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Heating and Cooling Systems
EEN-E4002 (5 cr)

Fundamentals of automatic control

Learning objectives

Student will learn to

- know the key terminology, control laws and control properties
- know the fundamentals of the temperature control of hydronic and electric heating systems
- apply the control laws and computational methods to heating and cooling systems

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Lesson outline

1. Fundamentals of control
   - terminology
   - control laws and algorithms
   - control properties
2. Control of hydronic heating systems
3. Control of direct electric heating
4. Valve as a component of control system
5. Particularities of the control of heating/cooling coils

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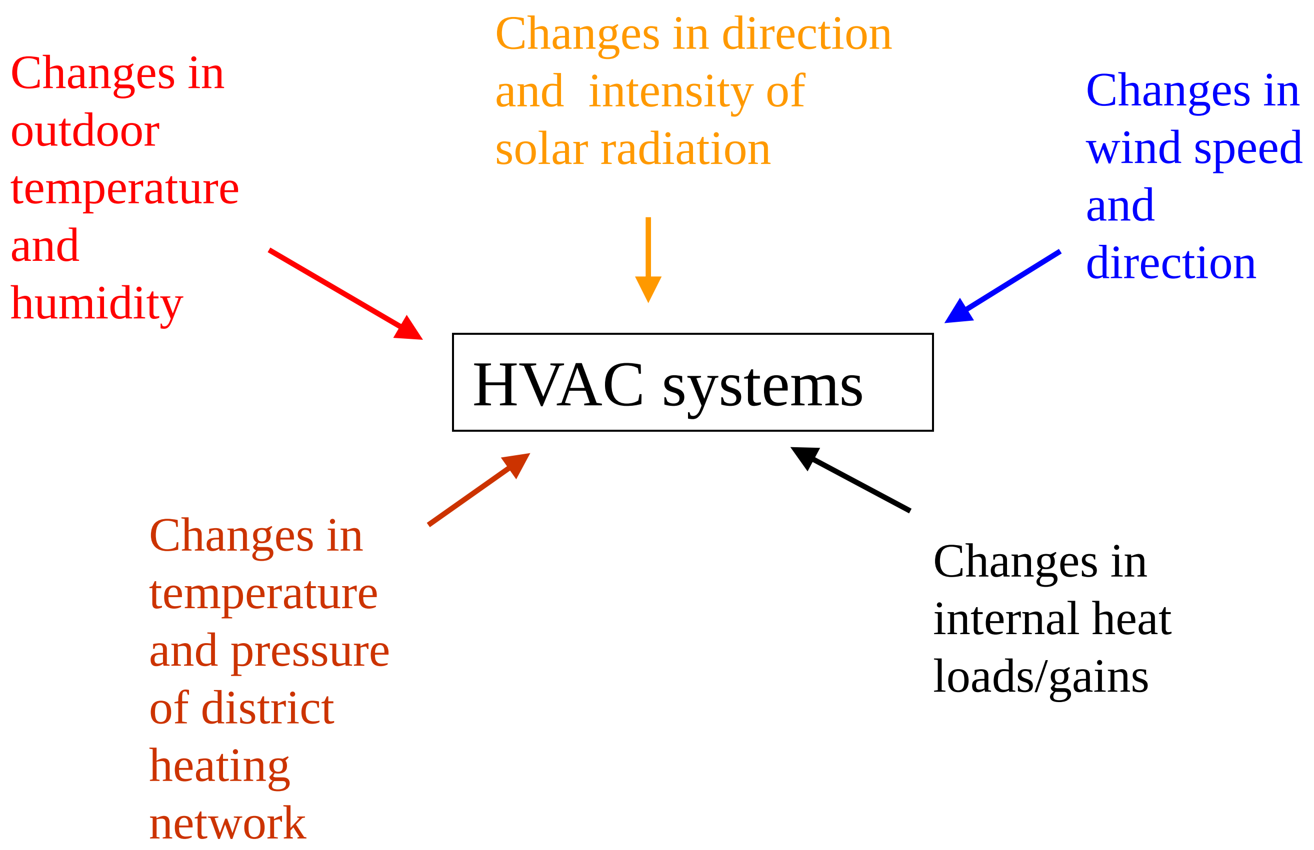
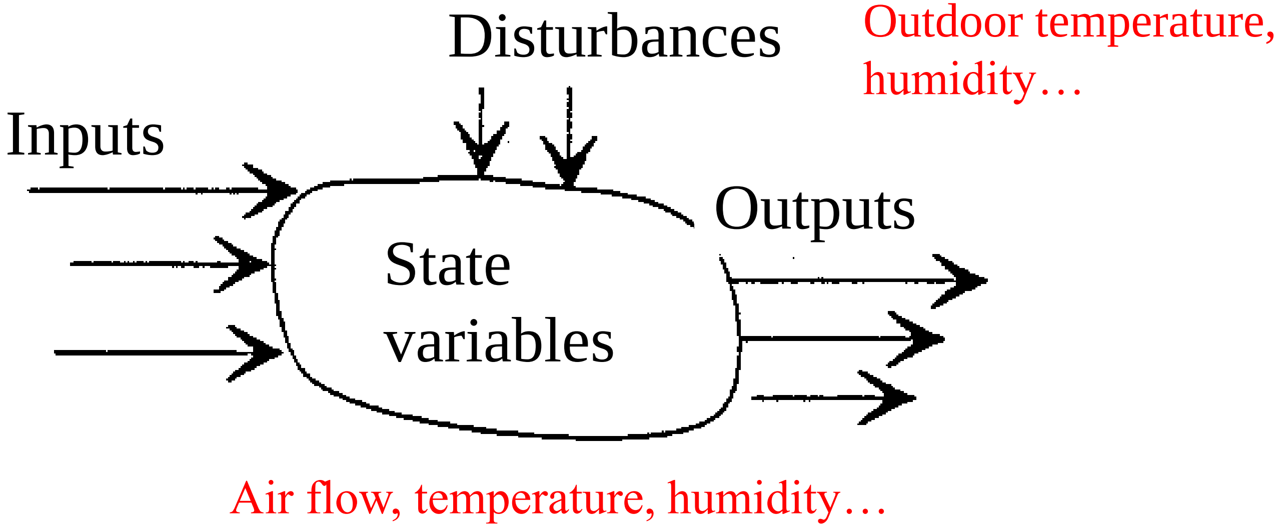
Terminology: disturbances

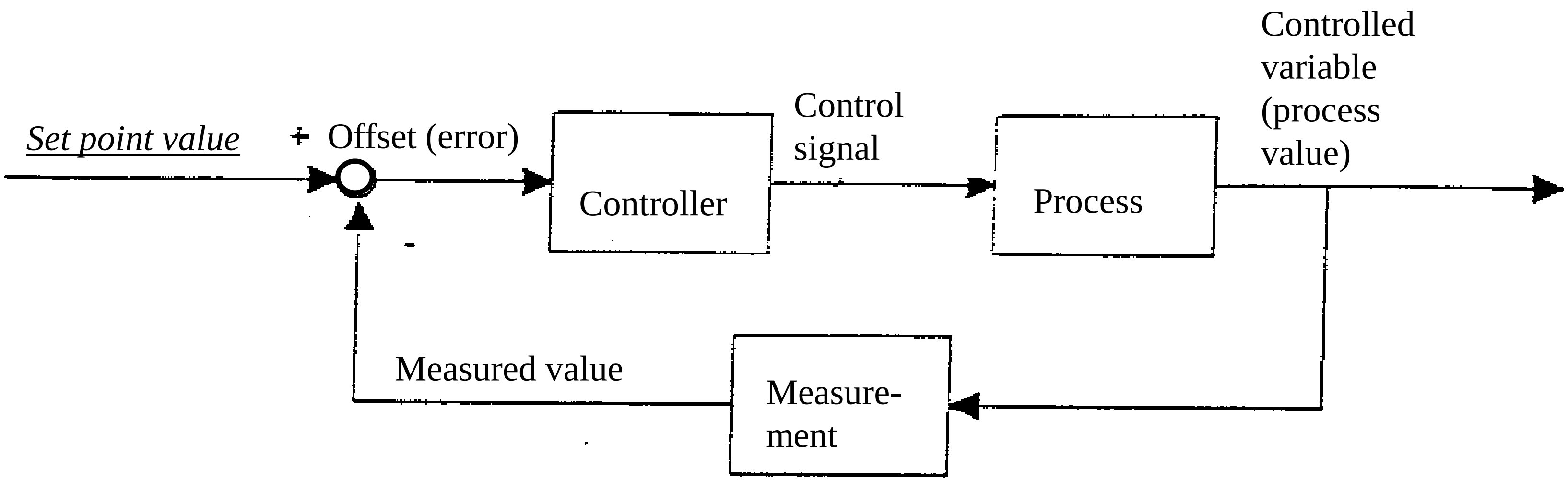


Terminology: control system



Terminology: closed loop

Closed loop: controlled variable is kept at *set point value*.



Offset = measured value – *set point value*

Figure: Operation of closed loop control

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Control laws and algorithms

1. ON/OFF control
   - A process is switched on/off, when the measured value exceeds/undercuts given upper/lower boundary value.
2. PID control
   1. *Proportional control (P)*
      - The manipulated variable is directly proportional to the offset.
   2. *Proportional integral control (PI)*
      - ”magnifies” the effect of long-lasting steady-state offsets
   3. *Proportional integral derivative control (PID)*
      - takes into account the rate-of-change of the offsets

   These aim at improving the accuracy of the control through recording ”historical” data.
3. Other control laws and principles
   - neural networks
   - optimized control
   - fuzzy logic
   - etc.etc.

P-control

Control signal is directly proportional to offset:

$$u(t) = K_p e(t)$$

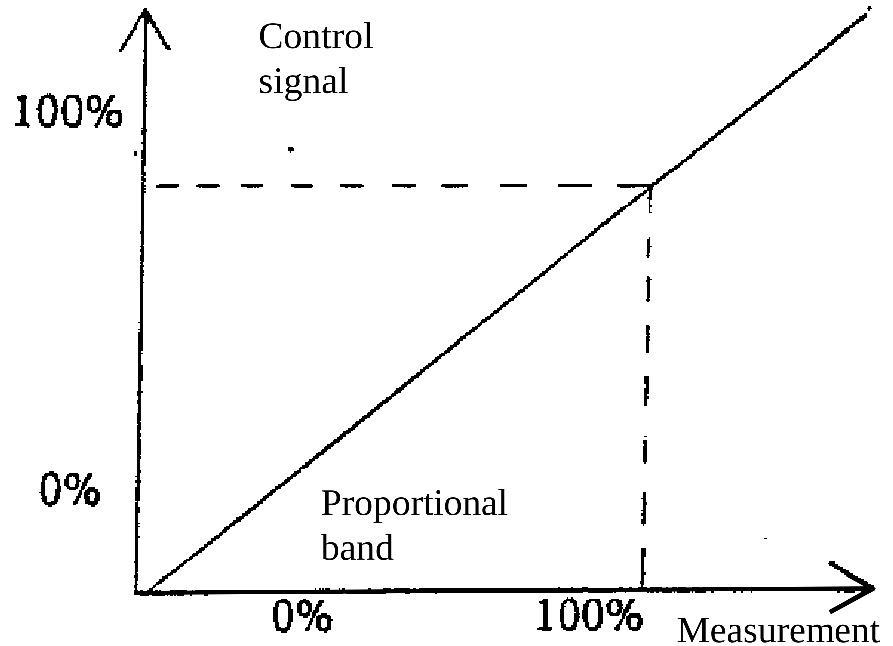
where $u(t) =$ control signal at time t

$e(t) =$ offset at t

$K_p =$ proportional control factor

Proportional control factor aka *proportional gain* indicates, how much the output value changes, when there is a certain change in the input value and the process has obtained the steady-state condition.

Proportional band is defined as a range of values of the controlled variable, which corresponds to the movement of the position of the *final control element* aka *actuator* (e.g. valve) between its extreme values.



$$\text{Proportional band } X_p = \frac{100\ \%}{K_p}$$

Examples

- Measured temperature changes from 15 ºC to 25 ºC, resulting in the movement of the actuator from an extreme value to another

  → proportional band = (25 – 15) ºC = 10 ºC.
- Proportional band of 4 degrees of an individual temperature controller (P) means that if the measured room temperature remains 4 degrees below the set point, the radiator valve is adjusted to fully open position.

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PI- and PID-control

- P-control never reaches the set point, but an offset remains. This problem can be solved using

  → PI-control (magnifies the offset over time)

  → PID-control (magnifies the offset over time and accounts for the rate-of-change of the offset)

$$u(t) = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de}{dt}$$

missä $K_i = \frac{K_p}{t_i}$ integral gain

$K_d = K_p t_d$ derivative gain

$t_i =$ integral time

$t_d =$ derivative time

__Integral__ and *__derivative times__* and control coefficients (gains) are also known as *__tuning parameters__*.

Discrete PID-algorithm

- Discrete *control algorithm* calculates the control signal for the current time step (u_n) from the control signal of the previous time step (u_{n-1}):

$$u_n = u_{n-1} + K_p \left[\left(e_n - e_{n-1}\right) + \underbrace{\frac{t}{t_i} e_n + \overbrace{\frac{t_d}{t} e_n \left(e_n - 2e_{n-1} + e_{n-2}\right)}^{= 0, \text{ when PI-controller}}}_{= 0, \text{ when P-controller}} \right]$$

where e_n, e_{n-1} and e_{n-2} offset at current time step(n), previous time step (n – 1) and the time step before (n – 2)

t *sampling interval* [s]

t_i integral time [s]

t_d derivative time [s]

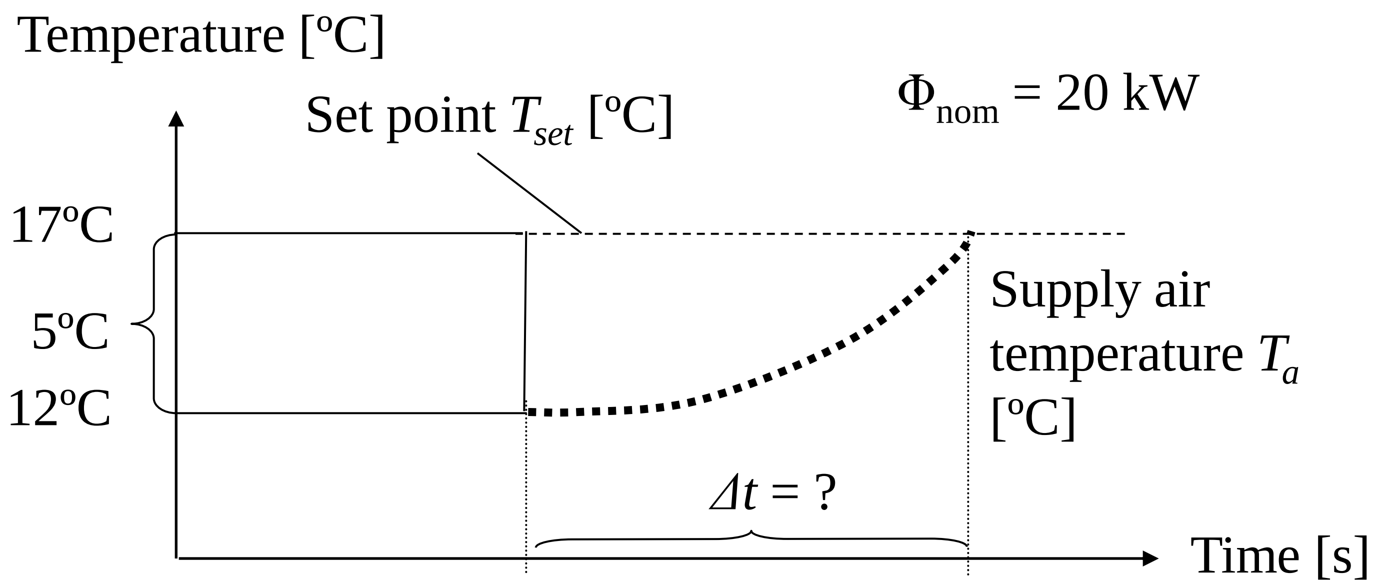
K control factor (gain)

Example

A heating coil (nominal thermal output 20 kW) is controlled using a PI-controller, the proportional gain being 0.01 1/ºC and integral time 1 s. Due to a sudden malfunction of pre-heating, the temperature of air flow entering the coil drops stepwise from +10ºC to +5 ºC. How long does it take before the air temperature (after the coil) achieves the set point (17ºC)? The air flow is 1.2 kg/s and The control signal (before the step change) is 40 %.

Assume the control is linear (control signal directly proportional to thermal output of the coil). The specific heat capacity of air is 1.0 kJ/kgK.

Illustration



Constant mass flow, → supply air temperature drops stepwise by 5ºC

Beginning:
e_0 = 5ºC
u_0 = 40 %

End:
e_n = 0 ºC
u_n = ?

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Solution – I

- Discrete PI-algorithm:

$$u_n = u_{n-1} + K_p \left[\left(e_n - e_{n-1} \right) + \frac{t}{t_i} e_n \right]$$

Thermal power: time step n (heating $T_{a1,n} \rightarrow T_{a2,n}$)

$$\Phi_n = q_{ma} c_{pa} \left(T_{a2,n} - T_{a1,n} \right) = u_n \Phi_{nom}$$

Supply air temperature after the coil

$$\rightarrow T_{a2,n} = T_{a1,n} + \frac{\Phi_n}{q_{ma} c_{pa}}$$

Offset (error)

$$\rightarrow e_n = T_{set} - T_{a2,n}$$

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Solution – II

- Procedure (example substitution: 1. time step):
  - – Choose sample interval: 1 s.
  1. Guess the offset: time step n = 1: (correct: e_1 = 4.63ºC)
  2. Calculate the control signal

$$u_1 = u_0 + K_p\left[\left(e_1 - e_0\right) + \frac{t}{t_i}e_1\right] = 0.4 + 0.01\left[\left(4.63 - 5\right) + \frac{1\ \mathrm{s}}{1\ \mathrm{s}}\cdot 4.63\right] = 0.44$$

  3. Calculate the thermal power: Φ_1 = 0.44 · 20 kW = 8.85 kW
  4. Calculate the air temperature after the coil

$$T_{i2,1} = T_{i1,1} + \frac{\Phi_1}{q_{mi}c_{pi}} = 5°\mathrm{C} - \frac{8.85\ \mathrm{kW}}{1.2\ \frac{\mathrm{kg}}{\mathrm{s}}\cdot 1.0\ \frac{\mathrm{kJ}}{\mathrm{kgK}}} = 12.37°\mathrm{C}$$

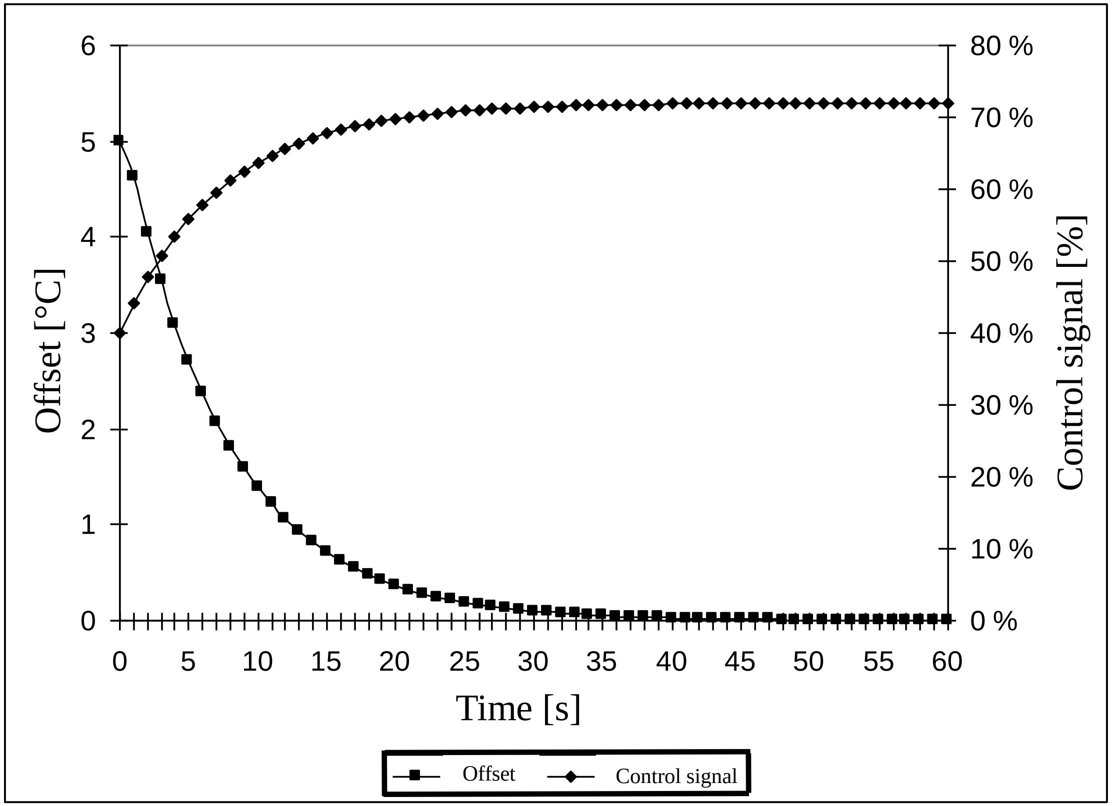
Use e.g.: The Circular Reference function of MS Excel.

  5. Calculate new offset: $e_1 = T_{set} - T_{a2,1}$ = (17 – 12.37)ºC = 4.63ºC
     - Repeat until the offset does not change between two sequential iteration.
  6. Run the procedure for each time step, until the offset becomes zero.
     - Here e_n = 0, when n = 87, i.e. the steady-state condition is reached after Δt = 87 · 1 s = 1 min 27 s after the step change. The control signal is then 72 % and thermal power 14.4 kW.

Solution – III

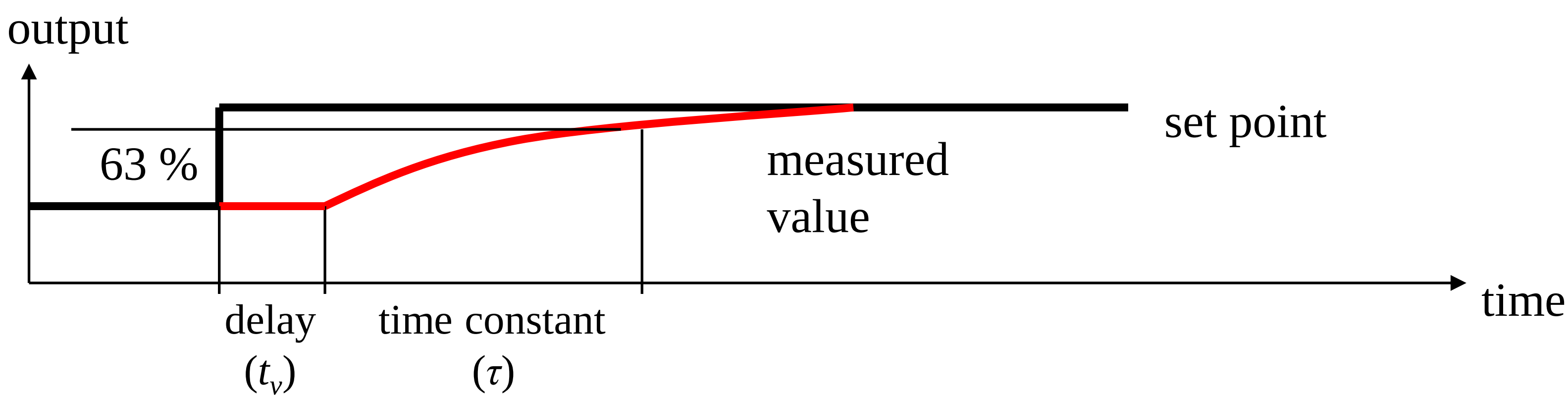
Perceptions:

- The solution describes ideal control (no delay).
- The procedure results in stable control, because proportional gain, integral time and sample interval are optimal. (In practice, to find optimal tuning parameters is a challenging task.)

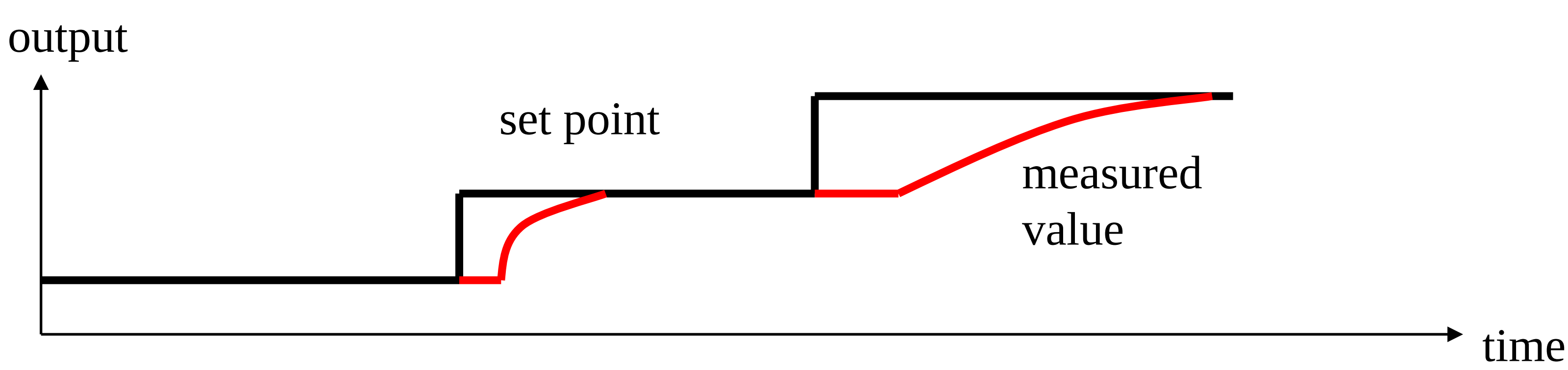


Control properties – I

- *Slowness:* output responds with delay (aka *dead time*) to changes in set points, input values and/or control signal



- *Non-linearity*: output behaves differently depending on, which range of values the changes in output/input take place



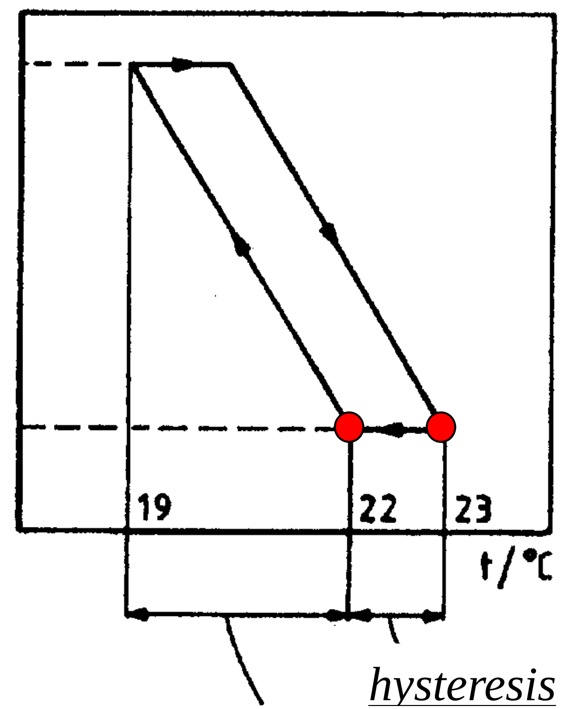
Control properties – II

- *Hysteresis*: behaviour of a system depending on its history (general definition).

  → one actuator position refers to two separate values of the controlled variable

- Requirements for heat distribution systems:
  – hysteresis < 1°C
  – proportional band: 2…4°C

Example: room temperature control with radiator valve



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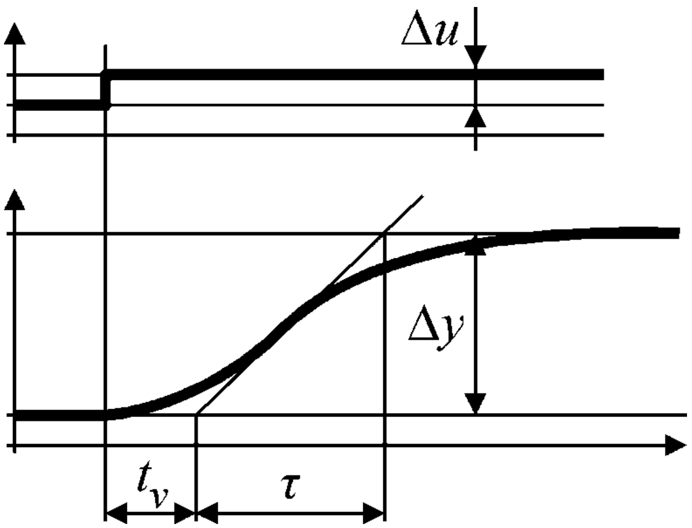
Control properties – III

- The controllability of a system is measured as the ratio of the dead time (delay, t_v) and the time constant (τ):

$$\sigma = \frac{t_v}{\tau}$$

- The ratio (σ) is determined experimentally on the basis of step response (graph).
- Criterion of good controllability: $\sigma < 0.2$
- The applicability of different control algorithms on the basis of controllability:



Controllability	Good	Satisfactory	Poor
Ratio σ	< 0.2	0.2 … 0.3	> 0.3
Algorithm	P, ON-OFF	PI, PD, PID	PID

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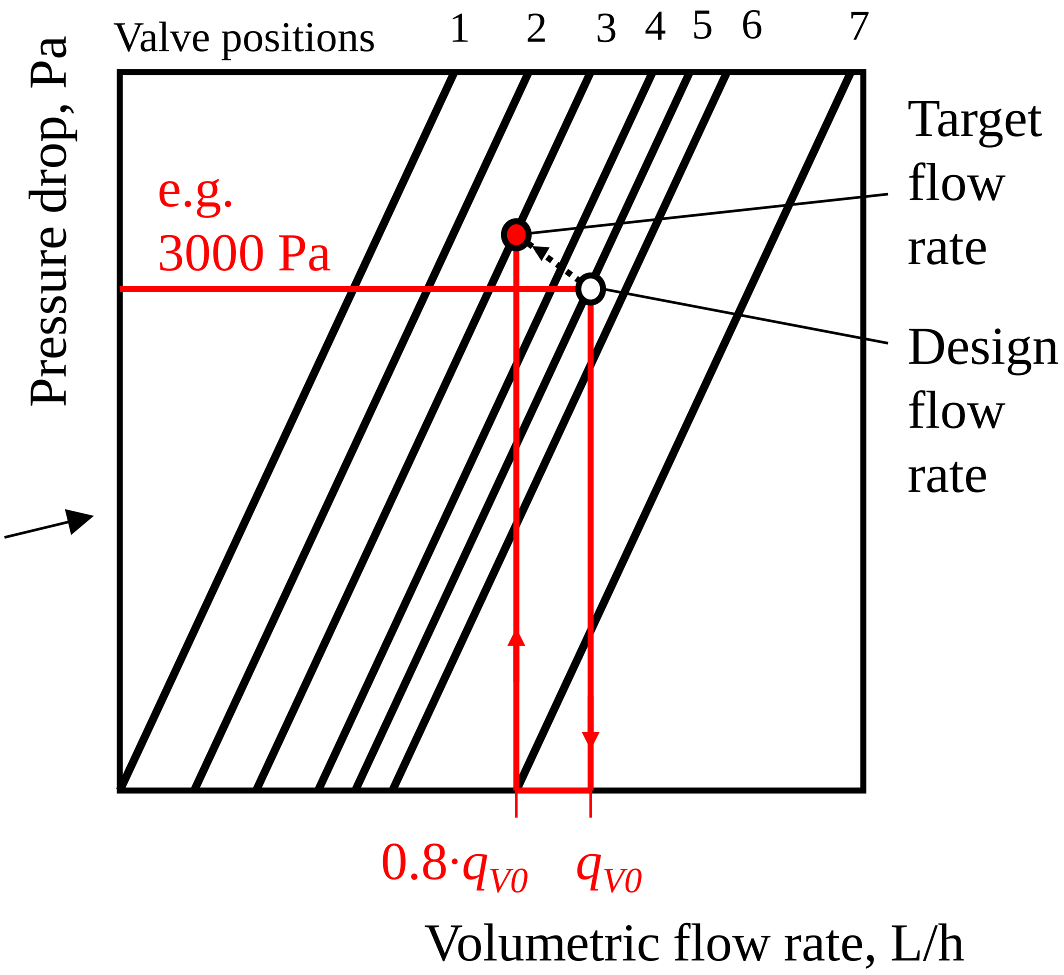
Example: Control characteristics for selected HVAC processes

Process	t_v	$\sigma = t_v / \tau$	X_p
Boiler temperature	1…5 min	0.05…0.15	~20 K
Mixing supply and return water	5…20 s	0.2…0.5	20…70 K
Room temperature	3…5 min	0.1…0.3	6…10 K
Mixing cold water and hot water	0.5…2 s	0.1…0.4	30…60 K
DHW heat exchanger	5…30 s	0.1…0.8	30…60 K
Swimming pool, supply	10…60 s	0.1…0.3	2…8 K
return	6…8 h		

Control of hydronic heating system – general principle

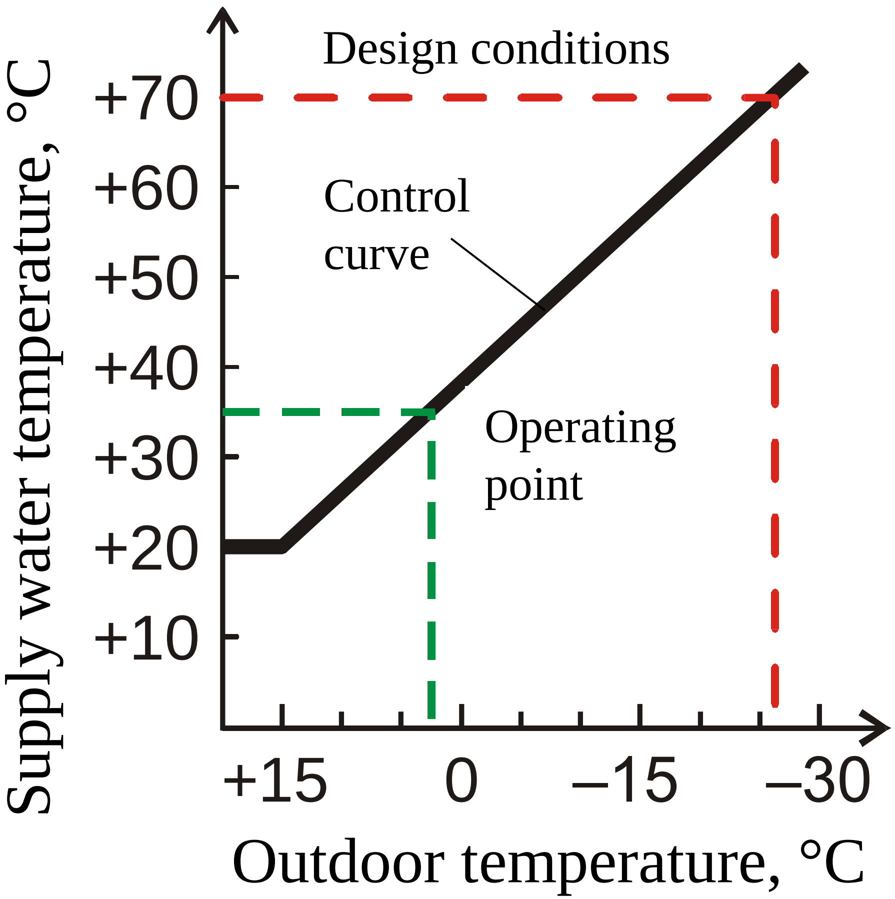
- The heating system is designed (heating load is determined) on the basis of calculational design temperature (extreme conditions and duration).
- The heating load varies due to disturbances.
- Possible controls:
  - flow control through valves (throttling)
  - burner ON/OFF (boiler plants)
- 2 levels of delivered thermal power/energy supply management:
  1. building level (system level): supply water temperature control (with mixing valve)
  2. room level: (”fine tuning”): flow control (with radiator valves)



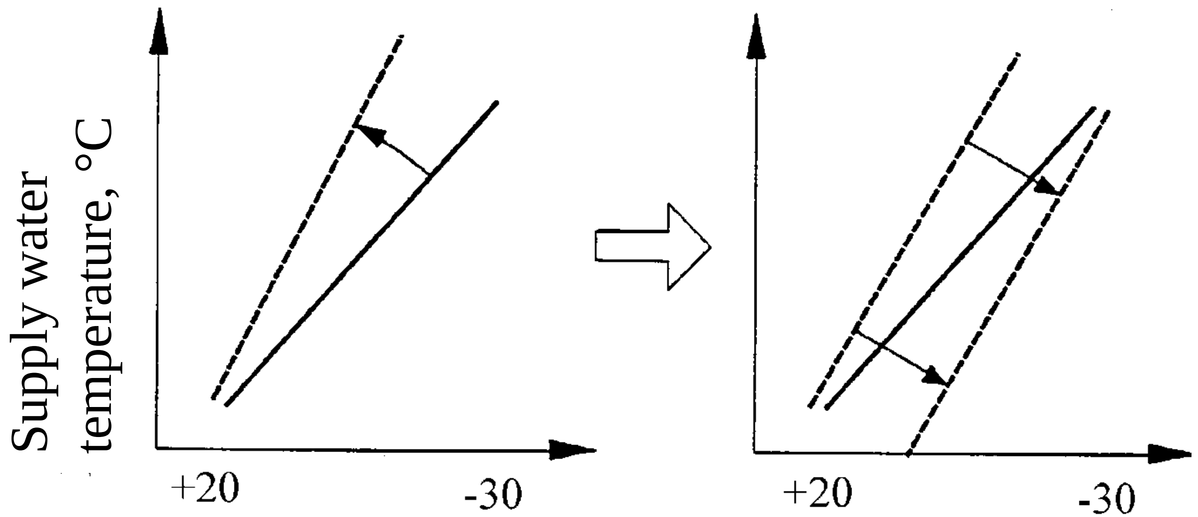
Supply water temperature control

- Heating load (heat loss) mostly depends on outdoor temperature

  → Building level control is based on changing the set point value of supply water temperature according to *control curve*
- The most common design temperatures in Finland: 70/40°C (supply/return).
- The return water temperature depends on the heat release of radiators/convectors/coils.
- In contrast with the graph, the control curve is not always linear, since internal and external heat gains affect the heating load.



Positioning control curve on the basis of realized temperatures



Outdoor temperature, °C Outdoor temperature, °C

- Too steep control curve:
  → too high room temperature (at low outdoor temperatures)
  → action: flattening the control curve
- Too gentle control curve:
  → too low temperature (at low outdoor temperatures)
  → action: steepening the control curve
- Too low/high room temperature (at all outdoor temperatures):
  → action: parallel move of the control curve

Positioning of the control curve on the basis of theory → see: next slides

Rule of thumb:
2°C change in supply water temperature corresponds approximately 1°C change in room temperature.

Positioning control curve on the basis of theory – I

- Starting point: Heat balance

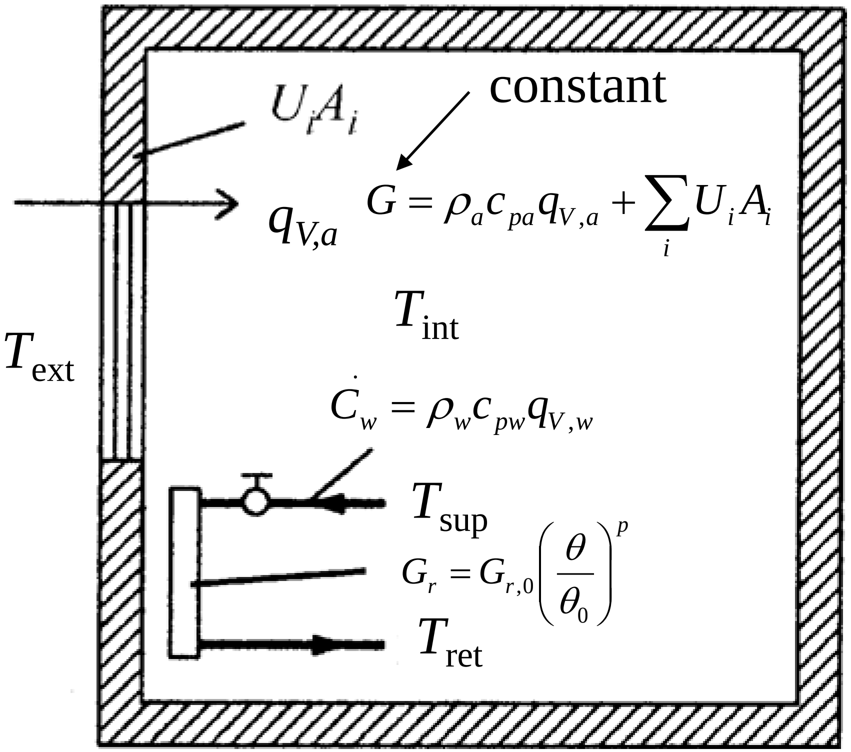
  Cooling of water in radiators

  = heating load (heat loss)

  = heat released by radiators into room

$$\dot{C}_w (T_{\text{sup}} - T_{\text{ret}}) = G(T_{\text{int}} - T_{\text{ext}}) = G_r \theta$$

$$\dot{C}_w (T_{\text{sup},0} - T_{\text{ret},0}) = G(T_{\text{int},0} - T_{\text{ext},0}) = G_{r,0} \theta_0$$



- Subject to:

  Conductance of radiator (Note: <u>variable</u>):

$$G_r = G_{r,0} \left(\frac{\theta}{\theta_0} \right)^p \Rightarrow G_r \theta = G_{r,0} \left(\frac{\theta}{\theta_0} \right)^p \theta = G_{r,0} \frac{\theta^{1+p}}{\theta_0^p}$$

Temperature difference between radiator and room

$$\theta = \frac{T_{\text{sup}} + T_{\text{ret}}}{2} - T_{\text{int}}$$

<u>Heat release exponent</u>: $p = 0.25 \ldots 0.30$

Subscript 0 refers to design (reference) condition.

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Positioning control curve on the basis of theory – II

Relationship between supply water and room temperatures (derived from differentiation of the heat balance and defining auxiliary variables *a* and *b* using the known temperatures and chosen heat release exponent):

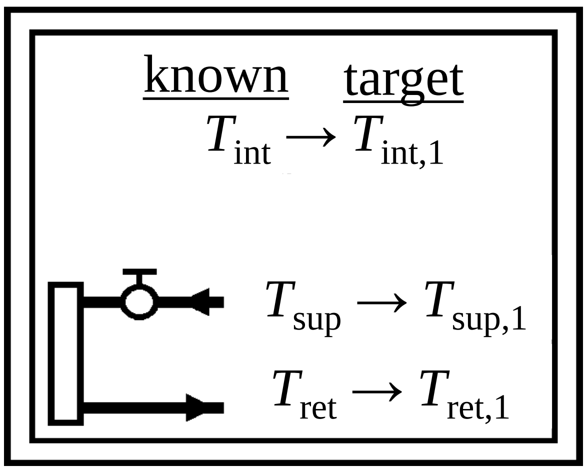
$$\Delta T_{sup} = \left(1 + \frac{a}{2} + \frac{1}{b}\right)\Delta T_{int}$$

where

$$a = \frac{T_{sup} - T_{ret}}{T_{int} - T_{ext}}$$

$$b = \frac{(T_{int} - T_{ext})(1+p)}{\frac{T_{sup}+T_{ret}}{2} - T_{int}}$$

$T_{ext} = \text{const} \qquad q_{V,w} = \text{const}$



$$\Delta T_{sup} = T_{sup,1} - T_{sup}$$

$$\Delta T_{int} = T_{int,1} - T_{int}$$

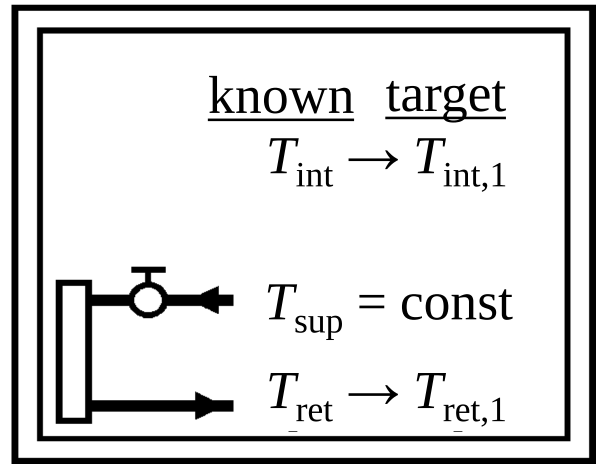
Subscript 1 refers to target condition (e.g. desired room temperature at certain T_{ext}).

Positioning control curve on the basis of theory – III

Relationship between return water and room temperatures :

$$\Delta T_{\text{ret}} = 2\left(1+\frac{1}{b}\right)\Delta T_{\text{int}}$$

$T_{\text{ext}} = \text{const} \quad q_{V,w} = \text{const}$



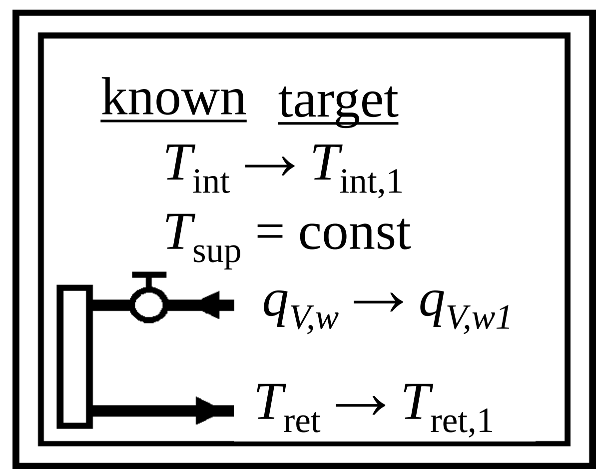
When flow rate is changed (T_{sup} = constant):

$$\frac{q_{V,w1}}{q_{V,w}} = \left(\frac{T_{\text{sup}} - T_{\text{ret}}}{T_{\text{sup}} - T_{\text{ret,1}}}\right)^{1+\frac{a}{2\left(1+\frac{1}{b}\right)}}; \quad T_{\text{ret,1}} = T_{\text{ret}} + \Delta T_{\text{ret}}$$

$$\frac{q_{V,w1}}{q_{V,w}} = \sqrt{\frac{\Delta p_1}{\Delta p}}$$

Δp = pressure difference over heat distribution network

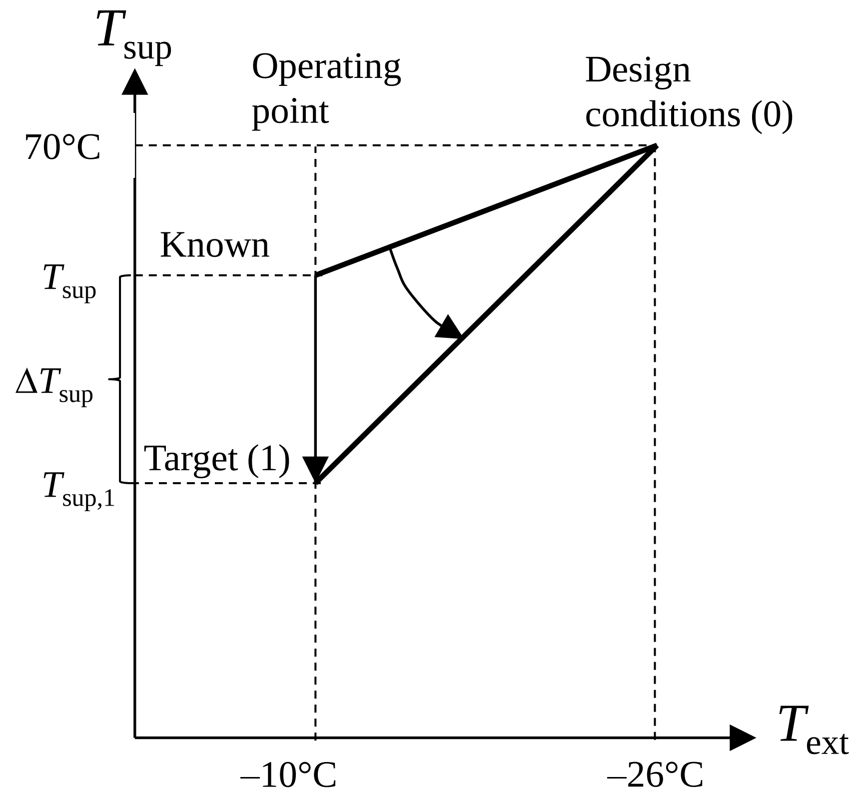
$T_{\text{ext}} = \text{const}$



Example

Assume a heating system with design temperatures 70/40/20°C (supply/return/room temperatures). The design thermal power is 1000 W and the system is located in southern Finland ($T_{ext,0}$ = –26°C). It is known that the realized indoor temperature is +22°C, when the outdoor temperature is –10°C (linear control curve 70°C → 20°C).
To save energy, the target room temperature is set down to 19°C.

Construct a summary table for temperatures, conductances and thermal powers for each operating point (design, known and target).
The heat release exponent can be chosen p = 0.3.



Solution – I

1. Design conditions (0):
   - Given values:
     - Φ_0 = 1000 W
     - $T_{\text{ext},0}$ = –26°C
     - $T_{\text{int},0}$ = 20°C
     - $T_{\text{sup},0}$ = 70°C
     - $T_{\text{ret},0}$ = 40°C
   - Calculated values:
     - Conductance of room (constant at all temperatures):

$$\Phi_0 = G(T_{\text{int},0} - T_{\text{ext},0}) \Rightarrow G = \frac{\Phi_0}{T_{\text{int},0} - T_{\text{ext},0}} = \frac{1000\ \text{W}}{(20-(-26))\,\text{K}} = 21.7\ \frac{\text{W}}{\text{K}}$$

     - Temperature difference between radiator and room:

$$\theta_0 = \frac{T_{\text{sup},0} + T_{\text{ret},0}}{2} - T_{\text{int},0} = \frac{(70+40)\,°\text{C}}{2} - 20°\text{C} = 35°\text{C}$$

     - Conductance of radiator:

$$\Phi_0 = G_{r,0}\theta_0 \Rightarrow G_{r,0} = \frac{\Phi_0}{\theta_0} = \frac{1000\ \text{W}}{35\,\text{K}} = 28.6\ \frac{\text{W}}{\text{K}}$$

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Solution – II

2. Known conditions:
   - Given (or constant) values:
     - $T_{ext} = -10°C$
     - $T_{int} = 22°C$
     - $G = 21.7$ W/K (constant)
   - Calculated values:
     - Realized thermal input to the room:

$$\Phi = G(T_{int} - T_{ext})$$

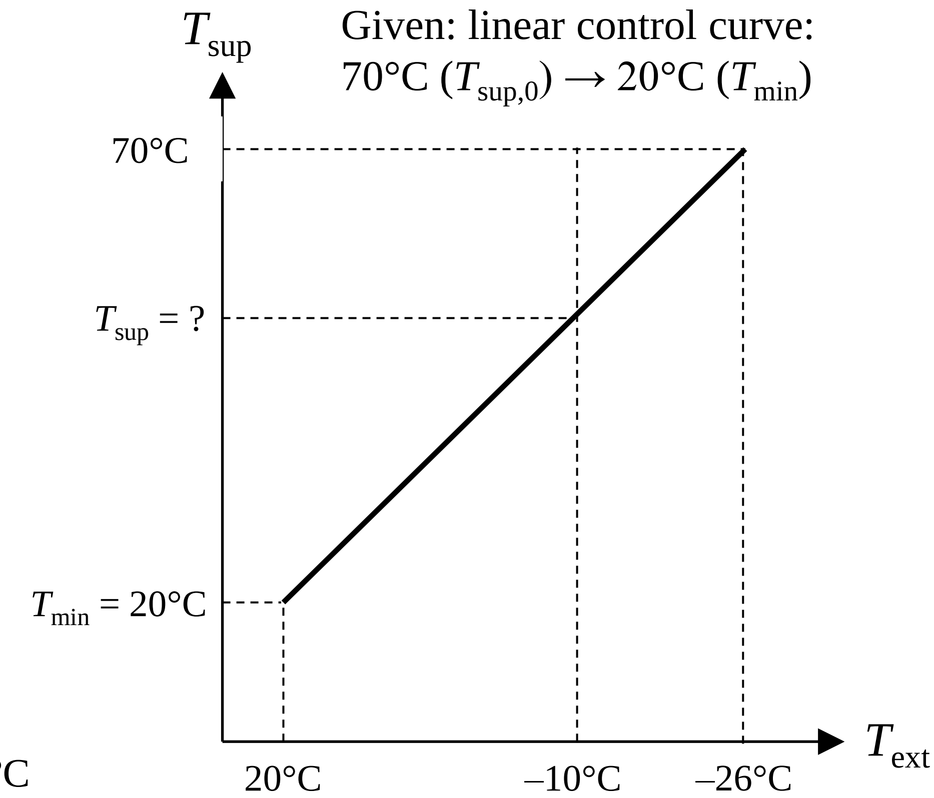
$$= 21.7 \frac{\text{W}}{\text{K}} \cdot (22 - (-10))\,\text{K} = 696\ \text{W}$$

     - Supply water temperature (from linearity):

$$T_{sup} = \frac{(T_{min} - T_{ext})\,°\text{C}}{(T_{min} - T_{ext,0})\,°\text{C}} \cdot (T_{sup,0} - T_{min})\,°\text{C} + T_{min}$$

$$= \frac{(20 - (-10))\,°\text{C}}{(20 - (-26))\,°\text{C}} \cdot (70 - 20)\,°\text{C} + 20°\text{C} = 52.6\,°\text{C}$$

Given: linear control curve:
70°C ($T_{sup,0}$) → 20°C (T_{min})



Solution – II

2. Known conditions (cont'd):
   - Calculated values:
     - Temperature difference between radiator and room:

$$\Phi = G_r\theta = G_{r,0}\left(\frac{\theta}{\theta_0}\right)^p \cdot \theta \Rightarrow \theta = \left(\frac{\Phi}{G_{r,0}}\right)^{\frac{1}{1+p}} \cdot \theta_0^{\frac{p}{1+p}} = \left(\frac{696\ \mathrm{W}}{28.6\ \frac{\mathrm{W}}{\mathrm{K}}}\right)^{\frac{1}{1+0.3}} \cdot (35\ \mathrm{K})^{\frac{0.3}{1+0.3}} = 26.5\ \mathrm{K}$$

     - Return water temperature:

$$\theta = \frac{T_{\mathrm{sup}} + T_{\mathrm{ret}}}{2} - T_{\mathrm{int}} \Rightarrow T_{\mathrm{ret}} = 2\cdot(\theta + T_{\mathrm{int}}) - T_{\mathrm{sup}} = 2\cdot(26.5+22)\,^\circ\mathrm{C} - 52.6\,^\circ\mathrm{C} = 44.3\,^\circ\mathrm{C}$$

     - Conductance of radiator:

$$\Phi = G_r\theta \Rightarrow G_r = \frac{\Phi}{\theta} = \frac{696\ \mathrm{W}}{26.5\ \mathrm{K}} = 26.3\ \frac{\mathrm{W}}{\mathrm{K}}$$

     - Auxiliary variables and required change in return water temperature:

$$\left.\begin{aligned} a &= \frac{T_{\mathrm{sup}} - T_{\mathrm{ret}}}{T_{\mathrm{int}} - T_{\mathrm{ext}}} = \frac{(52.6-44.3)\,^\circ\mathrm{C}}{(22-(-10))\,^\circ\mathrm{C}} = 0.26 \\ b &= \frac{(T_{\mathrm{int}} - T_{\mathrm{ext}})(1+p)}{\theta} = \frac{(22-(-10))\,^\circ\mathrm{C}\cdot(1+0.3)}{26.5\,^\circ\mathrm{C}} = 1.57 \end{aligned}\right\} \Delta T_{\mathrm{sup}} = \left(1 + \frac{a}{2} + \frac{1}{b}\right)\Delta T_{\mathrm{int}} = \left(1 + \frac{0.25}{2} + \frac{1}{1.57}\right)\cdot(22-19)\,^\circ\mathrm{C} = 5.3\,^\circ\mathrm{C}$$

Solution – III

3. Target conditions (1):
   - Given values:
     - $T_{\text{ext},1}$ = –10°C
     - $T_{\text{int},1}$ = 19°C
     - G = 21.7 W/K (constant)
   - Calculated values:
     - Desired thermal input to the room:

$$\Phi_1 = G(T_{\text{int},1} - T_{\text{ext},1}) = 21.7\,\frac{\text{W}}{\text{K}} \cdot \left(19 - (-10)\right)\text{K} = 630\ \text{W}$$

     - Temperature difference between radiator and room:

$$\theta_1 = \left(\frac{\Phi_1}{G_{r,0}}\right)^{\frac{1}{1+p}} \cdot \theta_0^{\frac{p}{1+p}} = \left(\frac{630\ \text{W}}{28.6\,\frac{\text{W}}{\text{K}}}\right)^{\frac{1}{1+0.3}} \cdot (35\ \text{K})^{\frac{0.3}{1+0.3}} = 24.5\ \text{K}$$

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Solution – IV

3. Target conditions (1)(cont'd):
   - Calculated values:
     - Conductance of radiator:

$$G_{r,1} = \frac{\Phi_1}{\theta_1} = \frac{630\ \mathrm{W}}{24.5\ \mathrm{K}} = 25.7\ \frac{\mathrm{W}}{\mathrm{K}}$$

     - Supply water temperature:

$$T_{\mathrm{sup},1} = T_{\mathrm{sup},1} - \Delta T_{\mathrm{sup}} = (52.5 - 5.3)°\mathrm{C} = 47.2°\mathrm{C}$$

Note: In the present example, the supply water temperature is reduced by ΔT_{sup}.

     - Return water temperature

$$T_{\mathrm{ret},1} = 2 \cdot (\theta_1 + T_{\mathrm{int},1}) - T_{\mathrm{sup},1} = 2 \cdot (24.5 + 19)°\mathrm{C} - 47.3°\mathrm{C} = 39.8°\mathrm{C}$$

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Solution – V

Summary table:

	Design (0)	Known	Target (1)
Φ [W]	1000	696	630
G [W/K]	21.7	21.7	21.7
G_r [W]	28.6	26.3	25.7
T_{sup} [°C]	70	52.6	47.3
T_{ret} [°C]	40	44.3	39.8
T_{ext} [°C]	–26	–10	–10
T_{int} [°C]	20	22	19
θ [°C or K]	35	26.5	24.5

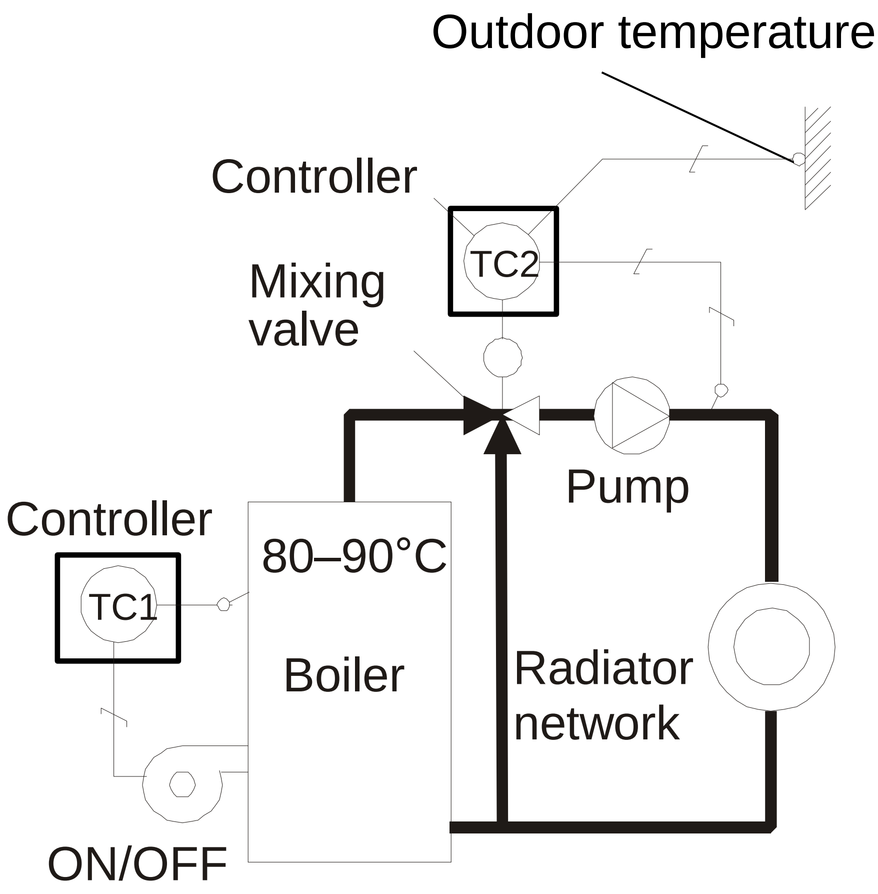
Supply water temperature control – boiler plants

Supply water temperature (TC2):

1. Outdoor temperature is measured.
2. The set point value is read from the control curve.
3. Supply water temperature is measured.
4. If the supply water temperature is higher than the set point value (positive offset), the mixing valve is opened to mix the return water at lower temperature to mix with the water coming from the boiler.

Boiler temperature (TC1):

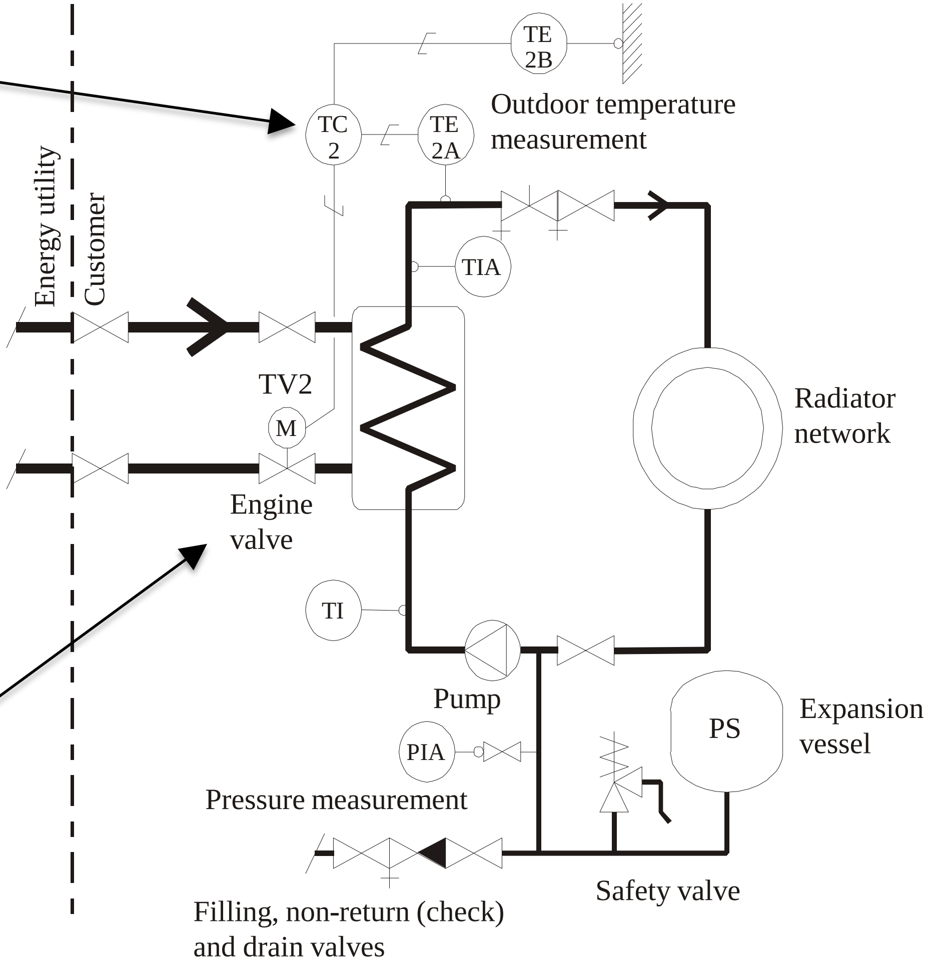
- ON/OFF control
- When the measured temperature exceeds the upper limit (90°C), the burner is switched off. When it undercuts the lower limit (80°C), the burner is turned on.



Supply water temperature control – district heating

Supply water temperature (TC2):

1. Outdoor temperature is measured.
2. The set point value is read from the control curve.
3. Supply water temperature is measured.
4. The district heating water flow rate is decreased/increased according to the offset by changing the position of the engine valve (TV2).



Supply water temperature control – air heating

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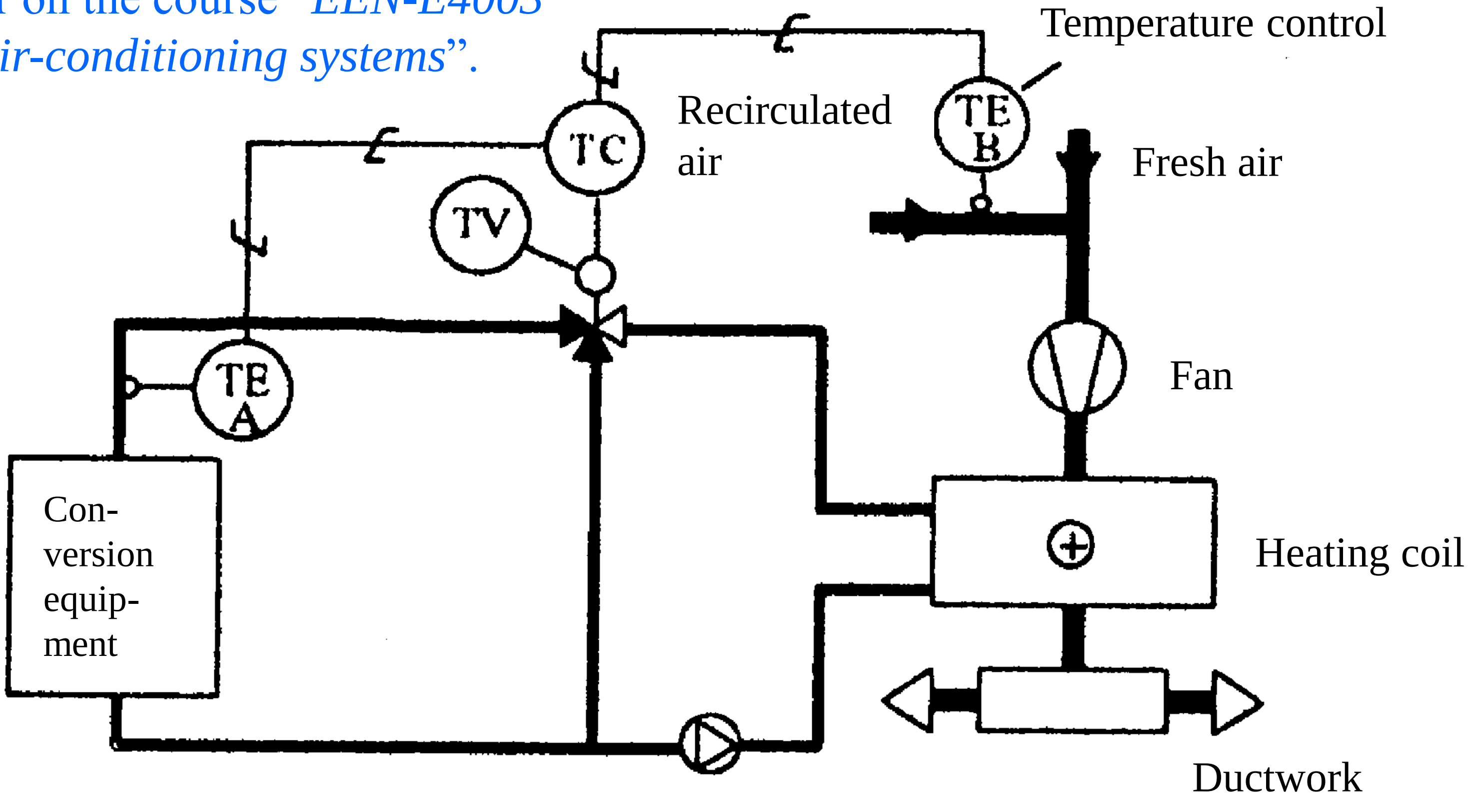
For air heating systems, the supply water temperature is controlled on the basis of the recirculated air temperature (which is close to room temperature). The principle will be developed further on the course ”*EEN-E4003 Ventilation and air-conditioning systems*”.



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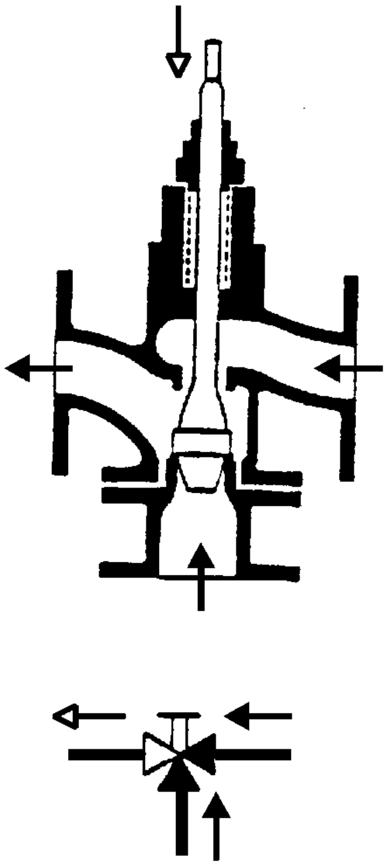
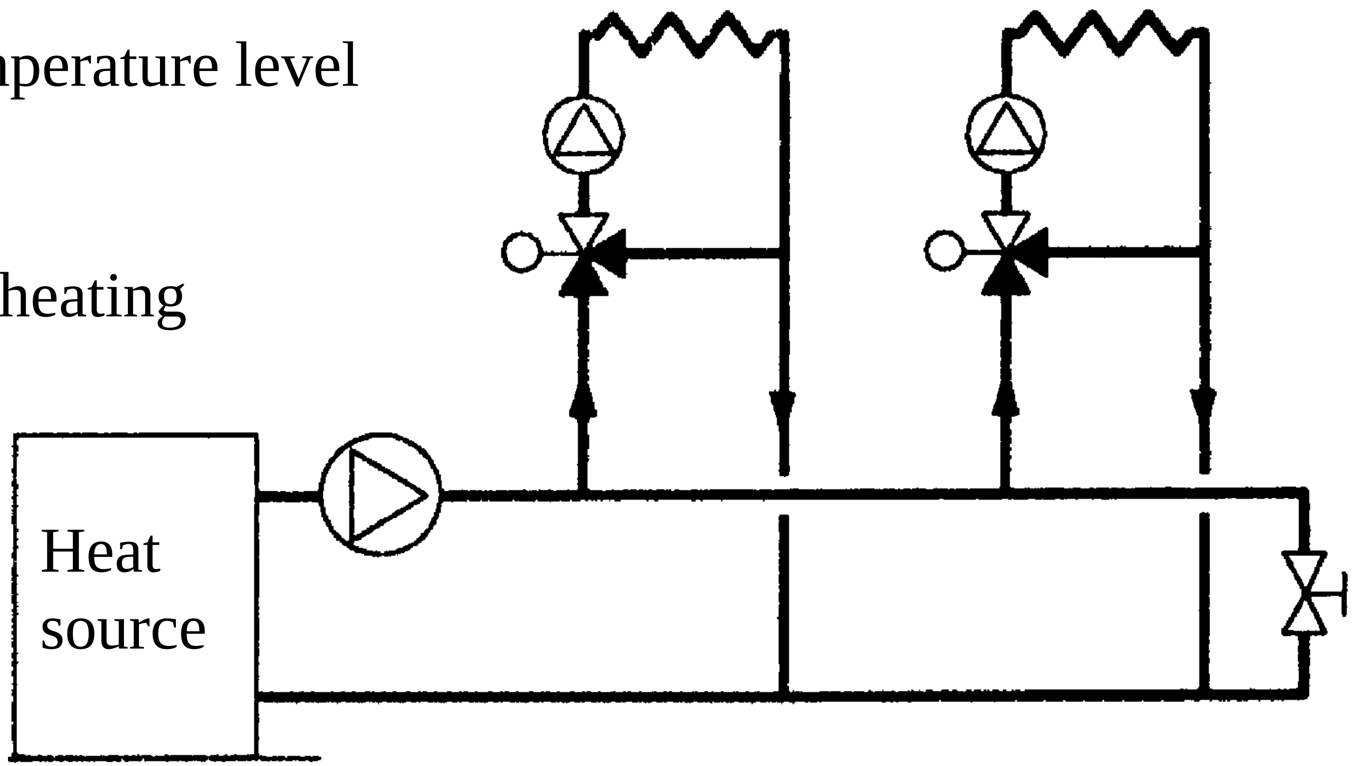
Structural example of mixing valve



Partitioning of building into zones

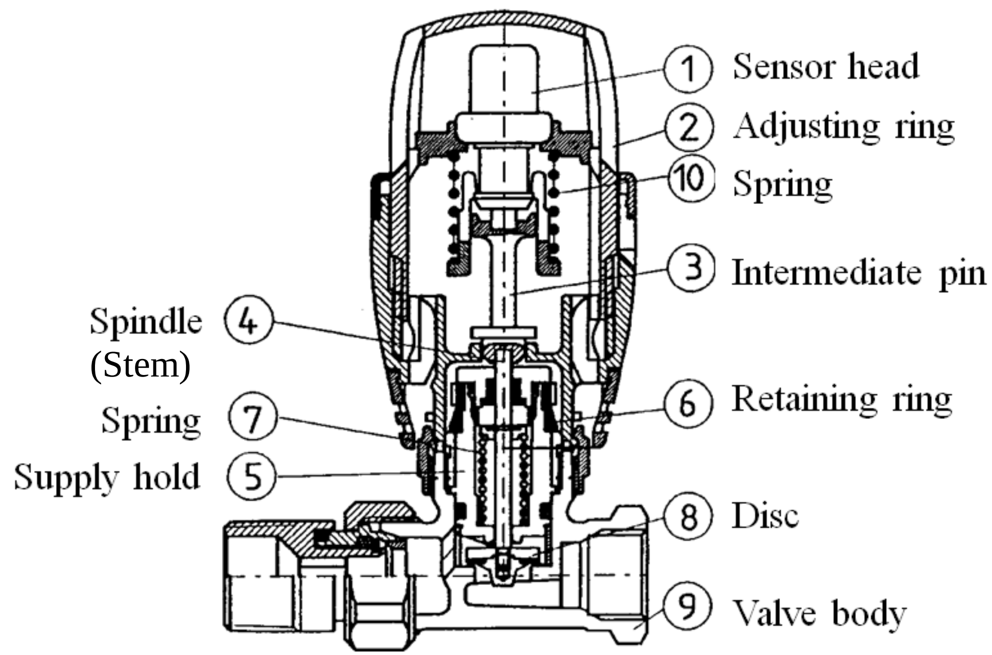
Large buildings are often partitioned into *control zones* due to divergent heating loads based on factors such as:

- occupancy
- purpose
- required temperature level
- orientation
- floor
- intermittent heating



Room temperature control with radiator valves

- Thermostatic valves provide a room level temperature control.
- The operation is based on a thermal element that expands due to the rise of temperature and closes the spindle. The setpoint value can be changed according to demand.
- *If* only room-level control was implemented (no supply water temperature control), high supply water temperature should be maintained all the time
  → significant systemic heat losses
  → no temperature control in spaces with no valves
  → valve positions would fluctuate a lot (→ risk of failures)
  → remarkable pressure loss and noise

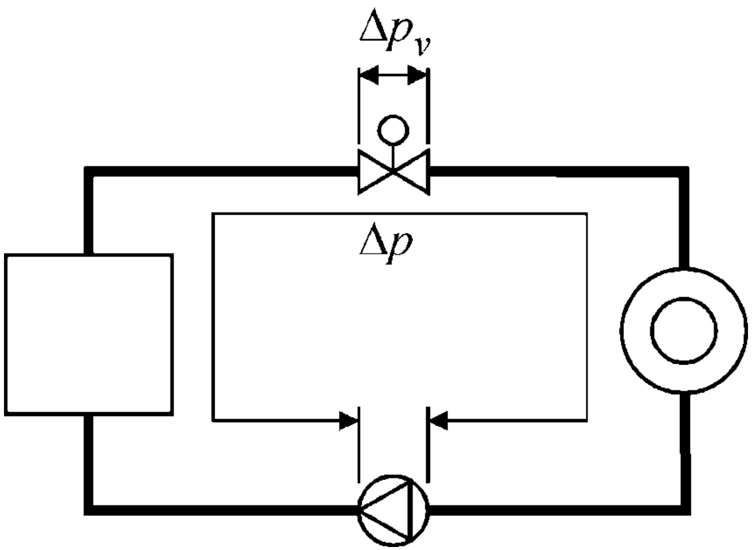


Temperature control – direct electric heating

- Fixedly mounted thermostat to control
  - individual baseboard heaters
  - one heater that again controls several ***slave heaters***, i.e. connected heaters with no individual thermostat
- Room thermostat to control one or more (slave) heaters
- Several opportunities for automatic control, e.g.:
  - The temperature drop of 2–15°C may be allowed to pursue energy savings, when the room is not occupied. In this case, the thermostat is equipped with additional resistance that results in the interpretation of the room temperature higher than it really is. The operation may be controlled by a timer.

Valve as a component of control system – I

The *authority of a control valve* (a_v) indicates the proportion of the pressure drop of a valve in the total pressure drop of the (water) loop in design conditions (valve fully open).



$$a_v = \frac{\Delta p_v}{\Delta p}$$

Δp_v = the pressure drop of valve (fully open)

Δp = the total pressure drop of the water loop (including the valve)

In the design conditions, a valve should represent at least a half (50 %) of the total pressure drop of the circulation loop to be controlled ($a_v > 0.5$).

Self-study: Find out the definition and significance of the *k_v-value of a valve*.

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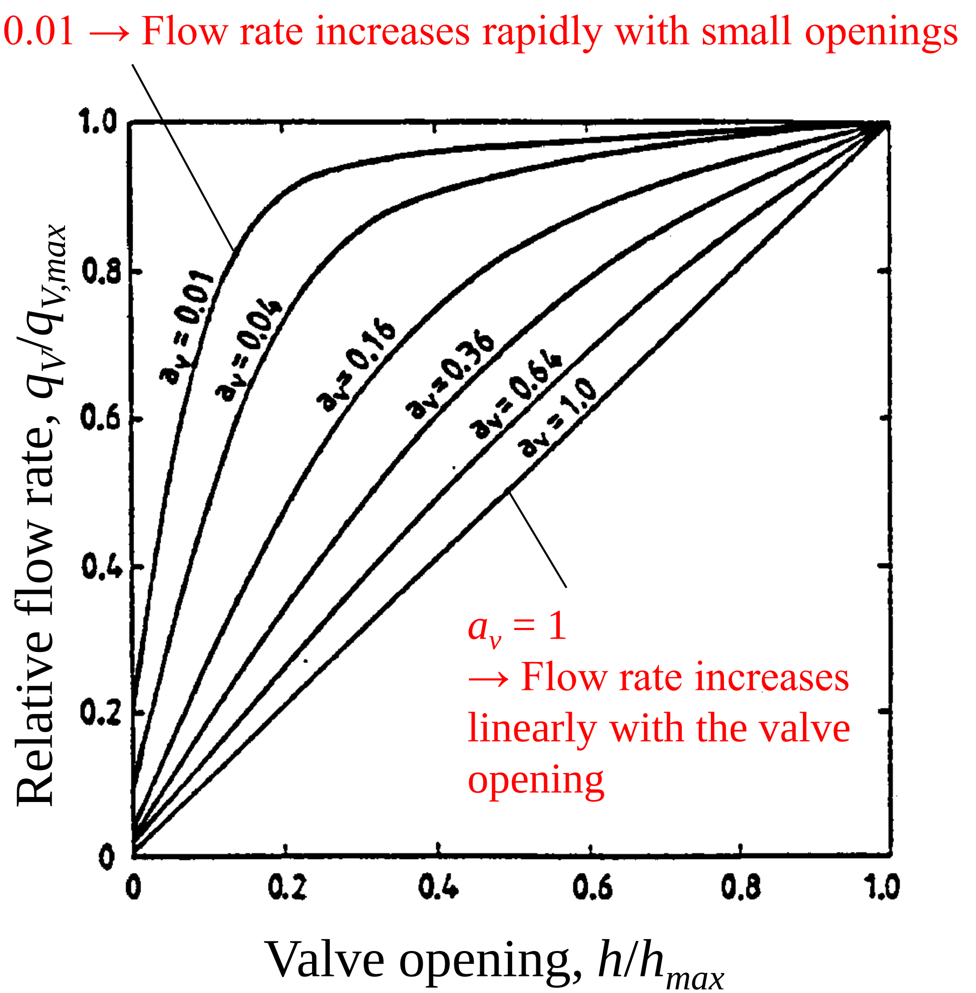
Valve as a component of control system – II

For an ideal control, the dependency between the valve position and the controlled variable (flow rate) is linear.

The greater the authority of a (linear) valve is, the better is the linearity between the valve position and the control variable.

Linear flow characteristics: →
The flow rate is directly proportional to the valve position (h), at given pressure difference. (The impact of the authority of valve is presented in the graph.)

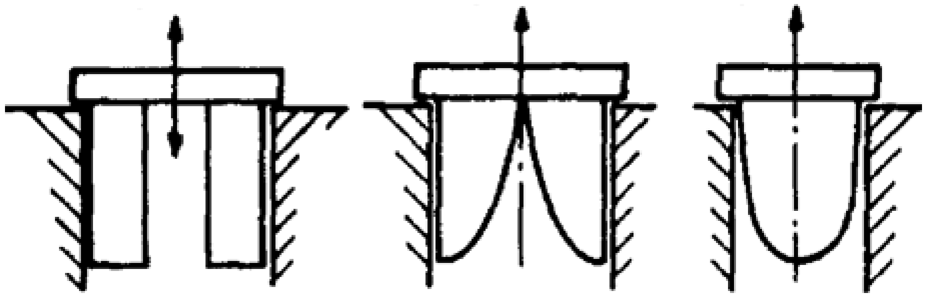


Valve as a component of control system – III

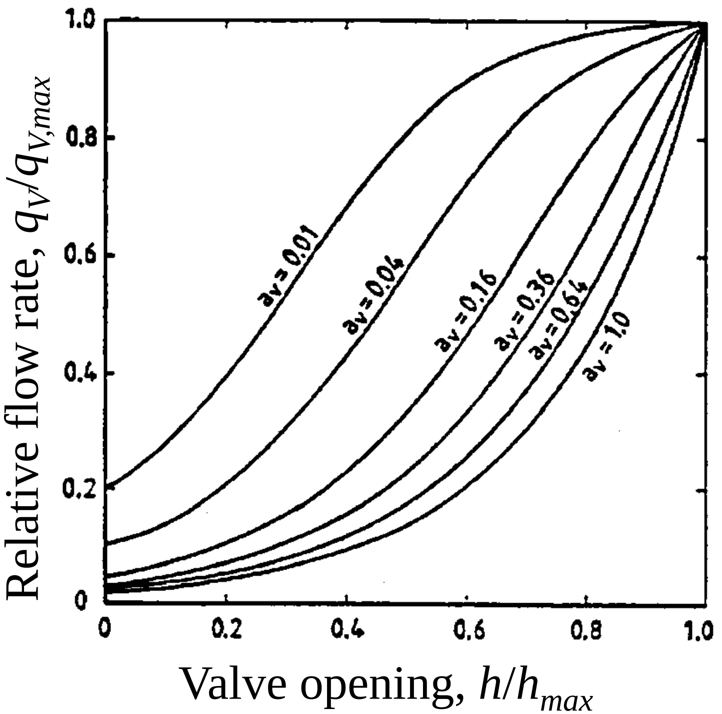
The authority of the valve cannot be = 1 (due to pressure losses of the heat distribution network). The linearity between the valve position and the flow rate can be improved by choosing a *non-linear valve*, i.e. the area of the *orifice* (flow channel) does not change in a linear proportion to the valve position.

Common non-linear flow characteristics:

- *Equal percentage*: Each increment in valve position increases the flow rate by a fixed percentage of the previous value. (The impact of the authority of valve is shown in the graph.)
- *Quick opening*: A small movement from the closed position will result in a large change in flow rate.

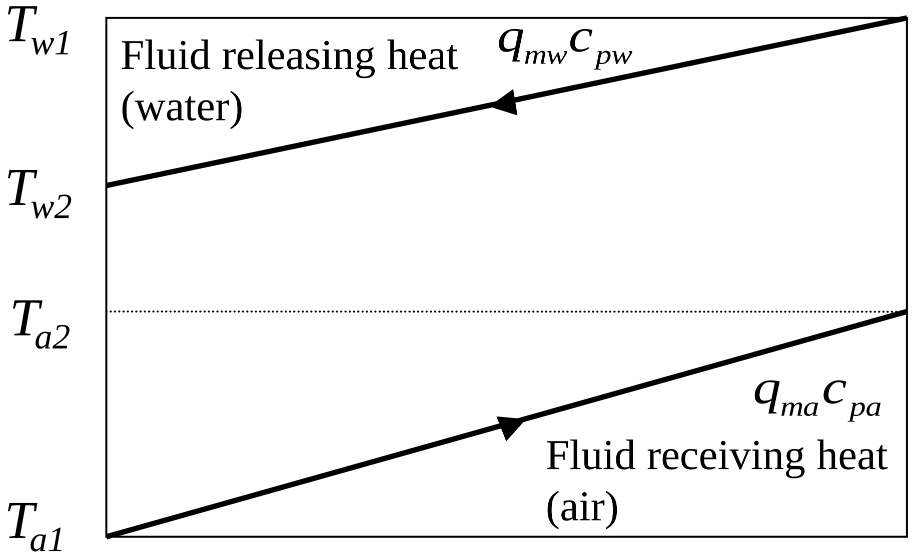


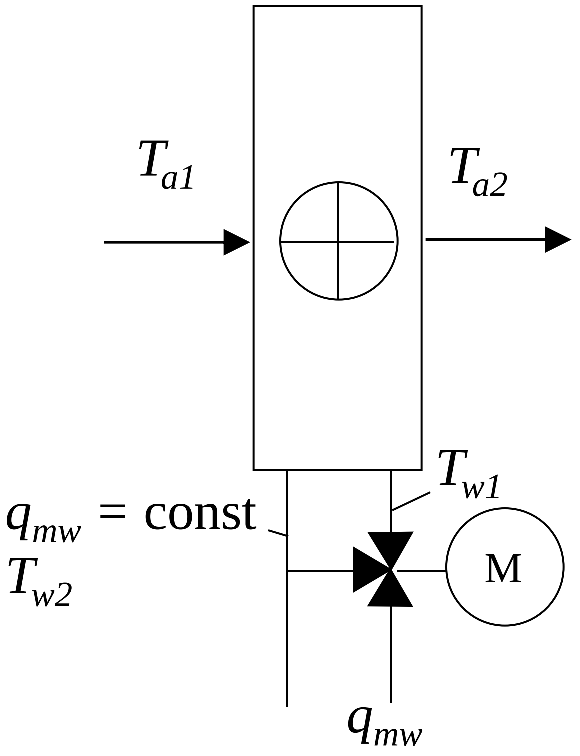
Linear   Equal Percentage



Particularities of the control of heating/cooling coils – I

- Heating mode
  - mixing control (mixing valve)
    - constant mass flow through heat exchanger
  - water flow control (2-way valve)
    - constant supply water temperature (to heat exchanger)
- Cooling mode
  - water flow control (mixing valve, bypass)
    - constant supply water temperature (to heat exchanger)





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Particularities of the control of heating/cooling coils – II

- Flow ratio (relative flow rate):

$$M = \frac{q_{mw}}{q_{mw,\max}} \left(\approx \frac{q_V}{q_{V,\max}} \right)$$

$q_{mw,\max}$ = (water) flow rate, when the valve is fully open [kg/s]

- Control ratio:

$$S = \frac{q_{mw,\max}}{q_{mw,\min}}$$

$q_{mw,\min}$ = (water) flow rate, when the valve is fully closed [kg/s]

Note: Valves let some flow through even if they are fully closed → $q_{mw,\min} > 0$.

The control ratio is commonly $S > 30$.

- Temperature coefficient:

$$a = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{a1}}$$

(temperatures as on the previous slide)

- Load factor:

$$\frac{\Phi}{\Phi_d} = \frac{1}{1 + \frac{a(1-M)}{M}}$$

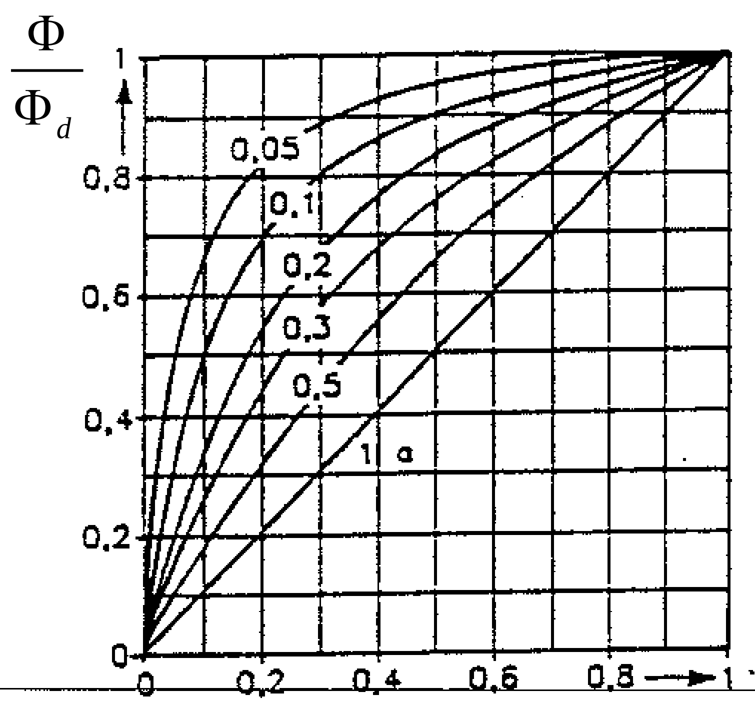
Φ = heat exchange rate [W]

Φ_d = heat exchange rate in design conditions [W]

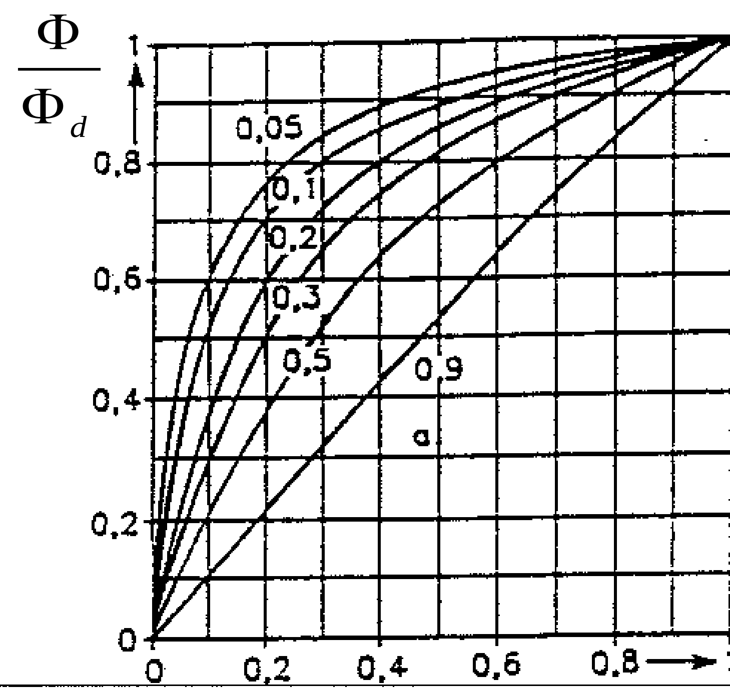
- No-load (stand-by) thermal power $\Phi_{\min}$
  - heat transfer rate when the valve is fully closed

Particularities of the control of heating/cooling coils – III

Mixing control



Water flow control



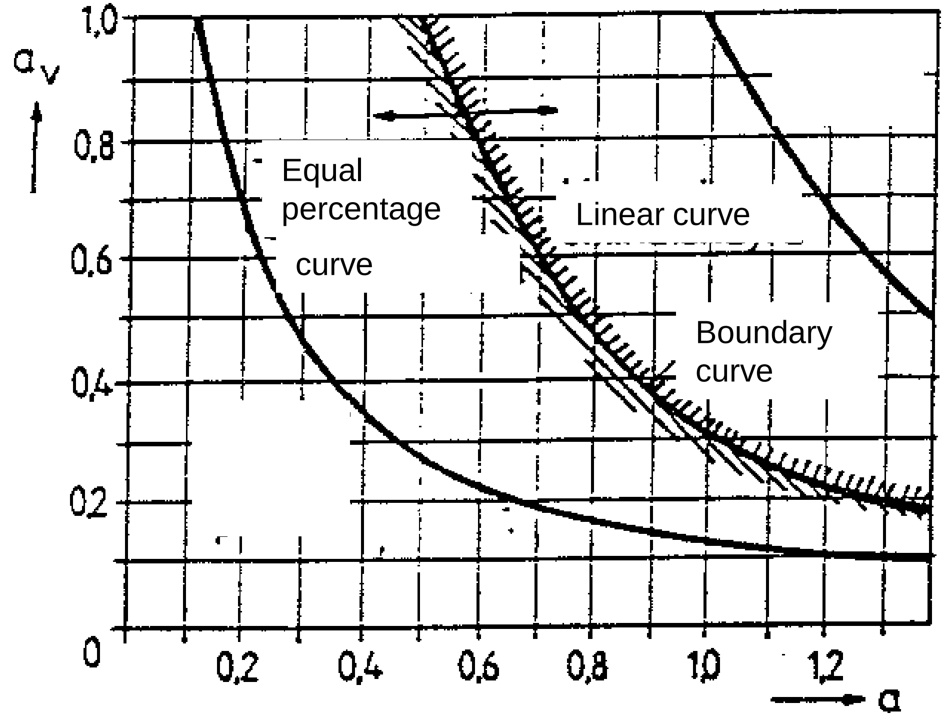
The smaller the temperature coefficient *a* is, the more non-linear is the control.

$$M = \frac{q_{mw}}{q_{mw,\max}}$$

$$M = \frac{q_{mw}}{q_{mw,\max}}$$

Particularities of the control of heating/cooling coils – IV

Relation between the flow characteristics, the temperature coefficient *a* and the authority of the valve a_v



Particularities of the control of heating/cooling coils – V

- The *accuracy of temperature control*, can be defined as the ratio of stand-by thermal power (Φ_{min}) and the nominal thermal power (Φ_d) (design conditions) as follows:

$$\frac{\Phi_{min}}{\Phi_d} = \frac{1}{1 + a\left[\sqrt{a_v\left(S^2 - 1\right) + 1} - 1\right]}$$

where	a	temperature coefficient
	a_v	authority of the valve
	S	control ratio of the valve

- When a heating coil operates at small thermal power (near stand-by/no-load conditions), the control ratio of the valve should be as great as possible (> 100).

Example

The supply and return water temperatures of a heating coil (in design conditions) are 60/40 ºC, air leaving/entering the coil at the temperature +15/–26 ºC. Determine the accuracy of the temperature control (in degrees centigrade), when the control ratio is

a) $S = 50$?

b) $S = 100$?

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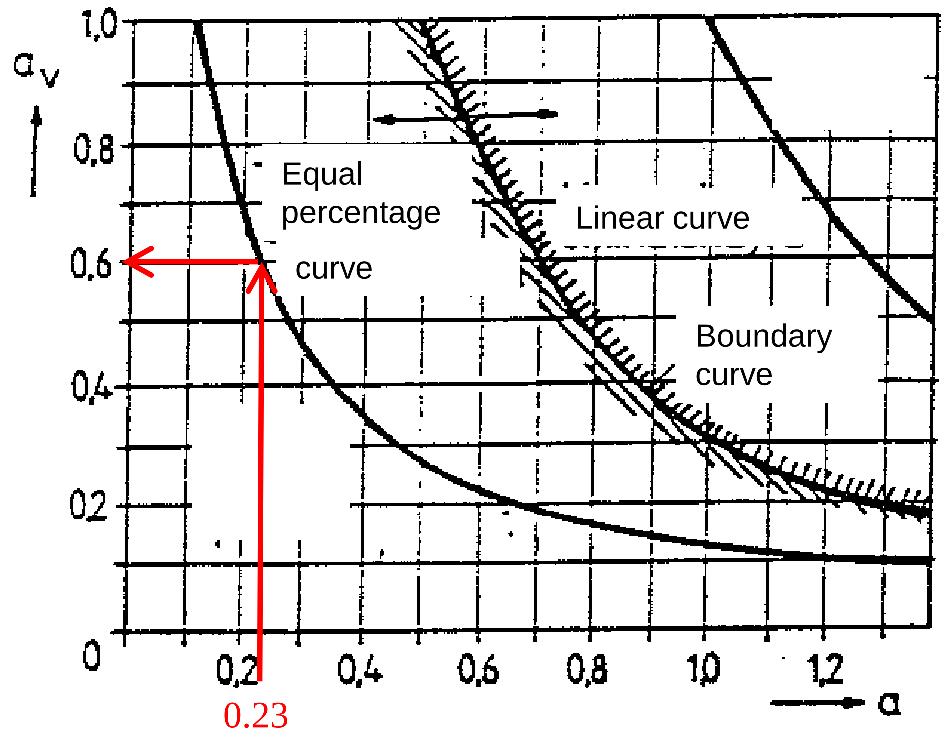
Solution – I

1. Temperature coefficient:

$$a = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{a1}} = \frac{(60 - 40)\,°C}{(60 - (-26))\,°C} = 0.23$$

2. Authority of the valve:
   – $a = 0.23$
   → Equal percentage curve:
   $a_v = 0.6$ (> 0.5)



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Solution – II

3. The standby thermal power / design thermal power:

$$\frac{\Phi_{\min}}{\Phi_d} = \frac{q_{ma} c_{pa} \Delta T_{\min}}{q_{ma} c_{pa} \Delta T_d} = \frac{\Delta T_{\min}}{\Delta T_d} = \frac{1}{1 + a\left[\sqrt{a_v\left(S^2 - 1\right) + 1} - 1\right]}$$

4. The accuracy of the temperature control (in °C):

a) $$\Delta T_{\min,S=50} = \frac{\Delta T_d}{1 + a\left[\sqrt{a_v\left(S^2 - 1\right) + 1} - 1\right]} = \frac{\left(15 - (-26)\right)°C}{1 + 0.23 \cdot \left[\sqrt{0.6\left(50^2 - 1\right) + 1} - 1\right]} = \underline{\underline{4.2°C}}$$

b) $\Delta T_{\min,S=100} = \underline{\underline{2.2\,°C}}$