = T_{\text{batt}}\left(t - t_{d,\text{batt}}\right) \tag{17}$$

Table 4: Heat (power) and energy parameters.

Symbol	Value (default)	Unit	Description
$P_{\text{devices\_per\_m2}}$	8	W/m^2	Specific heat from devices (electrical). Ref: (Dokka & Thyholt 2002)
$P_{\text{persons\_heat\_per\_pers}}$	100	W/n	Specific heat from person. Ref.: (Emilsen 2007)
$P_{\text{illum\_per\_m2}}$	7	W/m^2	Specific heat from illumination. Ref: (Dokka & Thyholt 2002)
$k_{\text{sun\_factor}}$	0.26	-	Sun factor. Ref: (Dokka & Thyholt 2002)
a_{sun}	30	degrees	Sun angle (from horizontal plane)
$P_{\text{sun\_vertical\_per\_m2}}$	500	W/m^2	Specific heat from perpendicular sun. Ref.: https://snl.no/solenergi.
$k_{\text{effic\_regen\_of\_heat\_regenerator}}$	0.7	K/K	Efficiency of heat regenerator. Ref.: (Zijdemans 2014), Ch. 7.1.1.
n_{persons}	1	-	Number of persons in the room

3 Controller tuning

3.1 Tuning of the TC1 controller

The TC1 controller is tuned as a PI controller using the SIMC method (Skogestad 2003) assuming the process dynamics is "integrator with time delay". The integrator dynamics is obtained by neglecting each of the P terms of at the right side of (18), but of course retaining the power demanded by the controller. The resulting model is

$$T_{\text{room}}(t)' = u_{\text{TC1}}\left(t - t_{d,\text{room}}\right) / \left(c_{\text{air}}\rho_{\text{air}}V_{\text{room}}\right) = K_i u_{\text{TC1}}\left(t - t_{d,\text{room}}\right) \tag{18}$$

That is,

$$K_{i,\text{room}} = \frac{1}{c_{\text{air}}\rho_{\text{air}}V_{\text{room}}} \tag{19}$$

The PI settings of TC1 become

$$K_{c,\text{TC1}} = \frac{1}{2K_{i,\text{room}}t_{d,\text{room}}} \tag{20}$$

$$T_{i,\text{TC1}} = 4t_{d,\text{room}} \tag{21}$$

Table 5: Temperature variables and settings.

Symbol	Value (default)	Unit	Description
T_{room}	-	°C	Temperature of room air
T_{vent}	-	°C	Temperature of ventilation air into room
T_{batt}	-	°C	Temperature of air in heater/cooler battery
$T_{\text{room,init}}$	22.0	°C	Initial temperature of room air
$T_{\text{batt,init}}$	22.0	°C	Initial temperature of heating/cooling battery
T_{attic}	0.0	°C	Temperature of attic
T_{basement}	0.0	°C	Temperature of basement
$T_{\text{regen\_secondary\_in}}$	T_{room}	°C	Temperature of secondary inflow to regenerator
$T_{\text{regen\_primary\_in}}$	T_{amb}	°C	Temperature of primary inflow to regenerator
$T_{\text{regen\_primary\_out}}$	See (14).	°C	Temperature of primary outflow from regenerator

3.2 Tuning of the TC2 controller

Also the TC2 controller is tuned as a PI controller using the SIMC method (Skogestad 2003) assuming the process dynamics is "integrator with time delay". The integrator dynamics is obtained by neglecting the heat advection term at the right side of (13), but of course retaining the power demanded by the controller. The resulting model is

$$T_{\text{batt}}(t)' = u_{\text{TC2}}(t)\,/(c_{\text{air}}\rho_{\text{air}}V_{\text{batt}}) = K_{i,\text{batt}}u_{\text{TC2}}(t) \tag{22}$$

That is,

$$K_{i,\text{batt}} = \frac{1}{c_{\text{air}}\rho_{\text{air}}V_{\text{batt}}} \tag{23}$$

The measurement used by the TC2 controller is T_{vent}, which is time delayed $T_{\text{batt}}(t)$. The time delay is $t_{d,\text{batt}}$, cf. (17).

The PI settings of TC2 become

$$K_{c,\text{TC2}} = \frac{1}{2K_{i,\text{batt}}t_{d,\text{batt}}} \tag{24}$$

$$T_{i,\text{TC2}} = 4t_{d,\text{batt}} \tag{25}$$

References

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