TRNSYS–Models for Radiator Heating Systems

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1 Static Radiator Model (TYPE 161)

- Steady state performance of a radiator.
- Uses the ideal heating system of the TYPE 56 Multizone Component.
- Calculates radiator mass flow and exhaust temperature.
- Only convective heating to building zones.
- No Limit on the number of TYPE 161 components per TRNSYS Deck.

2 Dynamic Radiator Model With Pipes (TYPE 162)

- Dynamic first order model of a radiator.
- Including a static model of an noninsulated pipe (Subroutine RADPIPE).
- Connection to the TYPE 56 Multizone Component via internal convective and radiative GAINS.
- The ideal TYPE 56 heating is switched off.
- Thermostatic valve control is modelled by an external PID - Controller (TYPE 120) acting on the radiator mass flow.
- No Limit on the number of TYPE 162 components per TRNSYS Deck.

3 PID–Controller as Thermostatic Valve (TYPE 120)

- PID–Controller model with separate P-band and PID-band for stable control.
- Different kinds of radiator control are possible.
- Limit of 10 TYPE 120 components per TRNSYS Deck.

1 Static Radiator Model (TYPE 161)

1.1 General Description

The performance of a radiator is described by an exponential relationship depending on the temperature difference between radiator and its environment, the 'characteristic curve' of the radiator:

$$\dot{Q} = const \cdot \Delta t^n \tag{1}$$

The radiator performance is therefore described if one value of heat emission under 'Nominal Conditions' and the radiator exponent n are known.

$$\dot{Q} = \dot{Q}_N \cdot \left(\frac{\Delta t}{\Delta t_N}\right)^n \tag{2}$$

Nominal Radiator Conditions:	
Radiator supply temperature:	$t_{su,N} = 90\,℃$
Radiator exhaust temperature:	$t_{ex,N} = 70\,℃$
Environment temperature :	$t_{en,N} = 20\,℃$
Difference of mean radiator temp. to environment temp. :	$\Delta t_N = 60\,\mathrm{K}$
Nominal radiator power:	$\dot{Q}_N$
Nominal radiator mass flow rate :	$\dot{m}_{w,N} = \frac{\dot{Q}_N}{c_w \cdot (t_{su,N} - t_{ex,N})}$

Using the logarithmic temperature difference

$$\Delta t_{lg} = \frac{t_{su} - t_{ex}}{ln \frac{t_{su} - t_{en}}{t_{ex} - t_{en}}} \tag{3}$$

together with the water side heat balance

$$\dot{Q} = \dot{m}_w \cdot (t_{su} - t_{ex}) \tag{4}$$

the heat emission of a radiator can be calculated:

$$\dot{m}_w \cdot (t_{su} - t_{ex}) = \dot{Q}_N \cdot \left(\frac{\Delta t_{lg}}{\Delta t_{lg,N}}\right)^n \tag{5}$$

1.2 Implemented Model

The static radiator heat balance equation

$$F(tex) = \dot{m}_w \cdot \dot{c}_w \cdot (t_{su} - t_{ex}) - \dot{Q}_N \cdot \left(\frac{t_{su} - t_{ex}}{ln \frac{t_{su} - t_{en}}{t_{ex} - t_{en}} \cdot \Delta t_{lg,N}}\right)^n \tag{6}$$

is solved by an Newton- Raphson iteration using:

$$t_{ex,new} = t_{ex,old} - \frac{F(t_{ex,old})}{\frac{\partial F(t_{ex,old})}{\partial t_{ex}}} \tag{7}$$

Extreme radiator operation conditions:

- At very high mass flow rates ($\dot{m}_w \geq 0.98 \cdot \dot{m}_{w,N}$) the logarithmic and arithmetic temperature difference are almost identical and the arithmetic temperature difference is used:

$$\Delta t = \frac{t_{su} + t_{ex}}{2} - t_{en} \tag{8}$$

- At very low mass flow rates ($\dot{m}_w \leq 0.02 \cdot \dot{m}_{w,N}$) the radiator exhaust temperature is nearly equal to room temperature and the heat emission is a linear function of the mass flow:

$$t_{ex} = t_{en} \qquad \dot{Q} = \dot{m}_w \cdot c_w (t_{su} - t_{en}) \tag{9}$$

1.3 TRNSYS Component Description

PARAMETERS

1. Maximum water mass flow rate [kg/h]
2. Nominal power of radiator (DT=60) [kJ/h]
3. Radiator exponent [–]
4. Specific heat of fluid [kJ/kg/K]

INPUTS

1. Water supply temperature [℃]
2. Inside room air temperature [℃]
3. Required emitted radiator power [kJ/h]

OUTPUTS

1. Outlet water temperature [℃]
2. Water mass flow rate [kg/h]
3. Power emitted by radiator [kJ/h]
4. Relative error of emitted power [–]
5. Mean radiator temperature [℃]

1.4 Connection to the TYPE 56 Multizone Building

In the Type 56 Multizone Building the integrated heating equipment is used to heat the building zones. The maximum transferable heating power of the radiators given at maximum mass flow rate and supply temperature, is used to define the maximum power of the HEATING card of each zone.

The calculated heating power of each building zone is given as input to the static radiator model. Together with radiator parameters, the temperature of the building zones and the supply fluid temperature, the radiator model calculates outlet water temperature and mass flow rate. The relative error of the required radiator power to the actually emitted radiator power is given as output of the TYPE 161 component.

2 Dynamic radiator model with pipes (TYPE 162)

2.1 General description

Radiator Section

To describe the dynamic behaviour of a radiator it is assumed that the total radiator heat capacitance is concentrated at the exhaust node (first order radiator model).

This leads to the heat balance equation

$$\dot{m}_w \cdot c_w \cdot (t_{su} - t_{ex}) = C_{rad} \cdot \frac{\partial t_{ex}}{\partial \tau} + \dot{Q}_N \Big(\frac{\Delta t_{lg}}{\Delta_{lg,N}}\Big)^n \tag{10}$$

with the lumped radiator capacitance of fluid and metal

$$C_{rad} = M_w \cdot c_w + M_{met} \cdot c_{met} \tag{11}$$

The radiator heat balance equation is solved using an equivalent heat transfer coefficient $U \cdot A$ for 3 different modes of radiator operation.

$$\dot{m}_w \cdot c_w = C_{rad} \frac{\partial t_{ex}}{\partial \tau} + U \cdot A \cdot (t_{ex} - t_{en}) \tag{12}$$

$$U \cdot A \cdot (t_{ex} - t_{en}) = \dot{Q}_N \cdot \Big(\frac{\Delta t_{lg}}{\Delta t_{lg,N}}\Big)^n \tag{13}$$

Radiator operation modes

1. Heating up the radiator ($t_{ex} \leq t_{en}$), a logarithmic temperature difference $\Delta t_{lg} = |t_{ex} - t_{en}|$ is assumed:

$$U \cdot A = \frac{\dot{Q}_N}{(\Delta t_{lg,N})^n} \cdot (|t_{ex} - t_{en}|)^{n-1} \tag{14}$$

2. Low mass flow rate: ($\dot{m}_w \leq 0.02 \cdot \dot{m}_{w,N}$), a linear superpostion of Δt_{lg} and $(t_{ex} - t_{en})$ is used for the logarithmic temperature difference Δt^*_{lg} :

$$U \cdot A = \dot{Q}_N \cdot \frac{\left(\frac{\Delta t^*_{lg}}{\Delta t_{lg,N}}\right)^n}{t_{ex} - t_{en}} \tag{15}$$

with

$$\Delta t^*_{lg} = \frac{\dot{m}_w}{\dot{m}_{w,N}} \cdot \Delta t_{lg} + \left(1 - \frac{\dot{m}_w}{\dot{m}_{w,N}}\right) \cdot (t_{ex} - t_{en}) \tag{16}$$

3. Normal radiator operation:

$$U \cdot A = \frac{\dot{Q}_N \cdot \left(\frac{\Delta t_{lg}}{\Delta t_{lg,N}}\right)^n}{t_{ex} - t_{en}} \tag{17}$$

The emitted radiator power is transferred to the room by convective and radiative heat exchange. Knowing the radiative fraction of the emitted power at normal radiator conditions s_N, the radiative fraction s at other operating conditions is obtained:
Separating the load ratio

$$\beta = \frac{\dot{Q}}{\dot{Q}_N} = \left(\frac{\Delta t_{lg}}{\Delta t_{lg,N}}\right)^n \tag{18}$$

into the convection part β_C and the radiaton part β_R

$$\beta = \beta_C + \beta_R \tag{19}$$

and the temperature dependence of β_R

$$\beta_R = s_N \cdot \frac{(T_{en} + \Delta t_{lg})^4 - T_{en}^4}{(T_{en} + \Delta t_{lg,N})^4 - T_{en}^4} \qquad \text{with} \quad T_{en} = t_{en} + 273,15\,\mathrm{K} \tag{20}$$

the radiative fraction of the actual emitted power $s = \frac{\beta_R}{\beta_C + \beta_R} = \frac{\beta_R}{\beta}$ reads

$$s = s_N \cdot \frac{\frac{(T_{en}+\Delta t_{lg})^4 - T_{en}^4}{(T_{en}+\Delta t_{lg,N})^4 - T_{en}^4}}{\left(\frac{\Delta t_{lg}}{\Delta t_{lg,N}}\right)^n} \tag{21}$$

Pipe Section

The supply and exhaust pipe of the radiator are described by a static model of an noninsulated pipe using a combined radiative and convective heat transfer coefficient.

$$U \cdot A = (h_c + h_r) \cdot A \tag{22}$$

with

$$h_r = 5.7 \cdot 10^{-8} \cdot \epsilon_0 \cdot (T_{su}^2 + T_{en}^2)(T_{su} + T_{en}) \tag{23}$$

and

$$h_c = 1.3 \cdot \left(\frac{t_{su} - t_{en}}{D_{pipe}}\right)^{\frac{1}{4}} \qquad \text{Horizontal} \quad \text{pipe} \tag{24}$$

$$h_c = 1.3 \cdot (t_{su} - t_{en})^{\frac{1}{3}} \qquad \text{Vertical} \quad \text{pipe} \tag{25}$$

Knowing the supply fluid temperature and the mass flow rate to the pipes at each iteration step the heat balance equation of the radiator pipes

$$\dot{m}_w \cdot c_w \cdot (t_{su} - t_{ex}) = U \cdot A \cdot \Delta t_{lg} \tag{26}$$

is solved using $NTU = \frac{U \cdot A}{\dot{m}_w \cdot c_w}$:

$$t_{ex} = \frac{t_{su} - t_{en} \cdot (1 - e^{NTU})}{e^{NTU}} \tag{27}$$

2.2 Implemented Model

The first order differential equation for the radiatior heat balance is solved using an analytical approch implemented in the TRNSYS subroutine DIFFEQ.

2.3 TRNSYS Component Description

PARAMETERS

Pipe Section :

1. Length of supply pipe 1 [m]
2. Length of exhaust pipe 2 [m]
3. Pipe diameter [m]
4. Horizontal(≥ 0) or vertical (else) pipe [–]
5. Emission coefficient of outter surface [–]
6. Specific heat of fluid [kJ/kg/K]

Radiator Section :

7. Maximum mass flow rate [kg/h]
8. Radiative fraction of total emitted power at nominal conditions (DT=60) [–]
9. Nominal power of radiator (DT=60) [kJ/h]
10. Radiator exponent (convection + radiation) [–]
11. Radiator thermal capacitance (metal and fluid) [kJ/K]
12. Initial radiator temperature [℃]

INPUTS

1. Supply temperature [℃]
2. Inside room temperature (TYPE 56: Star Node Temperature) [℃]
3. Mass flow rate control ($0 \leq$ control signal ≤ 1) [–]

OUTPUTS

1. Outlet water temperature [℃]
2. Water mass flow rate [kg/h]
3. Power emitted by radiator [kJ/h]
4. Power injected in radiator [kJ/h]
5. Total power emitted by radiator+pipes [kJ/h]
6. Total power injected in radiator+pipes [kJ/h]
7. Power emitted by pipes [kJ/h]
8. Energy change of radiator [kJ/h]
9. Effectivness of radiator [–]
10. Number of transfer units of radiator [–]
11. Radiative fraction of total emitted power [–]

2.4 Connection to TYPE 56 Multizone Building

From the emitted radiator power and its radiative fraction (Output of TYPE 162) the absolute convective and radiative emitted powers are calculated in EQUATION cards.

These heating powers are connected to the RADIATIVE and CONVECTIVE GAINS of the building zones. The TYPE 56 heating equipment is switched off.
The TYPE 56 transfers the star node temperature (TSTAR) of the building zones to the TYPE 162 radiator components. The radiator mass flow rates are controlled by TYPE 120 PID–Controllers receiving the actual air temperature of the controlled building zones. Negative control signals (i.e. cooling) of the controller are set to zero mass flow.

3 PID–Controller as Thermostatic Valve (TYPE 120)

3.1 General Description

This model of a Proportional–Integral–Differential Controller was adapted from a model by L. Laret of CSTB with modifications by V. Corrado of Polytechnico of Torino.
The TYPE 120 controller operating as a thermostatic valve generates a control signal s depending on the dynamic behaviour of two temperatures: the set temperature T_{set} and the feed back temperature T_{fb}, which could be a room air temperature or an operative air/wall temperature of the controlled building zone.
Type 120 has two general modes of operation depending on the temperature difference between feed back and set temperature $\Delta T_{er} = T_{fb} - T_{set}$:

$$|\Delta T_{er}| \leq \Delta T_{bw} \quad : \text{PID control mode (PID band)}$$

$$|\Delta T_{er}| > \Delta T_{bw} \quad : \text{P control mode (P band)}$$

The temperature difference (band width) ΔT_{bw} for operation in the PID band is given as a parameter to TYPE 120. The controller parameters in the two bands are specified seperately.
The TYPE 120 controller is capable of operating in a increasing or decreasing mode regarding the actual set point temperature difference. It can be operated with or without saturation of the control signal and an optional minimum action for zero set point difference may be specified.

3.2 Implemented Model

PID control mode

Operating in the PID band the controller evaluates three components to the total control signal s_T acting increasing ($pm = +1$) or decreasing ($pm = -1$) on the set point temperature difference ΔT_{er}:

- Proportional controller action

$$s_{P1} = pm \cdot x_{P1} \cdot \Delta T_{er} \tag{28}$$

  with the proportional gain x_{P1} given in 1/ K.

- Integral controller action

$$s_I = s_{I,old} + pm \cdot x_I \cdot (\Delta T_{er} - \Delta T_{er,old}) \cdot \frac{\Delta t}{2} \tag{29}$$

  using the trapezoidal rule with the integral gain x_I given in 1/ Kh and the values $s_{I,old}$ and $\Delta T_{er,old}$ of the last timestep $t - \Delta t$.

- Differential controller action

$$s_D = pm \cdot x_D \cdot (\Delta T_{er} - \Delta T_{er,old})/\Delta t \tag{30}$$

with the differential gain x_D given in h/ K and $\Delta T_{er,old}$ of the last timestep $t - \Delta t$.

The total controller action is given as the sum of the three components:

$$s_T = s_{P1} + s_I + s_D \tag{31}$$

P control mode

If the set point temperature difference $|\Delta T_{er}|$ reaches the band width ΔT_{bw} the controller switches to P band operation. The build up integral and differential actions are reset to zero and proportional controller action is performed using the proportional gain x_{P2}:

$$s_{P2} = pm \cdot x_{P2} \cdot \Delta T_{er} \qquad s_I = 0 \qquad s_D = 0 \tag{32}$$

Saturation modes

Three different saturation modes are available for TYPE 120.

ISAT=-2 : No saturation effects and zero action for zero set point difference.

$$s_T : [-\infty ... + \infty]$$

ISAT=-1 : Saturation on each effect and zero action for zero set point difference.

$$s_T : [-1 ... + 1]$$

ISAT=0 : Saturation on each effect and minimum action s_{min} for zero set point difference.

$$s_T : [s_{min} ... + 1]$$

$$s_T = 0.5 \cdot ((1 - s_{min}) \cdot (s_P + s_I + s_D) + 1 + s_{min})$$

3.3 TRNSYS Component Description

PARAMETERS

1. Temperature width of PID–band [K]
2. Proportional gain in PID-band [1/ K]
3. Integral gain in PID-band [1/ K h]
4. Differential gain in PID-band [h/ K]
5. Proportional gain in P-band [1/ K]

6. Saturation mode: -2: free , -1: [-1 ... +1], 0: [SMIN ... +1] [–]
7. Minimum value of controller action (SMIN) in saturation mode 0 [–]

INPUTS

1. Set temperature [°C]
2. Feedback (room) temperature [°C]
3. Control inversion option 1: increasing, 2: decreasing action [–]

OUTPUTS

1. Total control signal [–]
2. Proportional control signal [–]
3. Integral control signal [–]
4. Differential control signal [–]
5. Temperature difference to between control point and set point [K]