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Heating and Cooling Systems
EEN-E4002 (5 cr)

Fundamentals of system design

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Learning objectives

Student will learn to

- have a general view of an HVAC engineer’s contribution in the design of heating and cooling systems
- know the basics of selecting heat conversion and distribution methods
- apply the basic theories and computational tools for sizing heating and cooling systems

Lesson outline

1. Design process of heating and cooling systems
2. Perspectives on system level design
   – selection of heat conversion methods
   – selection of heat distribution methods
3. Sizing of heat exchangers
4. Sizing of heat distribution network
5. Heat losses and insulation of pipes

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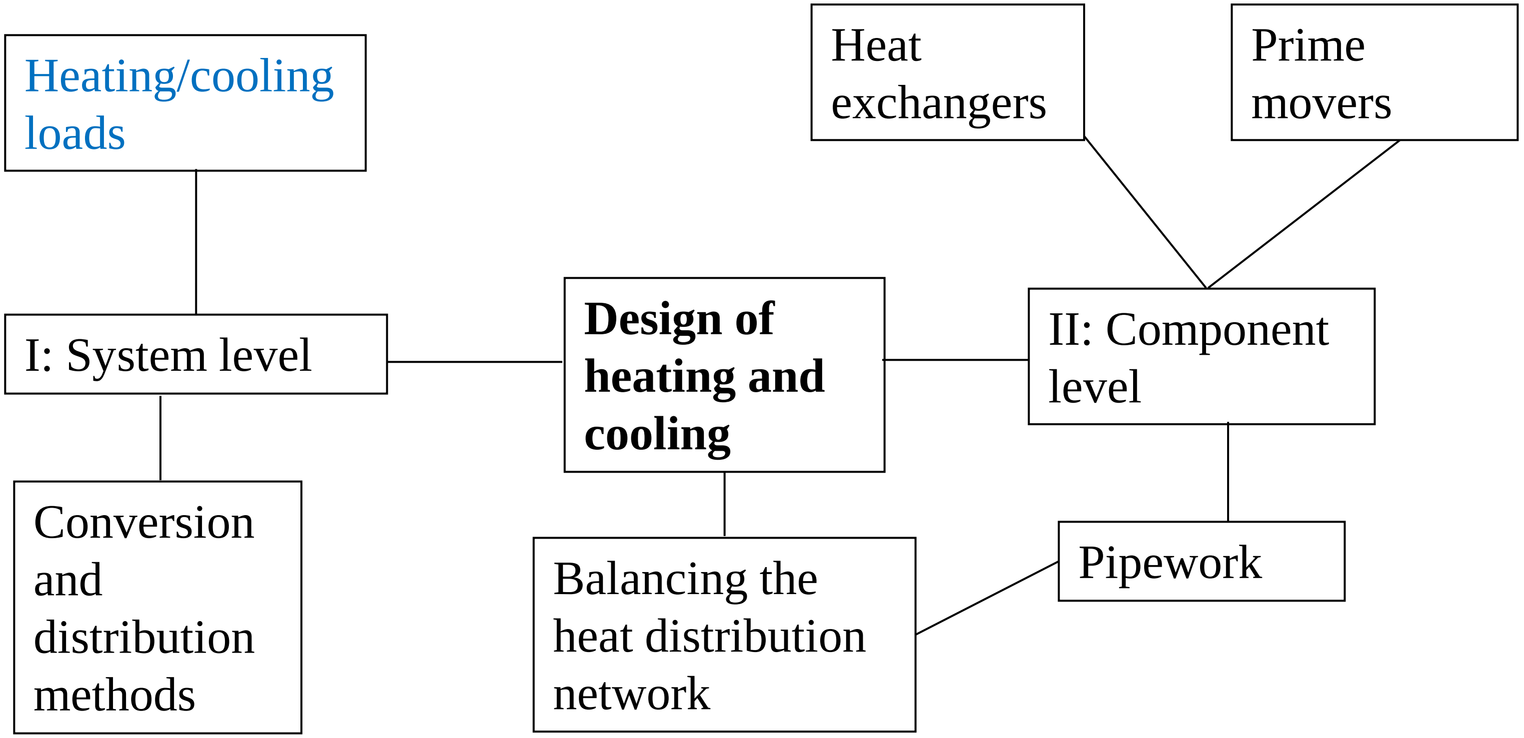
Duties of HVAC engineer in designing heating and cooling systems

1. Determining heating/cooling loads (for each space)
2. Choosing the energy conversion (e.g. district heating, heat pump) and distribution methods (e.g. floor heating)
3. Choosing the heat exchangers
4. Disposition of the heat exchangers and pipework in the target building aka *routing*
5. Sizing and balancing the pipework
6. Choosing the prime movers
7. Compiling the drawings (aka blueprints) and operational descriptions

The theoretical principles of *determining heating and cooling loads* have been treated under the topics 1-2. *The design process and its practical implementation* will be treated in detail in the courses "*EEN-E4005 Fundamentals of HVAC design*" and "*EEN-E4006 Advanced HVAC design*".

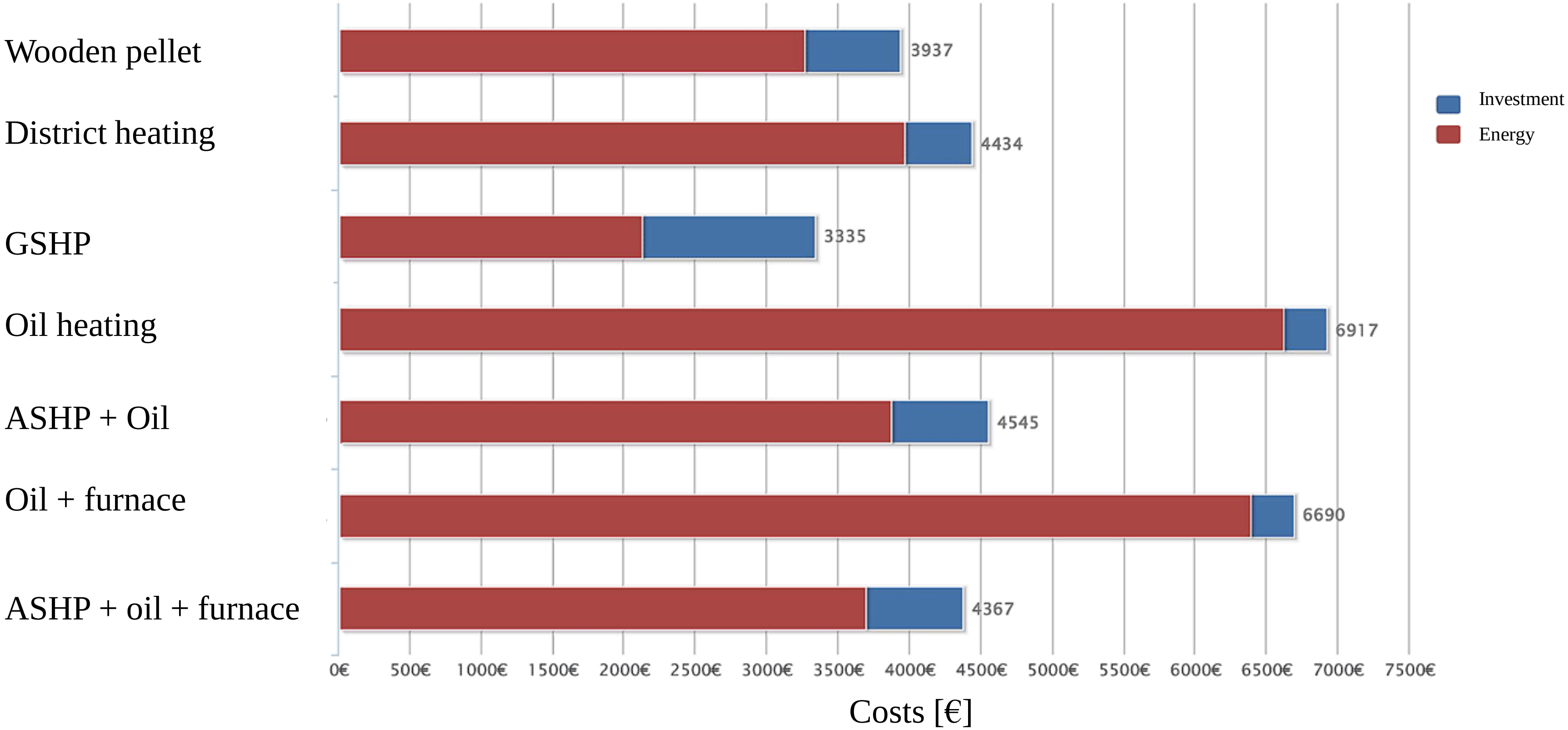
Areas to be covered



Choosing the conversion method – example of the share of investment and operational costs

- Heated area: 250 m²
- Room height: 2.60 m
- Number of occupants: 6
- Location: Central Finland
- Annual energy for DHW: 6000 kWh/a
- Annual thermal energy total: 50200 kWh/a

Annualized total costs including investment, inflation and energy



Reference: http://omakotilehdet.fi

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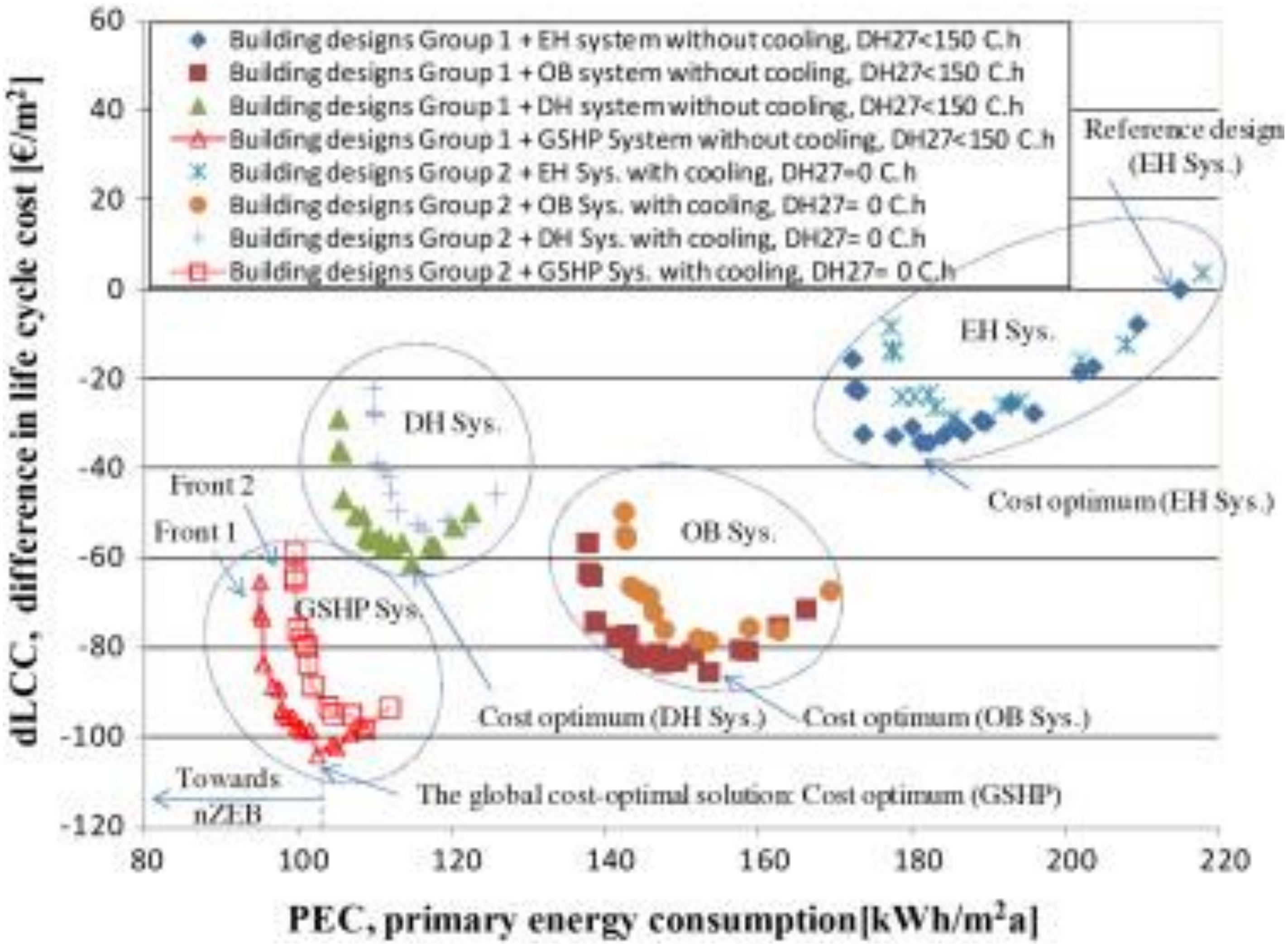
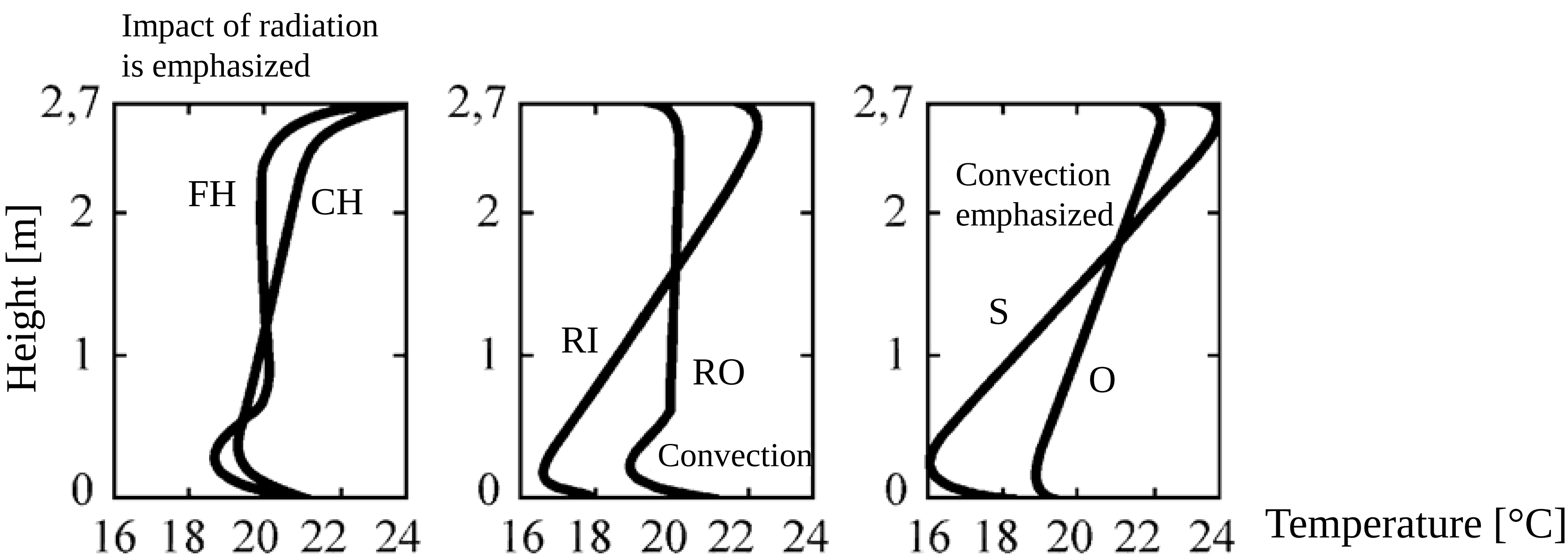
Choosing the conversion method – impact on the cost optimality



Choosing the heat distribution method – impact on thermal comfort



FH = Floor heating

CH = Ceiling heating

RO = Radiators outer wall

RI = Radiators inner wall

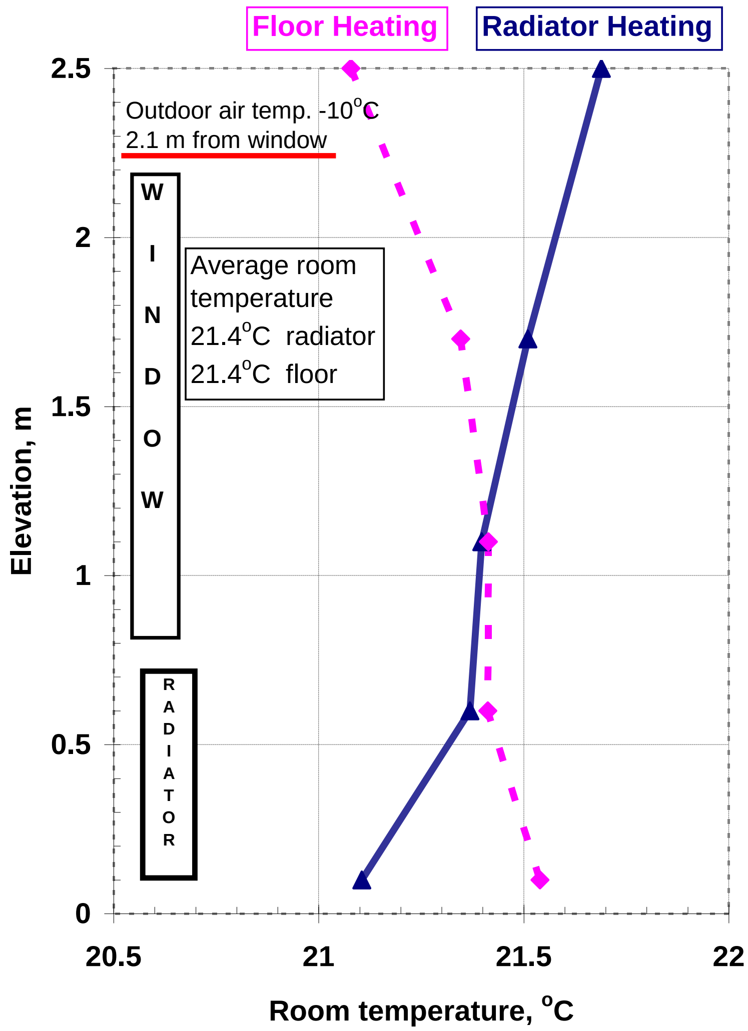
S = Stove

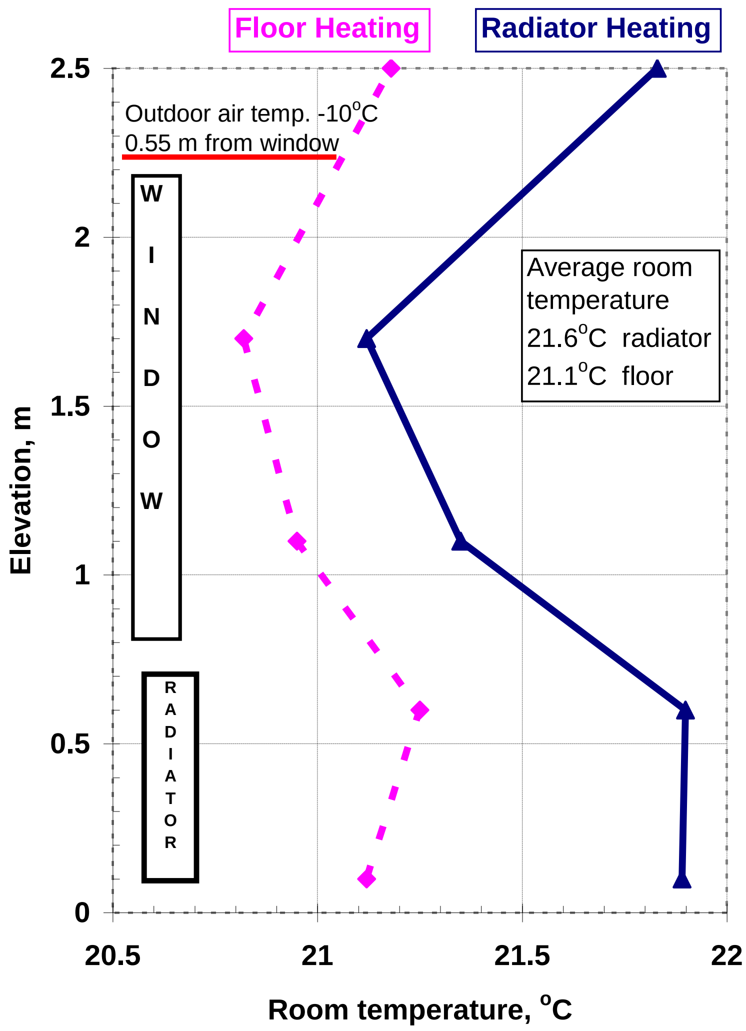
O = Oven

<u>Comfort criterion</u>: $T_{1.7\ \mathrm{m}} - T_{0.05\ \mathrm{m}} \leq 2 \ldots 3°C$

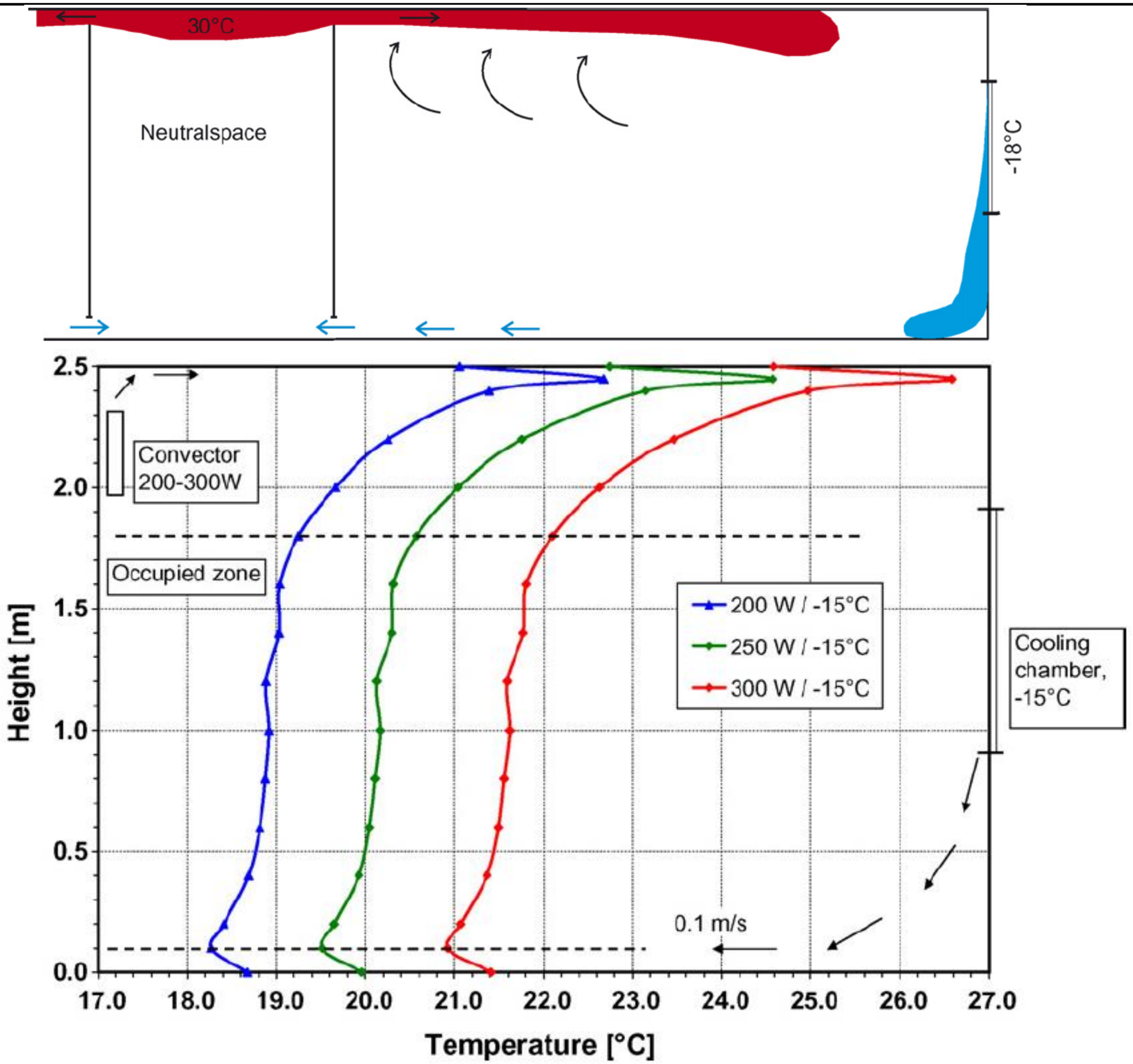
The temperature at floor level is critical.

Vertical temperature gradient for radiator and floor heating



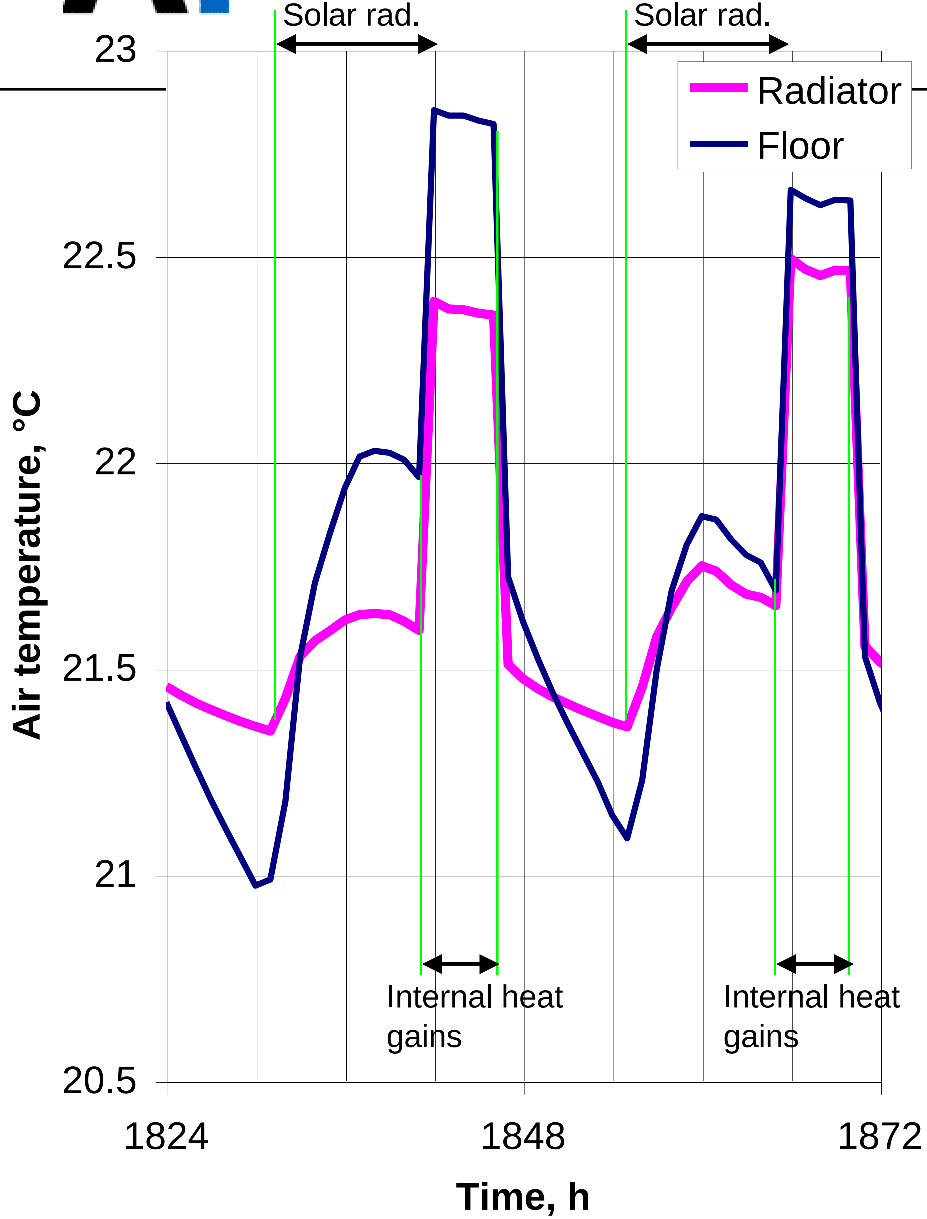


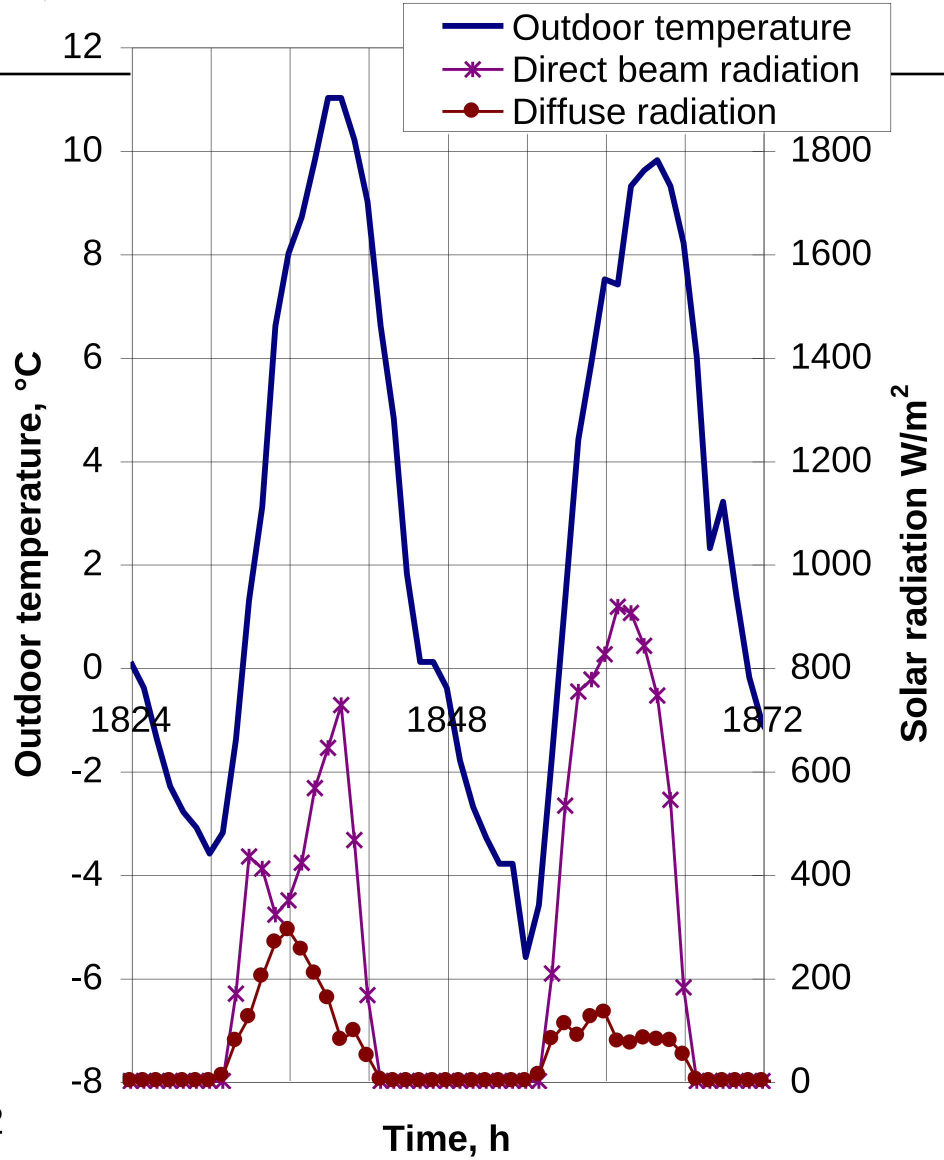
Vertical temperature gradient for air heating



- Significant temperature gradient and air velocity (draught problems expected)
- Difference in quality in comparison with radiator or floor heating can be perceived.

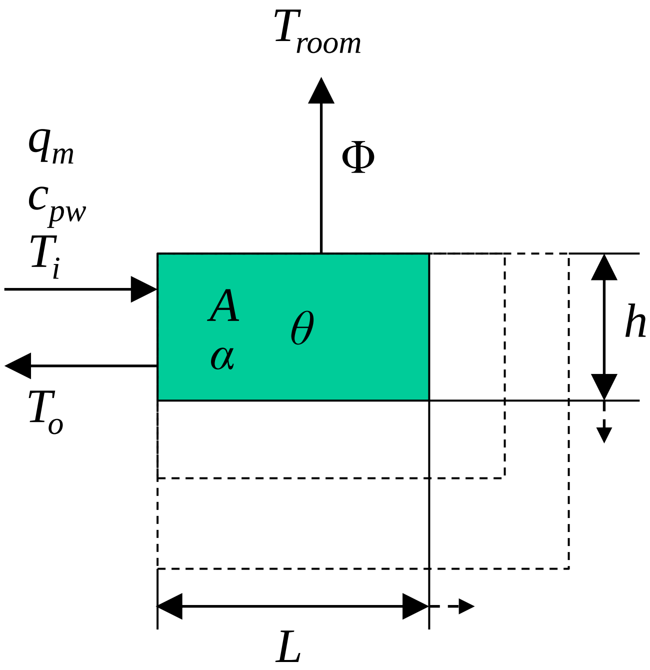
Dynamic response for radiator and floor heating (spring)





Sizing of radiators and convectors

- Sizing = choosing the type and geometry of a radiator/convector to release thermal power equal to heating load into the target room (i.e. given fluid flow q_m is cooled down from the supply temperature T_i to the return temperature T_o).
- Both convection and radiation are present.
- The heat release is affected by
  - surface area
  - heat transfer coefficient
- The heat transfer coefficient is affected by
  - installation of the radiator/convector
  - characteristics of the surfaces
  - characteristics of the air flow in the room

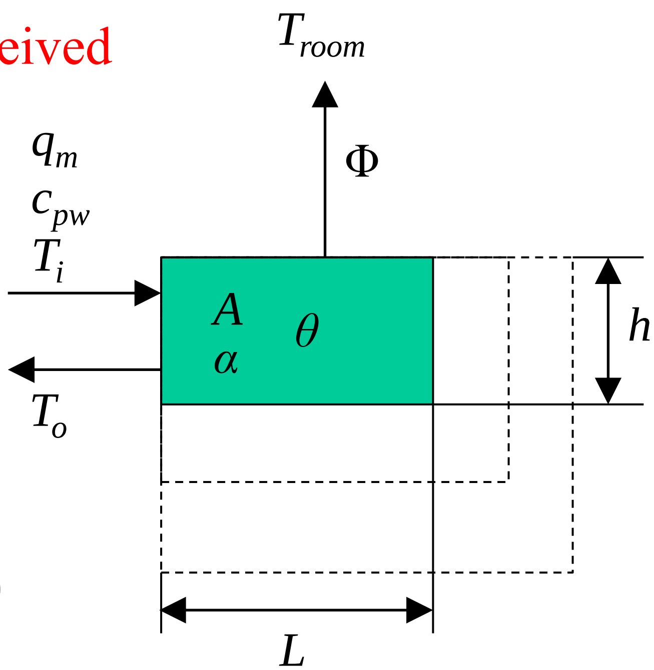


Electric radiators:
The surface temperature is constant
→ constant heat release

Heat release equation

$$\Phi = c_{pw} q_m (T_o - T_i) = \dot{C}(T_i - T_o) \quad \leftrightarrow \text{released} = \text{received}$$

$$= G \frac{T_i - T_o}{\ln \dfrac{T_i - T_{room}}{T_o - T_{room}}} \approx G\left(\frac{T_i + T_o}{2} - T_{room}\right)$$



<u>For brevity:</u>

$\dot{C} = q_m c_{pw}$ (= heat capacity flow)

$G = UA$ (= heat transfer coefficient aka conductance)

$$\theta_{\ln} = \frac{T_i - T_o}{\ln \dfrac{T_i - T_{room}}{T_o - T_{room}}} \text{ (= logarithmic temperature difference)}$$

$$\theta = \frac{T_i + T_o}{2} - T_{room} \text{ (= mean temperature difference between radiator and room)}$$

$$\Leftrightarrow \; \Phi = G\theta_{\ln} \approx G\theta$$

Heat transfer coefficient – I

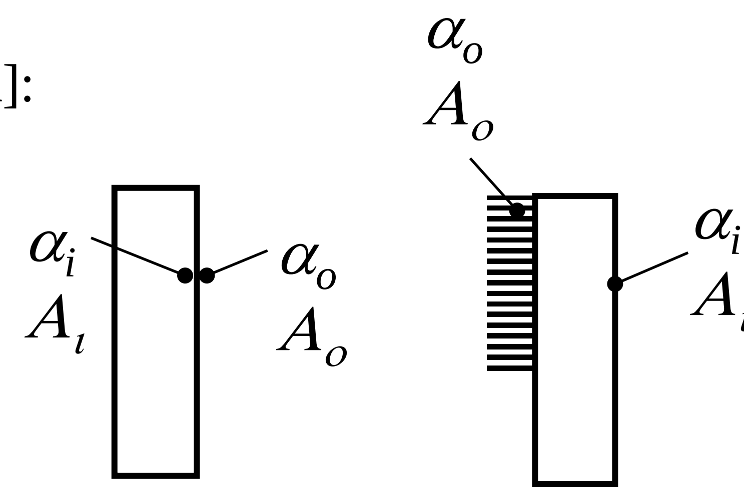
- Heat transfer coefficient (aka conductance) [W/K]:

$$G = UA = \frac{1}{R} \cdot A \qquad \text{where } A = A_i = A_o$$

$$R = \frac{1}{\alpha_i} + \frac{s}{\lambda} + \frac{1}{\alpha_o}$$

Determinative

s = thickness of tube material [m]
λ = conductivity of tube material [W/mK]



$A_i = A_o$ $\qquad$ $A_i < A_o$

<u>Magnitudes:</u> $\rightarrow \alpha_o$ determinative

$$\alpha_i > 100 \frac{\text{W}}{\text{m}^2\text{K}} \text{ (convection only)}$$

$$\alpha_o > 10 \frac{\text{W}}{\text{m}^2\text{K}} \text{ (convection + radiation)}$$

$$\lambda = 50 \frac{\text{W}}{\text{mK}} \text{ (steel)}$$

- For $A_i < A_o$ (convectors):

$[G''] = \text{W/m}^2\text{K}$

$$\left.\begin{aligned} &G = UA_o \\ &G'' = \frac{G}{A_i} = \frac{A_o}{A_i} \cdot U \end{aligned}\right\} \Leftrightarrow U = \frac{1}{\left(\frac{1}{\alpha_i} + \frac{s}{\lambda}\right)\frac{A_o}{A_i} + \frac{1}{\alpha_o}}$$

Heat transfer coefficient – II

- External heat transfer coefficient [W/m^{2}K]:

$$\alpha_o = \alpha_c + \alpha_r$$

$$\alpha_r = \frac{\sigma\left(T_i^{\,4} - T_s^{\,4}\right)}{T_i - T_s} \qquad \sigma = 5.67\cdot10^{-8}\ \mathrm{W/m^2K^4}$$

$$\alpha_c = 2.2\left[\frac{\theta}{h}\right]^{\frac{1}{4}} \quad \text{(vertical surface)}$$

$$\alpha_c = 3.0\left[\frac{\theta}{h}\right]^{\frac{1}{4}} \quad \text{(vertical surface close to wall)}$$

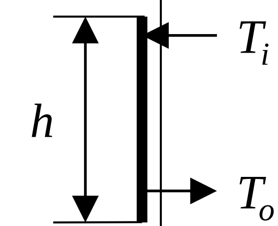
Expressions derived from the theory of natural convection.

$$\Rightarrow \alpha_o = C\cdot\left[\frac{\theta}{h}\right]^{\frac{1}{4}} \quad \text{(total external heat transfer coefficient)}$$

T_s = temperature of surfaces in the room

$$\alpha_o = \alpha_c + \alpha_r$$

θ



The variation of radiative heat transfer is minor in comparison with that of convection, particularly at low radiator temperatures:

T_i = 60°C $\rightarrow$ α_r = 7.1 W/m^{2}K
T_i = 40°C $\rightarrow$ α_r = 6.5 W/m^{2}K
(T_s = 20°C)

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Sizing equation

$$U \approx \alpha_o = C \cdot \left[\frac{\theta}{h}\right]^{\frac{1}{4}}$$

Sizing equation (derived from theory):

$$\Phi = UA\theta = CA \cdot \left[\frac{\theta}{h}\right]^{\frac{1}{4}} \cdot \theta = ChL \cdot \left[\frac{\theta}{h}\right]^{\frac{1}{4}} \cdot \theta$$

Standardized sizing equation (derived from experiments):

$\Phi = Ch^n L \theta^r$ (Reference: DIN 4707 standard)

Note: In practice the heat release is always measured in standardized laboratory conditions.

Example

The supply/return water temperatures are T_i/T_o = 70/40°C and the design heating load of the target room is 1000 W. The maximum allowable height of the radiator is 300 mm and length 2 m. Choose the radiator on the basis of the data below. The room temperature is 21°C.

Parameters *C*, *n* and *r* for selected ”Rettig” radiators and convectors:

	1 row			2 rows			3 rows		
	C	*n*	*r*	*C*	*n*	*r*	*C*	*n*	*r*
Convector (”Ratek K”)	11.1	0.63	1.29	19.4	0.62	1.31	26.0	0.61	1.33
Radiator (”Kompakt”)	10.5	0.86	1.29	14.6	0.83	1.30	21.6	0.80	1.32
Radiator (”Plate”)	10.2	0.86	1.29	17.6	0.81	1.31	21.4	0.81	1.32

Solution

1. Mean temperature difference between radiator and room:

$$\theta_{70/40^\circ C} = \frac{T_i + T_o}{2} - T_{room} = \frac{(70+40)^\circ C}{2} - 21^\circ C = 34^\circ C$$

2. Heat release of the available radiators/convectors:
   - L = 2 m, h = 0.3 m (assume: the given radiator size is available)
   - Sizing equation: $\Phi = Ch^n L \theta^r$
   - Calculations applying the sizing equation (e.g. MS Excel):

	1 row	2 rows	3 rows
	Φ [W]	Φ [W]	Φ [W]
Convector (”Ratek K”)	983	1866	2716
Radiator (”Kompakt”)	705	1053	1733
Radiator (”Plate”)	685	1347	1696

3. Decision: The closest higher heat release (1053 W > 1000 W) can be obtained with a two-row radiator (”Kompakt”).

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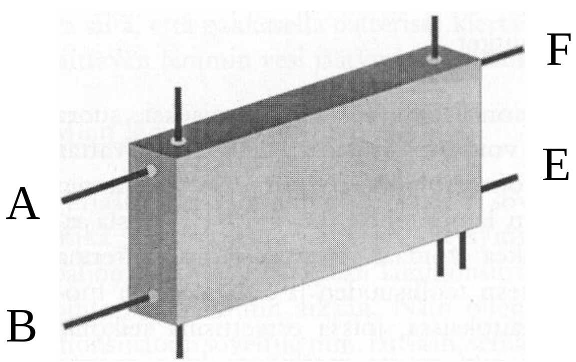
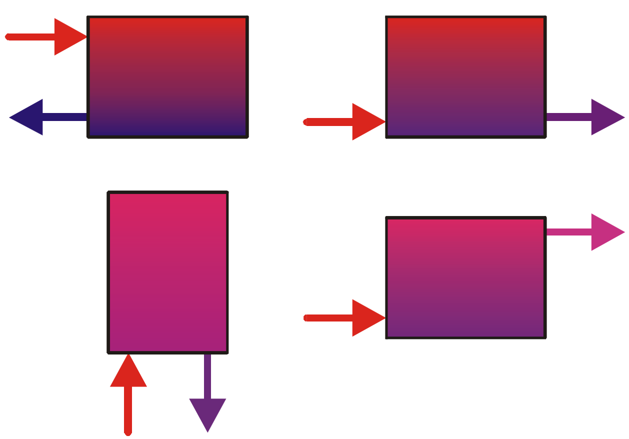
Impact of connection on the heat release

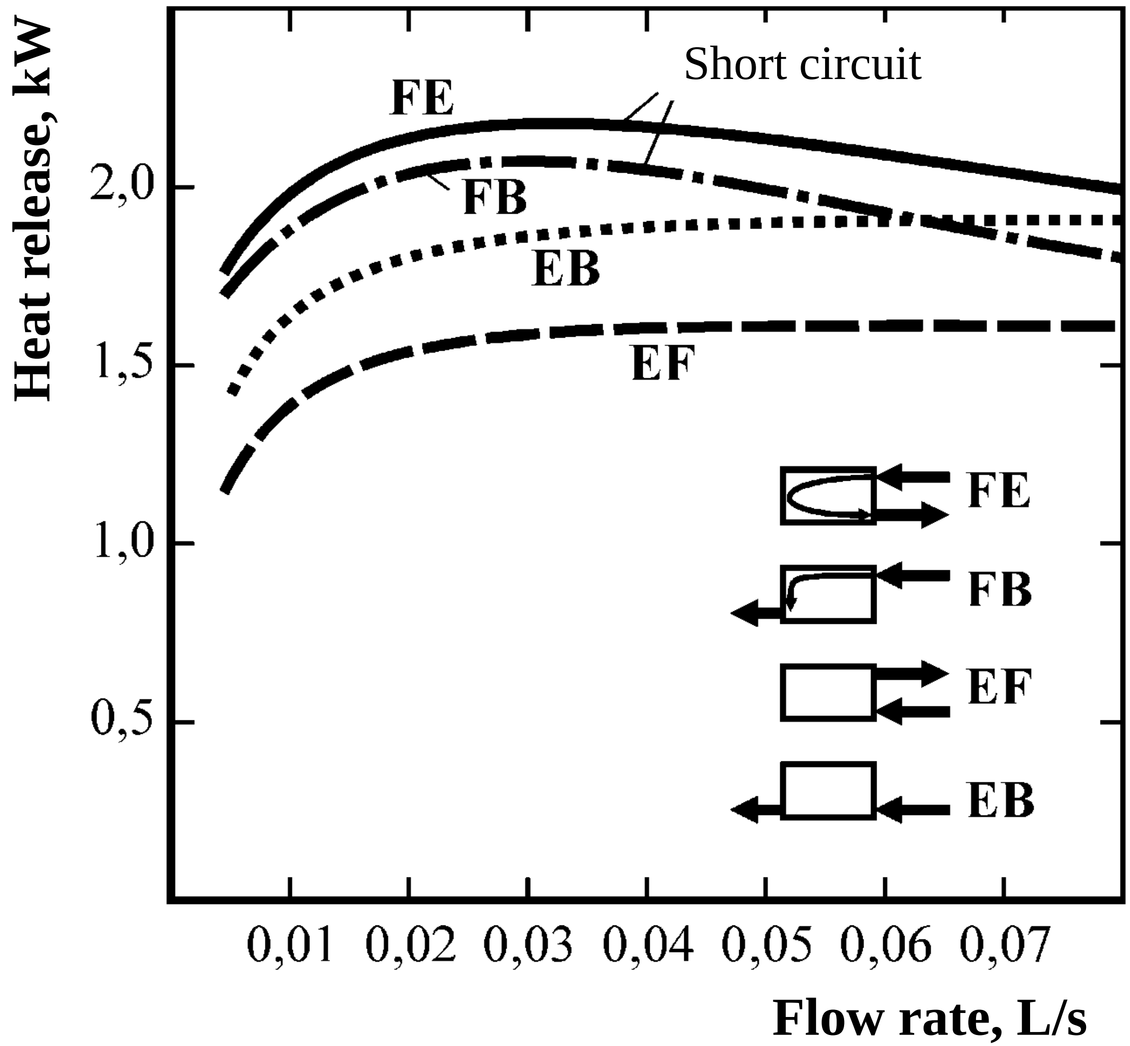
<u>Connections:</u>

End: AB/EF

Diagonal: AE/FB







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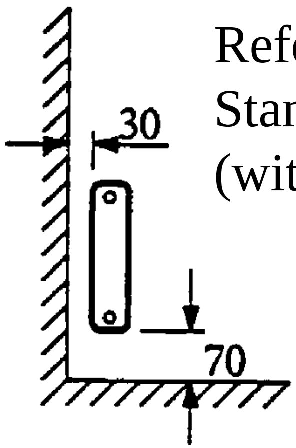
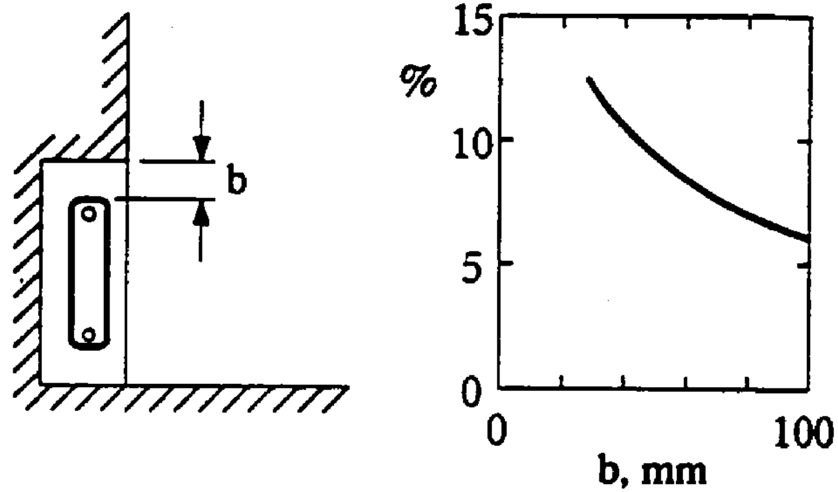
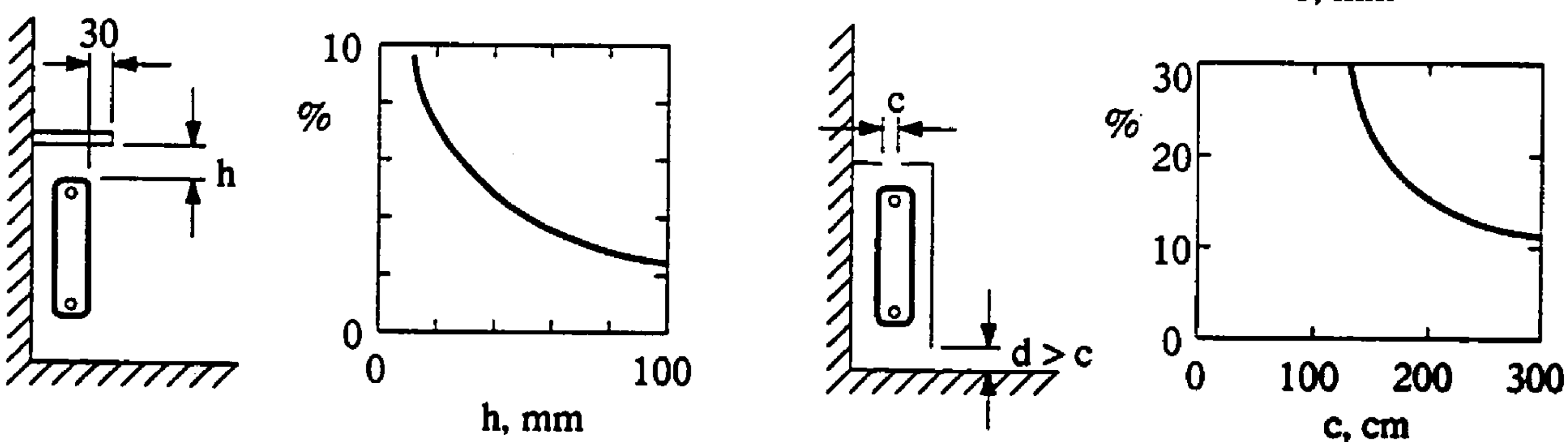
Impact of installation on the reduction of heat release



Reference:
Standard installation
(with no obstacles)

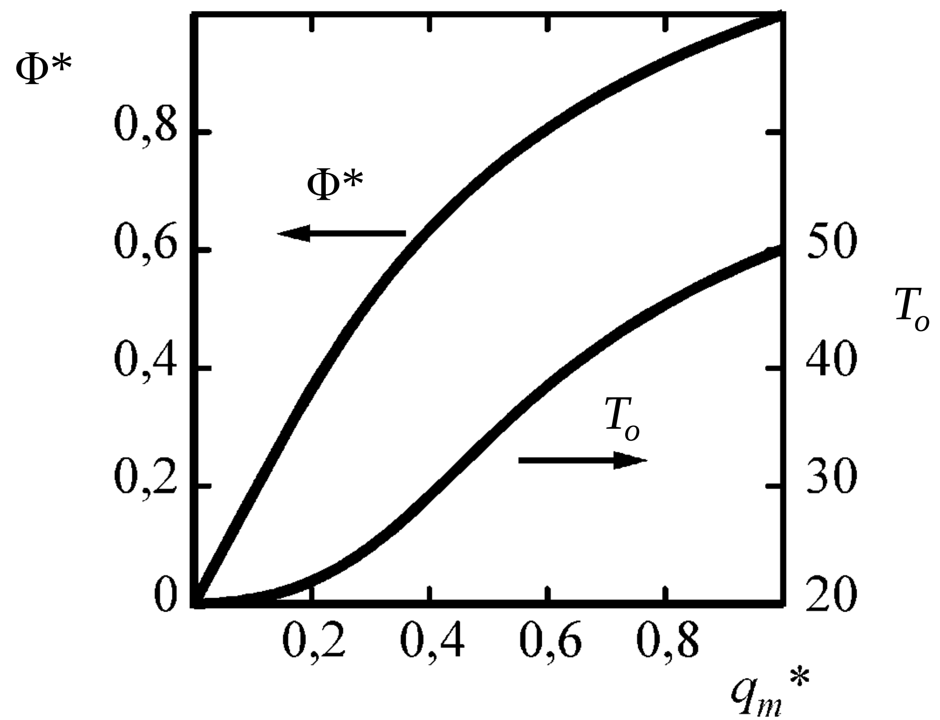




Impact of mass flow on the return temperature and heat release

When the fluid (water) mass flow rate reduces, the supply water and the mean temperatures reduce, as well. The impact on the heat release is *non- linear*.

<u>Example:</u> The graph indicates the change of the proportional heat release with respect to the proportional fluid flow given that the supply water temperature is T_i = 80°C and the return water temperature T_o = 50°C in the design conditions (subscript 0).



$$\Phi^* = \frac{\Phi}{\Phi_0}$$

$$q_m^* = \frac{q_m}{q_{m,0}}$$

Example

The heat release of a radiator at T_i/T_o = 90/70°C is 1000 W. Calculate the heat release at T_i/T_o = 80/50°C. The room temperature is 20°C.

Solution – I

1. Principle
   - constant surface area A, length L and width h → to be reduced
   - heat transfer coefficient depends on the mean temperature difference θ

→ the ratio of temperature differences also determines the ratio of heat release rates:

$$\Phi_{90/70°C} = U_{90/70°C} A \theta_{90/70°C} \; (= 1000\ \mathrm{W})$$

$$\Phi_{80/50°C} = U_{80/50°C} A \theta_{80/50°C} \; (= ?)$$

$$\Rightarrow \frac{\Phi_{80/50°C}}{\Phi_{90/70°C}} = \frac{U_{80/50°C} A \theta_{80/50°C}}{U_{90/70°C} A \theta_{90/70°C}} = \frac{U_{80/50°C} \theta_{80/50°C}}{U_{90/70°C} \theta_{90/70°C}}$$

$$\Rightarrow \Phi_{80/50°C} = \frac{U_{80/50°C}}{U_{90/70°C}} \cdot \frac{\theta_{80/50°C}}{\theta_{90/70°C}} \cdot \Phi_{90/70°C}$$

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Solution – II

2. Mean temperature differences between radiator and room:

$$\left.\begin{aligned}\theta_{90/70°C} &= \frac{T_i + T_o}{2} - T_{room} = \frac{(90+70)°C}{2} - 20°C = 60°C \\ \theta_{80/50°C} &= \frac{T_i + T_o}{2} - T_{room} = \frac{(80+50)°C}{2} - 20°C = 45°C\end{aligned}\right\} \Rightarrow \frac{\theta_{80/50°C}}{\theta_{90/70°C}} = \frac{45°C}{60°C} = 0.75$$

3. Heat transfer coefficients: Constant → reduced

$$\left.\begin{aligned}U_{90/70°C} &\approx C \cdot \left[\frac{\theta_{90/70°C}}{h}\right]^{0.25} = \frac{C}{h^{0.25}} \cdot 60^{0.25} = 2.78 \cdot \frac{C}{h^{0.25}} \\ U_{80/50°C} &\approx C \cdot \left[\frac{\theta_{80/50°C}}{h}\right]^{0.25} = \frac{C}{h^{0.25}} \cdot 45^{0.25} = 2.59 \cdot \frac{C}{h^{0.25}}\end{aligned}\right\} \Rightarrow \frac{U_{80/50°C}}{U_{90/70°C}} = \frac{2.59}{2.78} = 0.93$$

4. Heat release rate:

$$\Phi_{80/50°C} = \frac{U_{80/50°C}}{U_{90/70°C}} \cdot \frac{\theta_{80/50°C}}{\theta_{90/70°C}} \cdot \Phi_{90/70°C} = 0.93 \cdot 0.75 \cdot 1000\ \text{W} = \underline{\underline{700\ \text{W}}}$$

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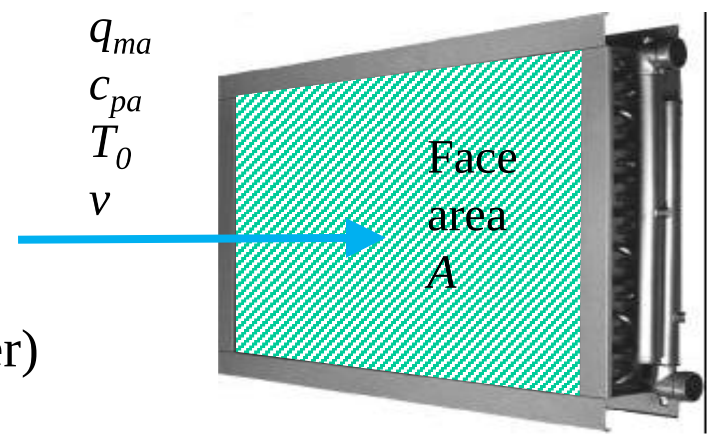
Sizing of heating and cooling coils

- Sizing = choosing the depth of the coil aka the number of rows to release thermal power equal to heating/cooling load into air flow
- A row is considered a single heat transfer unit. The units are connected in series.
- The size of a (finned-tube) heating/cooling coil depends on:
  - heat transfer rate (from a fluid to another)
  - heat transfer area
  - heat exchanger type (counter-flow, parallel flow, cross flow)
  - heat transfer coefficients
- The heat exchanger surface area is commonly fixed. The face velocity is 2…5 m/s.



Face area is a known parameter fixed on the basis of the geometry of the flow path.

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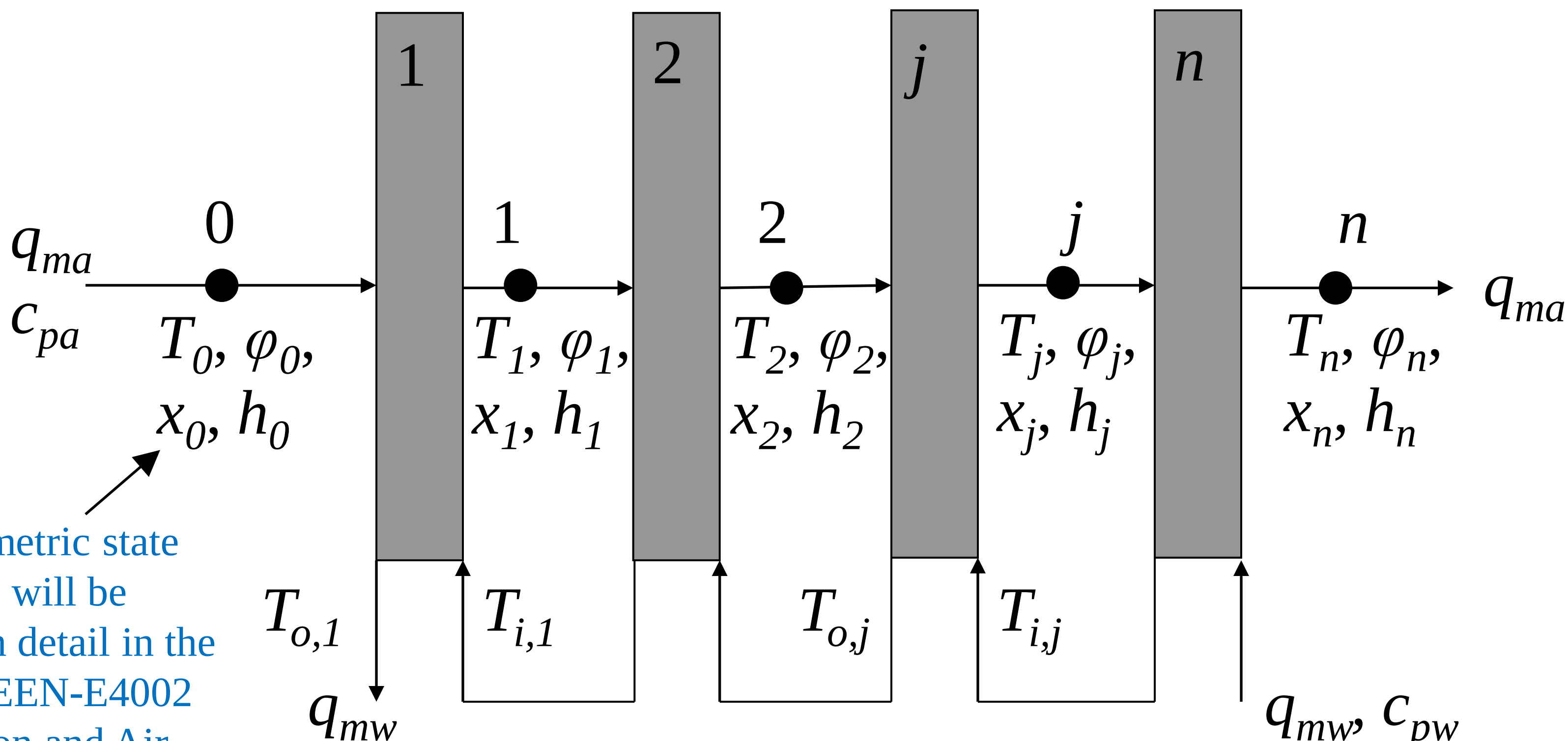
The flow chart of a coil consisting *n* units

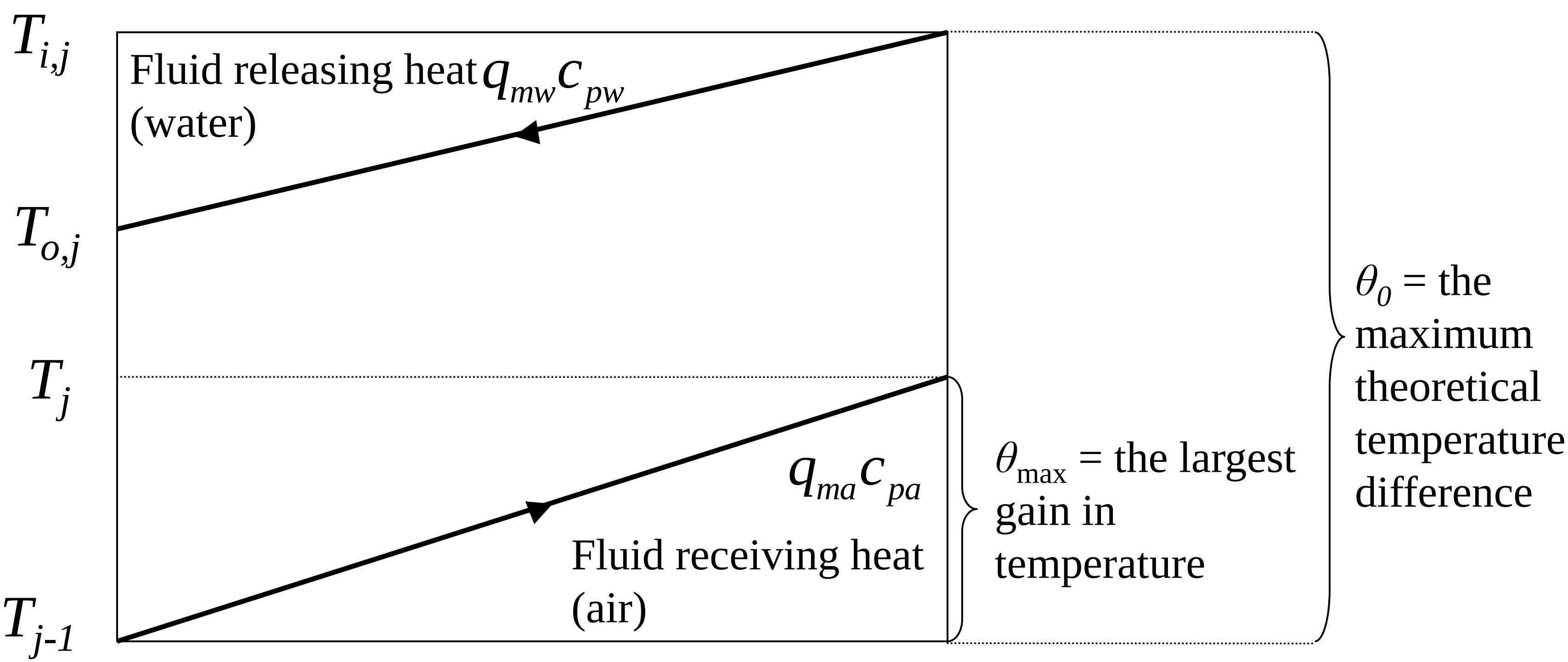
Example: counter-flow heat exchanger, units 1,…*j*…,*n*



Psychrometric state variables will be treated in detail in the course “EEN-E4002 Ventilation and Air-Conditioning systems”.

Subscripts: *a* = air, *w* = water

Temperature change in the *j*-th unit



Heat balance: $q_{mw}c_{pw}\left(T_{i,j}-T_{o,j}\right)=q_{ma}c_{pa}\left(T_j-T_{j-1}\right)$

Heat exchanger effectiveness

- *Heat exchanger effectiveness* is defined as...

$$\varepsilon = \frac{\theta_{\max}}{\theta_0}$$

- ...and it is determined by the heat exchanger's flow pattern and parameters (R and Z) as follows:

Parallel flow:

$$\varepsilon = \frac{1 - e^{-(1+R)Z}}{1 + R}$$

Counter-flow:

$$\varepsilon = \frac{1 - e^{-(1-R)Z}}{1 - R \cdot e^{-(1-R)Z}} \qquad R \neq 1$$

$$\varepsilon = \frac{Z}{1 + Z} \qquad R = 1$$

Parameters

1. Heat capacity flow:

$$\dot{C}_w = q_{mw} c_{pw}$$

$$\dot{C}_a = q_{ma} c_{pa}$$

$$\dot{C}_{\max} = \max\left[\dot{C}_w, \dot{C}_a\right]$$

$$\dot{C}_{\min} = \min\left[\dot{C}_w, \dot{C}_a\right]$$

2. Heat capacity ratio:

$$R = \frac{\dot{C}_{\min}}{\dot{C}_{\max}}$$

3. Dimensionless conductance :

$$Z = \frac{G}{\dot{C}_{\min}} = \frac{UA_o}{\dot{C}_{\min}}$$

Sizing equation

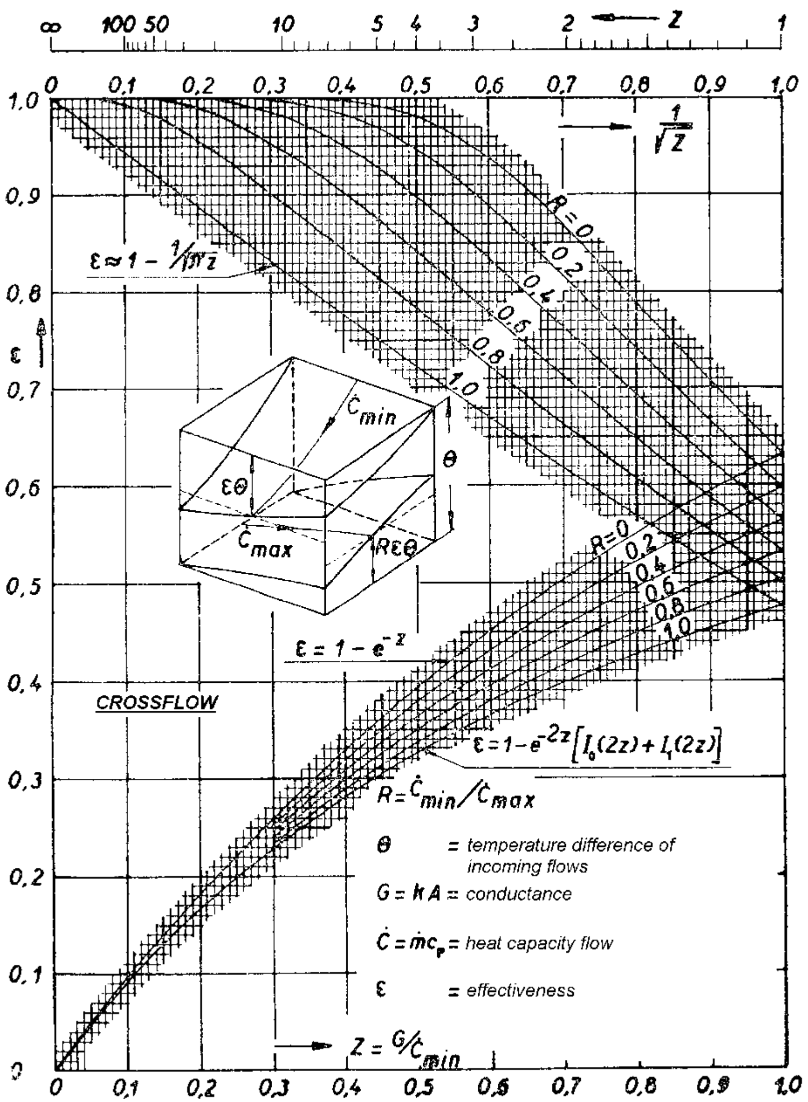
- …returns the required number of heat transfer units (”rows”) (rounded up to the closest $n \in \{1,2...\}$).
- …is derived from the unit-specific heat balances through the definitions of heat capacity rates and the heat exchanger effectiveness.

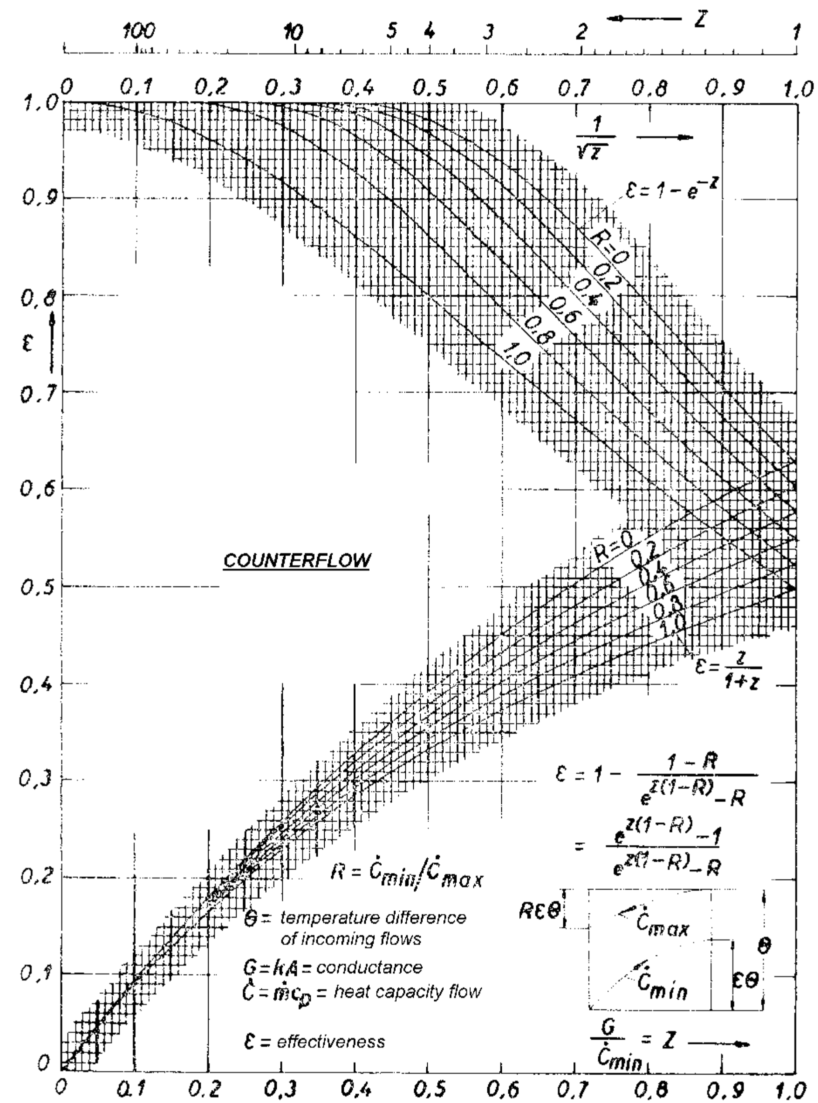
$$n = \frac{\ln\left[\left(1-\frac{\dot{C}_{\min}}{\dot{C}_{\max}}\right)\frac{\varepsilon}{1-\varepsilon}+1\right]}{\ln\left[\frac{1-\frac{\dot{C}_{\min}}{\dot{C}_{\max}}\varepsilon_e}{1-\varepsilon_e}\right]}$$

where ε = the heat exchanger effectiveness of the whole set of units

ε_e = the heat exchanger effectiveness of a single unit (with an assumption that all units are identical)

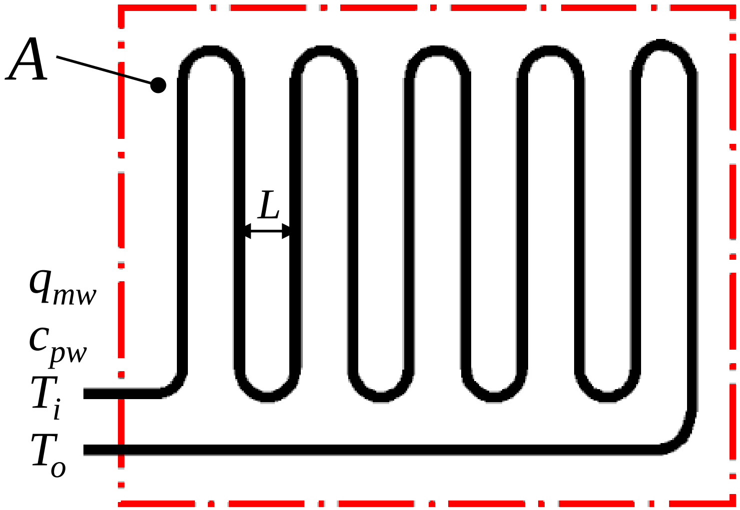
Sizing diagram

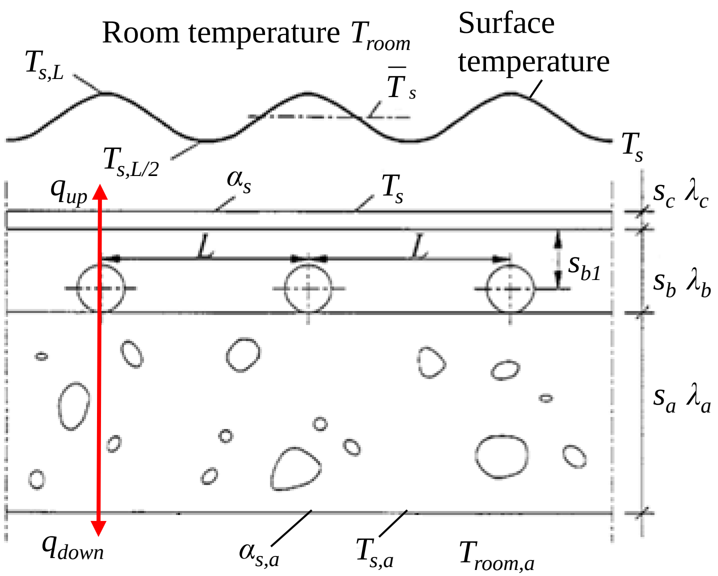




Sizing of floor (and ceiling) heating

- Sizing = choosing the required floor heating area (A) and water mass flow (q_{mw}) to release thermal power equal to heating load into the target room
- Heat release is determined by surface temperature (T_s), which is at highest on the pipe ($T_{s,L}$) and at the lowest between the pipes ($T_{s,L/2}$), the mean value being ($\overline{T}_s$).
- Heat flux [W/m^2] both upwards (q_{up}) and downwards (q_{down}) takes place. The heat flux q_{down} is significant in condition that there is no insulation below the pipework.
- T_i = 30...45°C, $T_i - T_o$ = 5...10°C
- The surface temperature should fall within the range T_s = 25...30°C





Sizing floor heating as a process

1. Heating load
2. Locations for piping and manifolds (routing)
3. Fixing the supply water temperature (35…45 °C)
4. Determining the spacing of pipes (*L*)
   – Calculating surface temperatures and heat release rates using the sizing equations
   – Comparison: heat release vs. allowable surface temperatures
   – Adjustment of spacing (if required)
5. Determing the required area and water mass flow
6. Sizing the network
7. Balancing the network

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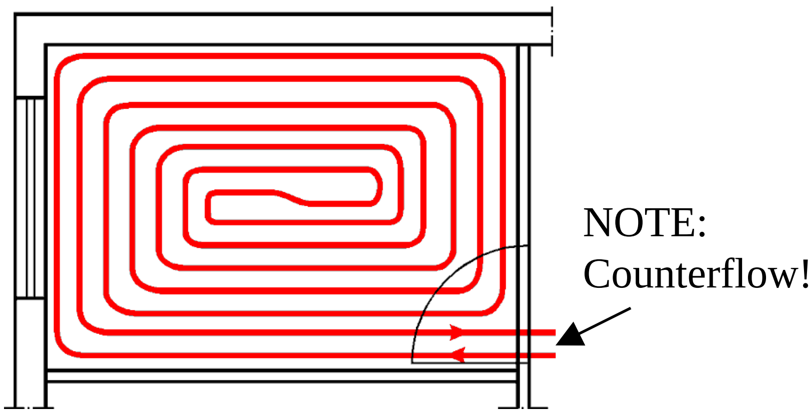
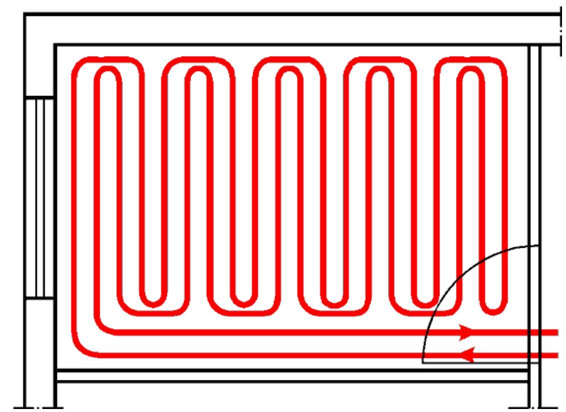
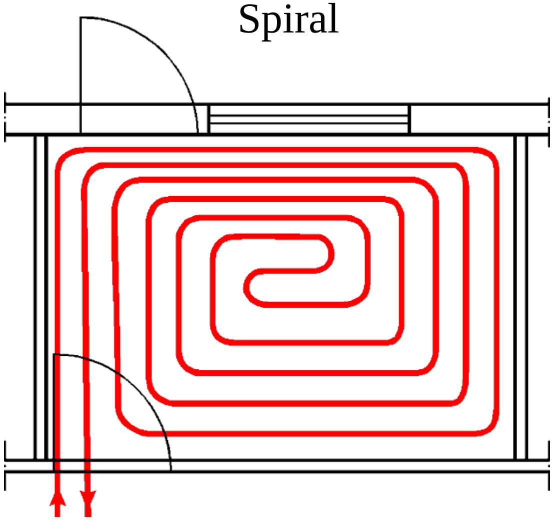
Layout patterns for floor heating



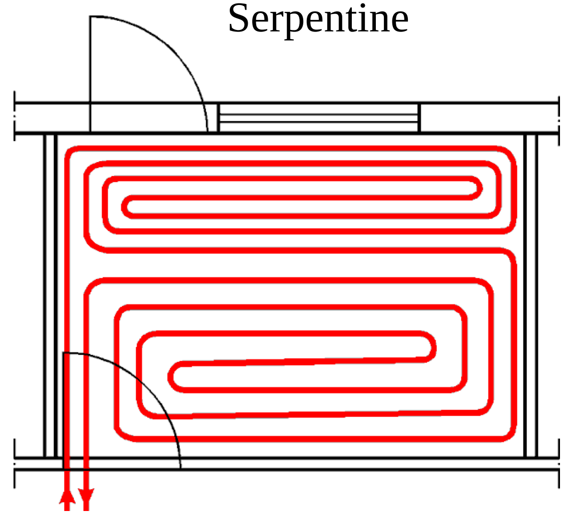
Spiral



Serpentine



Spiral counterflow with dense spacing close to cold zone (window)



Double spiral counterflow with dense spacing close to cold zone (window)

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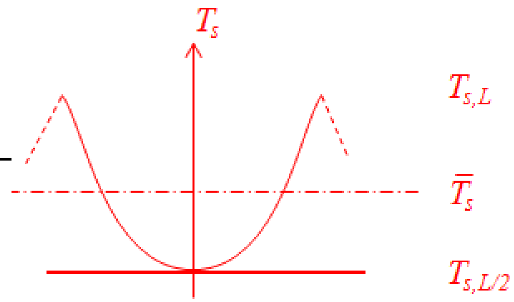
Calculation of surface temperature

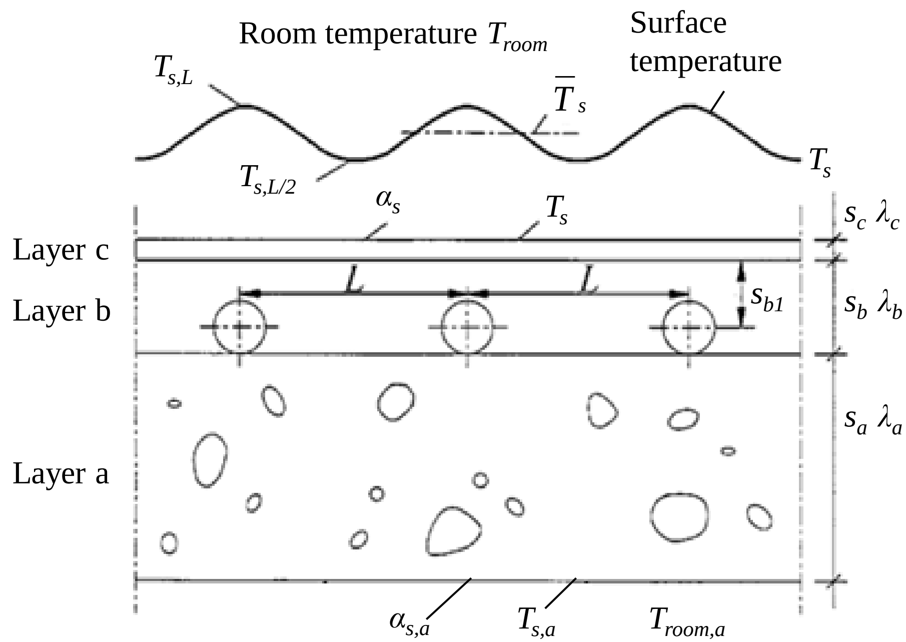


The equations are derived for a surface element from energy conservation.

$$\overline{T}_s = T_{s,L/2} + \frac{1}{3}\left(T_{s,L} - T_{s,L/2}\right)$$

where

$$\begin{cases} T_{s,L/2} = T_{room} + \dfrac{U_{up}}{\alpha_s}\left[\dfrac{\overline{T}_w - T_{room}}{\cosh(\frac{mL}{2})} + \left(\dfrac{U_{down}\left(T_{room} - T_{room,a}\right)}{U_{up} + U_{down}}\right)\cdot\left(\dfrac{1}{\cosh(\frac{mL}{2})} - 1\right)\right] + \dfrac{U_{down}}{\alpha_{s,a}}\left(T_{room} - T_{room,a}\right) \\ T_{s,L} = T_{room} + \dfrac{U_{up}}{\alpha_s}\left(\overline{T}_w - T_{room}\right) \\ \overline{T}_w = \dfrac{T_i + T_o}{2} \\ m = \sqrt{\dfrac{U_{down} + U_{up}}{s_b \lambda_b}} \\ R_{up} = \dfrac{1}{U_{up}} = \dfrac{s_{b1}}{\lambda_b} + \dfrac{s_c}{\lambda_c} + \dfrac{1}{\alpha_s} \\ R_{down} = \dfrac{1}{U_{down}} = \dfrac{s_a}{\lambda_a} + \dfrac{1}{\alpha_{s,a}} \end{cases}$$



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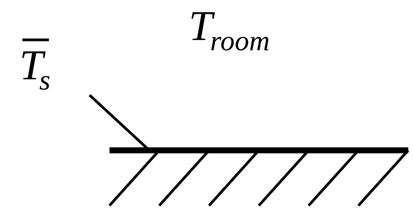
Heat release and sizing equations

Heat flux from surface to room is calculated from:

$$q = \alpha\left(\overline{T}_s - T_{room}\right) = \left(\alpha_r + \alpha_c\right)\left(\overline{T}_s - T_{room}\right)$$



where α_r = heat transfer coefficient for radiation [W/m^{2}K]
α_c = heat transfer coefficient for convection [W/m^{2}K]

<u>Useful default values for heat transfer coefficients:</u>

- α_r = 6...7 W/m^{2}K (depending on the temperatures or surrounding surfaces)
- α_c = 4...5 W/m^{2}K (floor)
- α_c = 2...3 W/m^{2}K (ceiling)
- $\alpha = \alpha_r + \alpha_c$ = 11.6 W/m^{2}K (design heat transfer coefficient provided by Uponor Oy)

Standardized sizing equation (from experiments):

$$q = C\theta^r$$

where r = 1.03...1.12

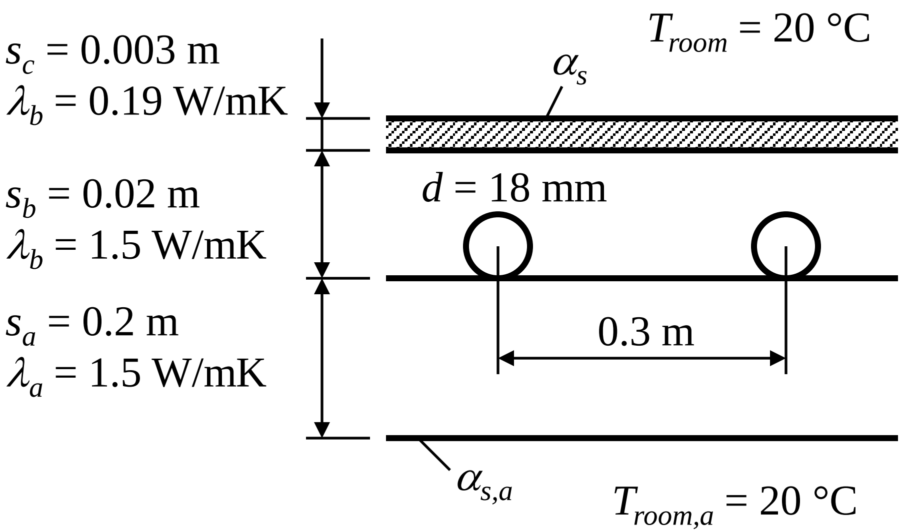
Coefficients of the sizing equation depend on installation (surface material, depth, distance between pipes) and are provided by manufacturers.

Example

Determine the area and supply water mass flow for the floor heating besides assuming that the supply water temperature is 45°C and the return water temperature is 35 °C. The design heating load of the upper space is 500 W.

Heat transfer coefficients:

$$\begin{cases} \alpha_r = 6.4 \text{ W/m}^2\text{K} \\ \alpha_{c,a} = 2.2 \text{ W/m}^2\text{K} \\ \alpha_{c,s} = 4.2 \text{ W/m}^2\text{K} \end{cases}$$



Solution – I

1) Total heat transfer coefficients:

$$\begin{cases} \alpha_r = 6.4\ \mathrm{W/m^2K} \\ \alpha_{c,a} = 2.2\ \mathrm{W/m^2K} \\ \alpha_{c,s} = 4.2\ \mathrm{W/m^2K} \end{cases} \Rightarrow \quad \begin{aligned} \alpha_{s,a} &= (6.4+2.2)\ \mathrm{W/m^2K} = 8.7\ \mathrm{W/m^2K} \\ \alpha_s &= (6.4+4.2)\ \mathrm{W/m^2K} = 10.6\ \mathrm{W/m^2K} \end{aligned}$$

2) Mean temperature of water:

$$\overline{T}_w = \frac{(45+35)\,°\mathrm{C}}{2} = 40\ °\mathrm{C}$$

3) Heat transfer coefficients U_{down} and U_{up}:

$$s_{b1} = s_b - \frac{d}{2} = 0.02\ \mathrm{m} - \frac{0.018\ \mathrm{m}}{2} = 0.11\ \mathrm{m}$$

$$\frac{1}{U_{up}} = \frac{s_{b1}}{\lambda_b} + \frac{s_c}{\lambda_c} + \frac{1}{\alpha_s} = \frac{0.11\ \mathrm{m}}{1.5\ \frac{\mathrm{W}}{\mathrm{mK}}} + \frac{0.003\ \mathrm{m}}{0.19\ \frac{\mathrm{W}}{\mathrm{mK}}} + \frac{1}{10.6\ \frac{\mathrm{W}}{\mathrm{m^2K}}} = \frac{1}{8.51\ \frac{\mathrm{W}}{\mathrm{m^2K}}}$$

$$\Rightarrow U_{up} = 8.51\ \frac{\mathrm{W}}{\mathrm{m^2K}},\ \text{correspondingly}:\ U_{down} = 4.01\ \frac{\mathrm{W}}{\mathrm{m^2K}}$$

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Solution – II

4) Surface temperatures for upper space:

$$m=\sqrt{\frac{U_{down}+U_{up}}{s_b\lambda_b}}=\sqrt{\frac{(8.51+4.01)\,\dfrac{\mathrm{W}}{\mathrm{m^2K}}}{0.02\,\mathrm{m}\cdot 1.5\,\dfrac{\mathrm{W}}{\mathrm{mK}}}}=20.43$$

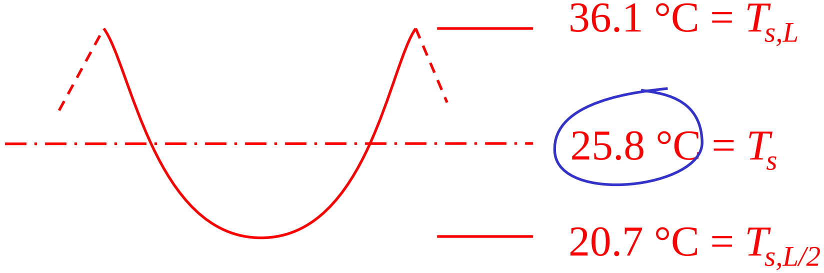
$$\cosh\left(\frac{mL}{2}\right)=\cosh\left(\frac{20.43\cdot 0.3\,\mathrm{m}}{2}\right)=10.73$$

Considering $T_{room}=T_{room,a}=20°\mathrm{C}$:

$$T_{s,L/2}=T_{room}+\frac{U_{up}}{\alpha_s}\left[\frac{\overline{T}_w-T_{room}}{\cosh(\frac{mL}{2})}-1\right]=20°\mathrm{C}+\frac{8.51\,\dfrac{\mathrm{W}}{\mathrm{m^2K}}}{10.6\,\dfrac{\mathrm{W}}{\mathrm{m^2K}}}\left[\frac{(40-20)°\mathrm{C}}{10.73}-1\right]=20.7°\mathrm{C}$$

$$T_{s,L}=T_{room}+\frac{U_{up}}{\alpha_s}\left(\overline{T}_w-T_{room}\right)=20°\mathrm{C}+\frac{8.51\,\dfrac{\mathrm{W}}{\mathrm{m^2K}}}{10.6\,\dfrac{\mathrm{W}}{\mathrm{m^2K}}}(40-20)°\mathrm{C}=36.1°\mathrm{C}$$

$$\overline{T}_s=T_{s,L/2}+\frac{1}{3}\left(T_{s,L}-T_{s,L/2}\right)=20.7°\mathrm{C}+\frac{1}{3}(36.1-20.7)°\mathrm{C}=25.8°\mathrm{C}$$



Solution – III

5) Surface temperatures for lower space:

$$m = \sqrt{\frac{U_{down} + U_{up}}{s_a \lambda_a}} = 6.46$$

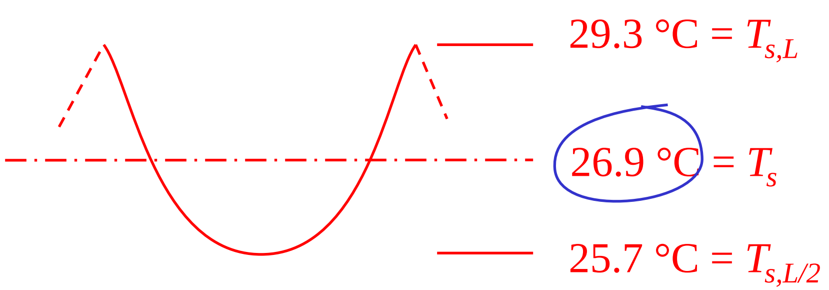
$$\cosh\left(\frac{mL}{2}\right) = 1.51$$

Considering $T_{room} = T_{room,a} = 20°\mathrm{C}$:

$$T_{s,L/2} = T_{room,a} + \frac{U_{down}}{\alpha_{s,a}}\left[\frac{\overline{T}_w - T_{room,a}}{\cosh(\frac{mL}{2})} - 1\right] = 25.7°\mathrm{C}$$

$$T_{s,L} = T_{room,a} + \frac{U_{down}}{\alpha_{s,a}}\left(\overline{T}_w - T_{room,a}\right) = 29.3°\mathrm{C}$$

$$\overline{T}_s = T_{s,L/2} + \frac{1}{3}\left(T_{s,L} - T_{s,L/2}\right) = 26.9°\mathrm{C}$$



Solution – IV

6) Heat release rates:

$$\text{Upper space}: q_{up} = \alpha_s\left(\overline{T}_s - T_{room}\right) = 10.6\,\frac{\text{W}}{\text{m}^2\text{K}}\cdot(25.8-20)\text{K} = 61.7\,\frac{\text{W}}{\text{m}^2}$$

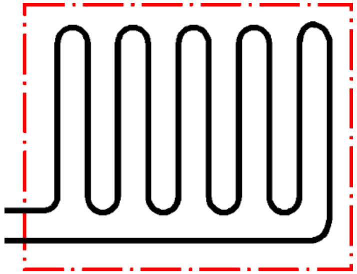
$$\text{Lower space}: q_{down} = \alpha_{s,a}\left(\overline{T}_s - T_{room,a}\right) = 8.7\,\frac{\text{W}}{\text{m}^2\text{K}}\cdot(26.9-20)\text{K} = 59.5\,\frac{\text{W}}{\text{m}^2}$$

$$\text{Total}: q = q_{up} + q_{down} = (61.7+59.5)\frac{\text{W}}{\text{m}^2} = 121.1\,\frac{\text{W}}{\text{m}^2}$$

7) Required heat release area and supply water mass flow rate:

$$A = \frac{\Phi_{up}}{q_{up}} = \frac{500\ \text{W}}{61.7\,\frac{\text{W}}{\text{m}^2}} = \underline{\underline{8.1\,\text{m}^2}}$$

$$q_{mw} = \frac{\Phi}{c_{pw}\left(T_i - T_o\right)} = \frac{0.001\,\frac{\text{kW}}{\text{W}}\cdot 121.1\,\frac{\text{W}}{\text{m}^2}\cdot 8.1\,\text{m}^2}{4.186\,\frac{\text{kJ}}{\text{kgK}}(45-35)\text{K}} = \underline{\underline{0.023\,\frac{\text{kg}}{\text{s}} = 85\,\frac{\text{kg}}{\text{h}}}}$$



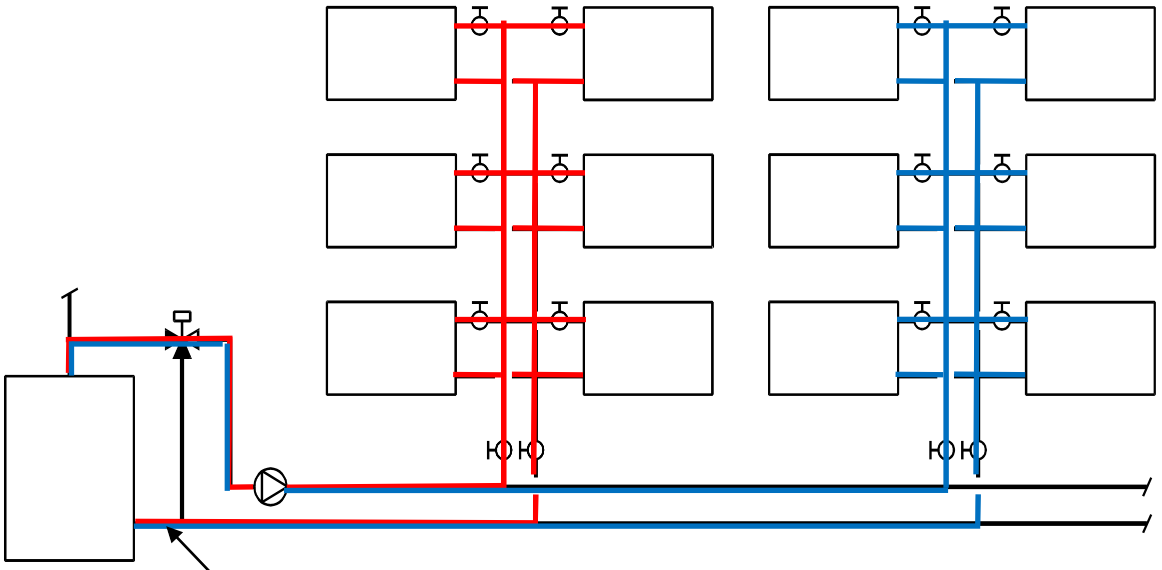
Sizing of heat distribution network

- Sizing = choosing appropriate diameters of pipes to distribute a thermal power equal to heating load (i.e. fluid flow at design temperature difference) into the target building and choosing a prime mover for the heat distribution
- Theoretical principle: The fluid seeks the ”easiest” flow path (i.e. the path with the lowest pressure drop). The pressure drop of each flow path is balanced to equal. The pipe sizes and valves have to be chosen so that the flow is distributed to each radiator/convector in a desired proportion (↔ desired heat flow).

Loop 1: Δp_1, q_{m1}

Loop 2: Δp_2, q_{m2}

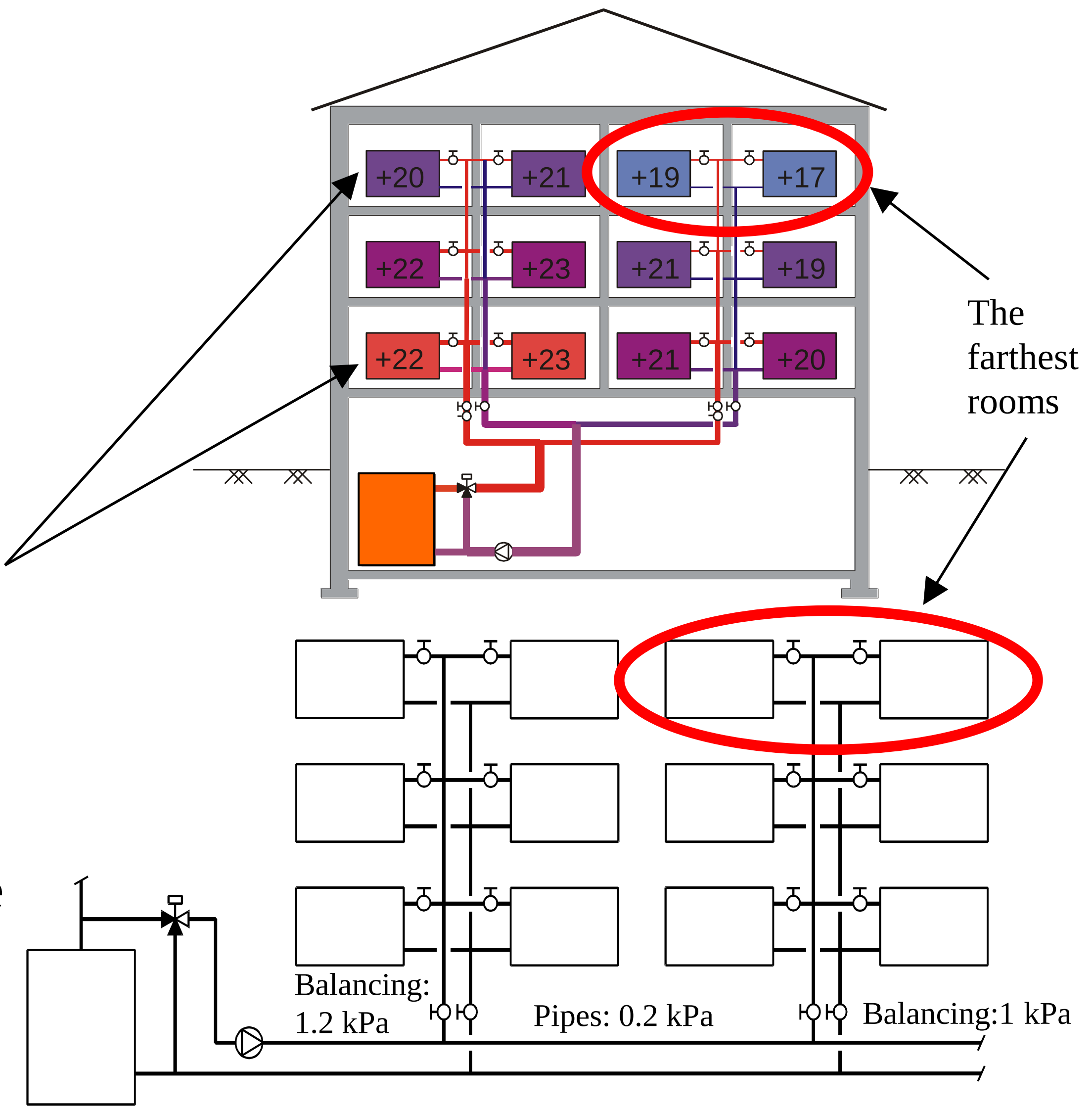
$$\begin{cases} q_m = q_{m1} + q_{m2} \\ \Delta p_1 = \Delta p_2 \end{cases}$$

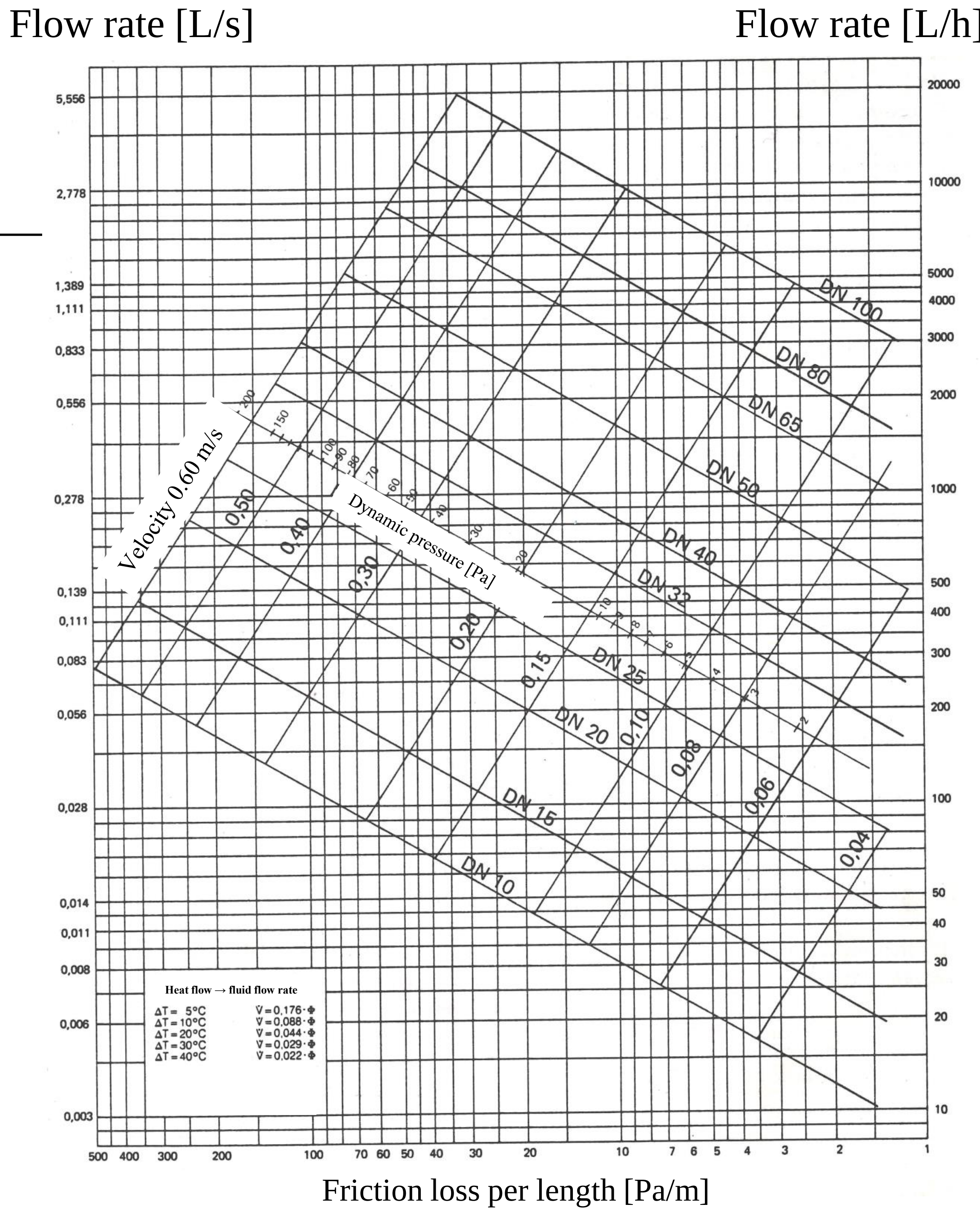


Design conditions: All the fluid flow is circulated via the heat source.

Balancing of heat distribution network

- Balancing = establishing a desired total pressure drop using valves.
- The total pressure drop is designated by the longest loop (= largest pressure drop).
- In case of an unbalanced network the farthest rooms will remain cold whereas the closes rooms will be overheated (→ increased energy demand).
- The typical pressure drop of a radiator valve is 2...4 kPa. The typical pressure drop of a balancing valve is ≈ 1 kPa.





Pipe sizing based on friction loss

- Useful principle:
  Experiments show that to prevent noise generation and to make the appropriate selection of valves possible, the pipes should be chosen so that the friction loss per length

$$R = \frac{\Delta p_f}{L} \leq 50 \, \frac{\text{Pa}}{\text{m}}$$

  where L = length of pipe, m
- The chart visualizes the key relations between standardized pipe sizes (steel), fluid velocities, pressure drops and flow rates.

Accounting the pressure drop of pipe components

The pressure drop of pipe components (bends, elbows etc.) depends on turbulence. The impact is accounted as a fraction of the dynamic pressure (p_d) using the minor loss coefficient K (sometimes ξ):

$$\Delta p = K \frac{1}{2} \rho v^2 = K \cdot p_d$$

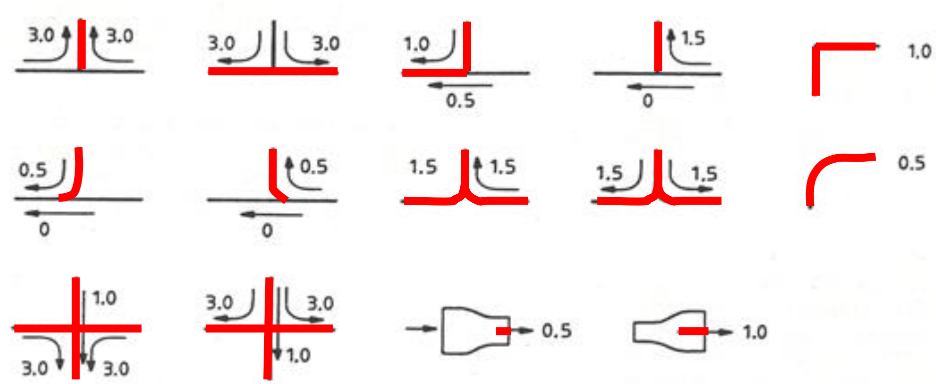
The greatest minor loss coefficient is associated with sudden change of flow velocity and direction.

In the case of reductions and expansions, the minor loss is calculated on the basis of the *greater fluid velocity*.

Be careful not to double account a minor loss within the network to be designed!

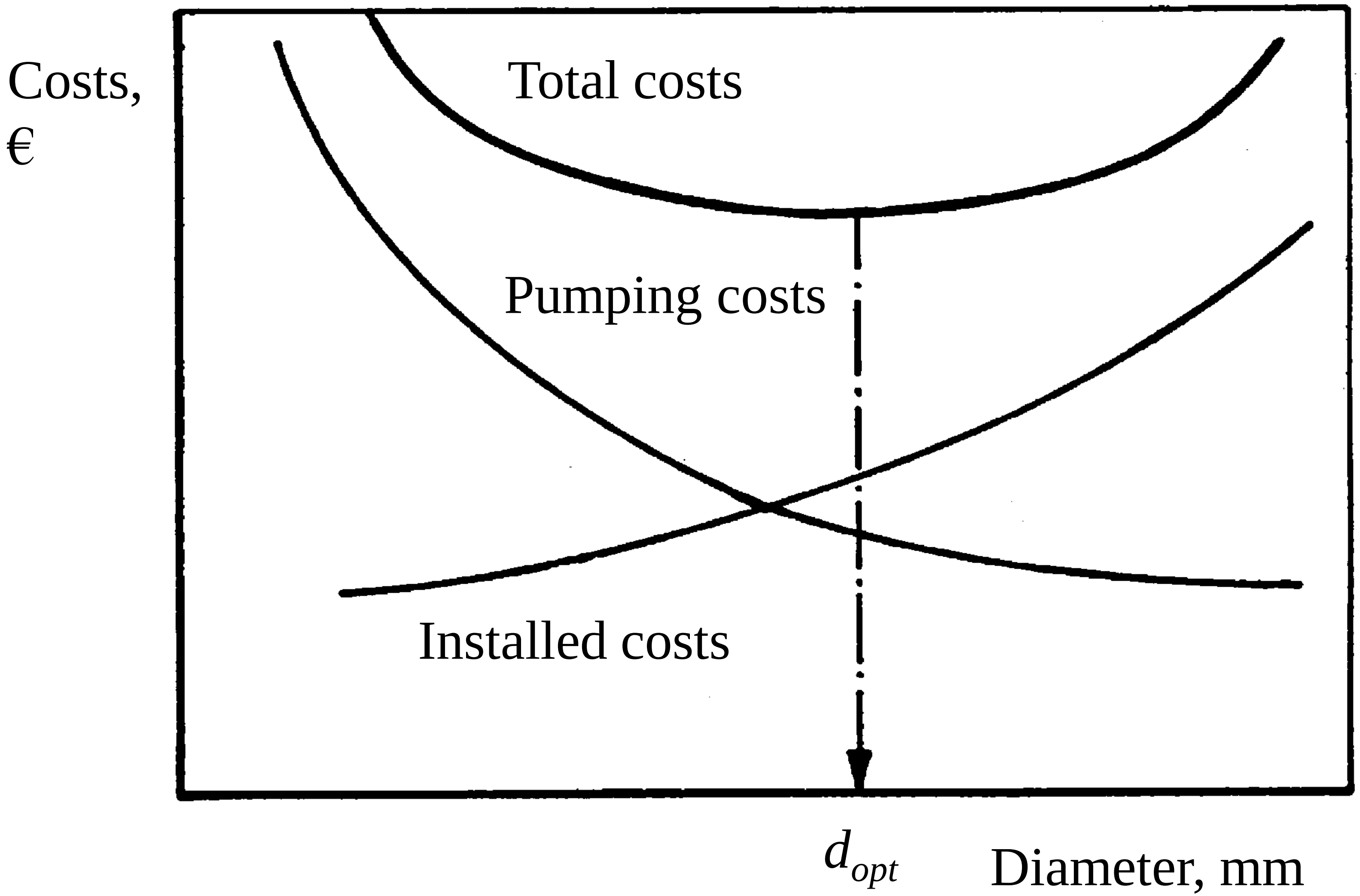
Self-learning: Find data on minor losses from

- ASHRAE DATA & GUIDEBOOK (USA)
- RECKNAGEL & SPRENGER (GERMANY)
- GIBS GUIDE (UK)
- VUS HANDBOKEN (Sweden)
- EngineeringToolbox



The branch in which the minor loss is accounted, is highlighted red.

Cost optimality of heat distribution network



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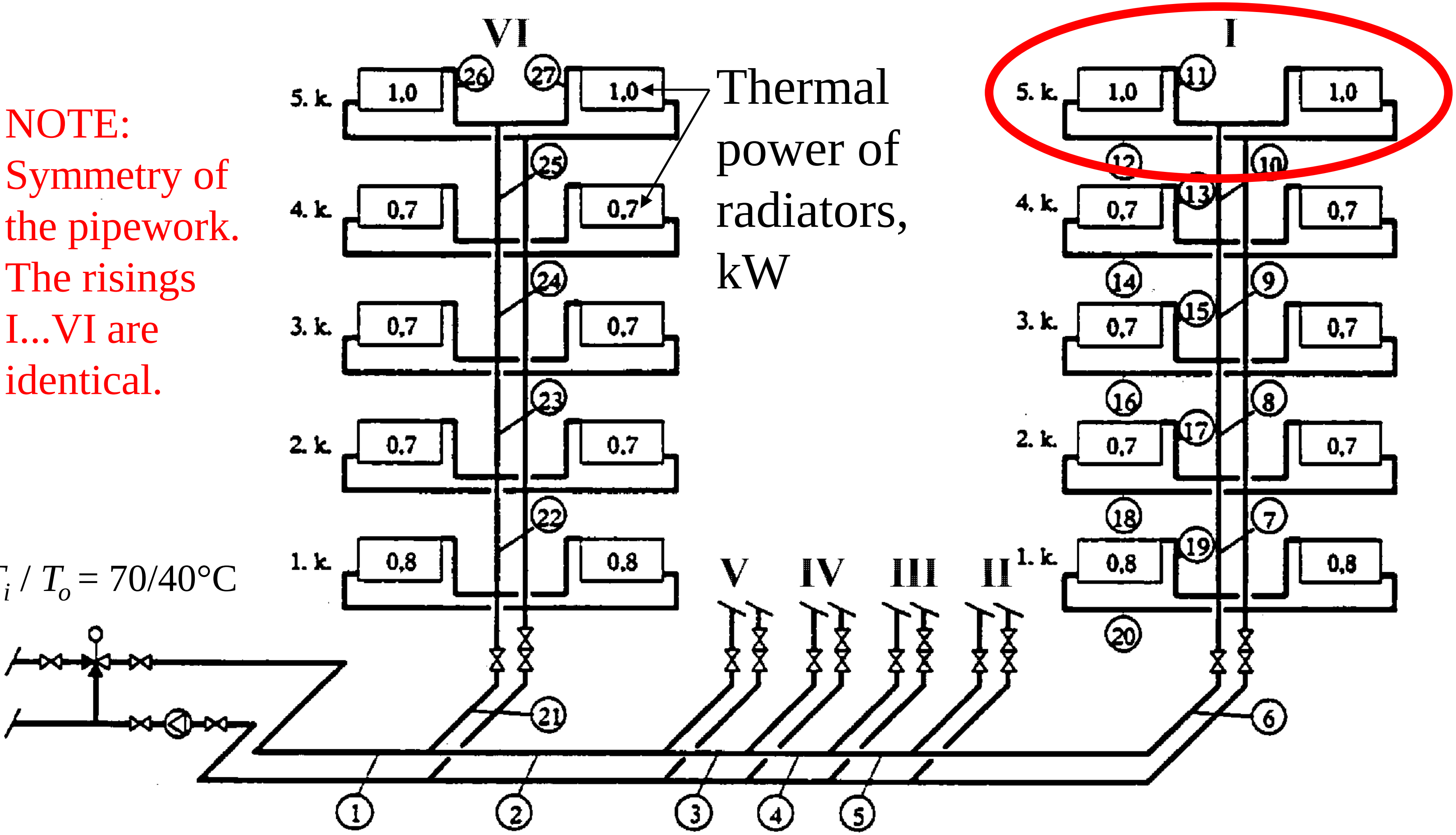
Sizing of heat distribution network in a nutshell

1) Build calculation sheet.
2) Name and number pipes and indicate pipe lengths.
3) Calculate the flow rates (design thermal power & temperatures)
4) Determine pipe sizes: target $R \leq 50$ Pa/m
5) Calculate pressure losses for each loop:
   - Choose pressure drop for radiator/convector + valve: 2…4 kPa
   - Determine the pressure drop (= friction + minor losses).
   - Determine the longest loop (= pick the largest pressure drop)
6) Calculate the required pressure drops for balancing valves
   - Choose pressure drop for the balancing valve of the farthest rising: ≈1 kPa
   - Calculate the pressure drop required by other risings.
7) Select pump and calculate its power demand.

Example: Sizing of a two pipe system

NOTE: Symmetry of the pipework. The risings I...VI are identical.



T_i / T_o = 70/40°C

Solution – I

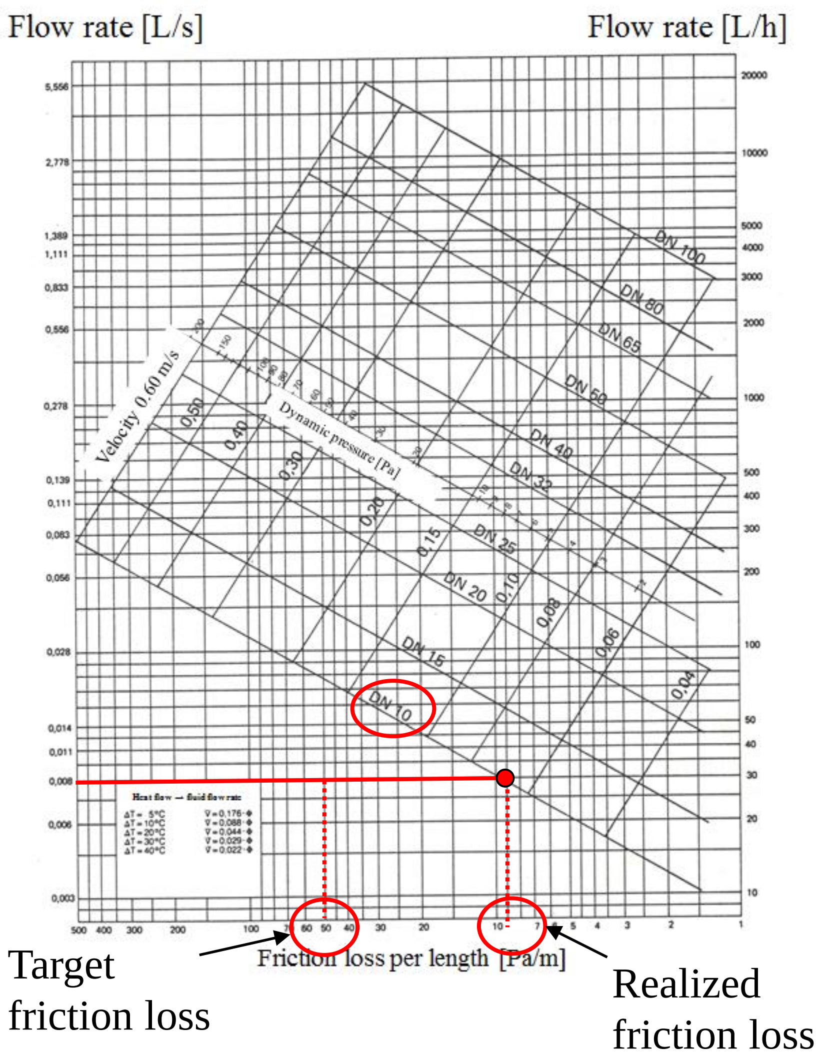
Example of applying the design routine: sections 11 and 12 (the longest flow path)

1) Volumetric water flow rate:
   - Average temperature (70/40)°C = 55°C
     $\rightarrow \rho_w = 986\ \text{kg/m}^3$
   - Specific heat (55°C) $\longrightarrow c_{pw} = 4.18\ \text{kg/m}^3$

$$q_V = \frac{q_m}{\rho_w} = \frac{\Phi}{c_{pw}\Delta T}\cdot\frac{1}{\rho_w}$$

$$= \frac{1\,\text{kW}}{4.18\,\frac{\text{kJ}}{\text{kgK}}\cdot(70-40)\text{K}}\cdot\frac{1}{0.986\,\frac{\text{kg}}{\text{L}}} = 0.008\,\frac{\text{L}}{\text{s}}$$

2) Pipe size 11 and 12 (target $R \leq 50$ Pa/m):
   - From graph: DN10 (the smallest available size)
   - From graph: realized friction loss R = 9 Pa/m
   - From graph: fluid velocity v = 0.07 m/s



Solution – II

3) Sum of minor losses:

- Assumption: Minor loss coefficient of radiator 2.5
- Section 11: T-branch + 2 rounded elbows + radiator:

$$\sum K_{11} = 3.0 + 2 \cdot 0.5 + 2.5 = 6.5$$

- Section 12: 2 rounded elbows + T-branch

$$\sum K_{12} = 2 \cdot 0.5 + 3.0 = 4.0$$

4) Dynamic pressure:

$$\Delta p_d = \frac{1}{2}\rho v^2 = \frac{1}{2} \cdot 990.2 \frac{\text{kg}}{\text{m}^3} \cdot \left(0.07 \frac{\text{m}}{\text{s}}\right)^2 = 2.4 \text{ Pa}$$

5) Pressure drop:

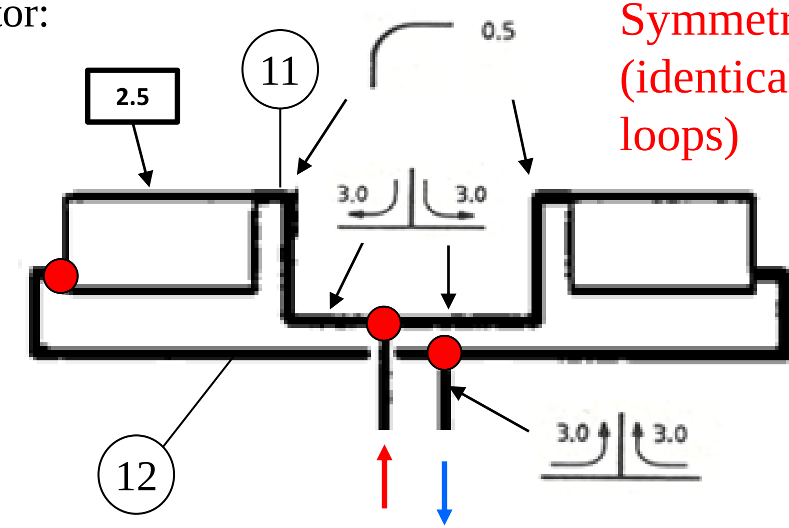
- Minor loss:

$$\Delta p = \left(\sum K_{11} + \sum K_{12}\right) \cdot p_{dyn} = (6.5 + 4.0) \cdot 2.4 \text{ Pa} = 25 \text{ Pa}$$

- Friction loss: $L = 2$ m $\rightarrow \Delta p_f = RL = 9$ Pa/m · 2 m = 18 Pa
- Total pressure drop (sections 11 and 12): (25 + 18) Pa = 43 Pa
- Choose: pressure drop of valve = 2 kPa

  → Total pressure drop: (2000 + 43) Pa = 2043 Pa

NOTE: Symmetry (identical loops)



● = boundary of the numbered pipe

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Example of calculation sheet

Section	Φ	q_V	*DN*	*R*	*L*	ΣK	p_d		Δp
	kW	l/s	mm	Pa/m	m		Pa	Pa	Pa
11,12	1.0	0.008	10	8	2	10.5	2.4	2000	2043
10	2.0	0.016	10	29	5	0.5	10.1		150
9	3.4	0.027	15	22	5	0.5	11.8		116
8	4.8	0.039	15	43	5	0.5	21.7		226
7	6.2	0.050	15	70	5	0.5	37.5		369
6	7.8	0.063	20	25	8	6.5	17.3	1000	1312
5	15.6	0.126	25	26	5	0.5	26.5		143
4	23.4	0.188	25	53	5	0.5	57.7		294
3	31.2	0.251	32	24	5	0.5	37.5		139
2	39.0	0.314	32	33	5	0.5	50.5		190
1	46.8	0.377	32	50	5	16.0	77.8		1495
								TOT	**6477**

Thermostatic valve of the farthest radiators.

Balancing valve of the farthest rising.

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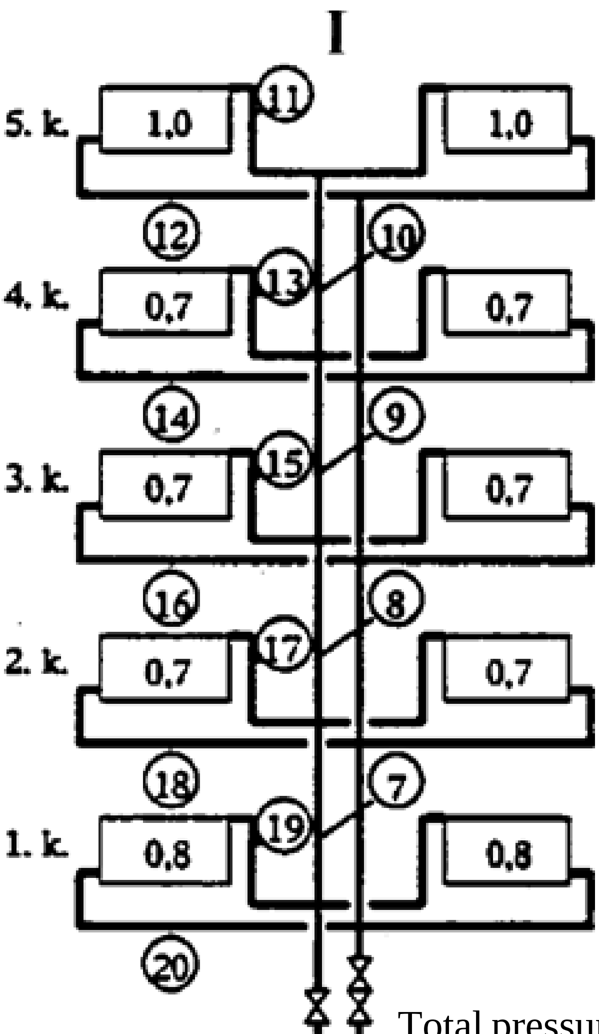
Solution: Balancing the first rising



Pressure drops by section:	Required pressure drops for radiator valves (to obtain Δp = 2904 Pa):
43 Pa	2000 Pa (chosen)
36 Pa	2000 + 150 + (43 – 36) = 2157 Pa
36 Pa	2150 + 116 + (43 – 36) = 2273 Pa
36 Pa	2266 + 226 + (43 – 36) = 2499 Pa
44 Pa	2492 + 369 + (43 – 44) = 2860 Pa

$$\text{Total pressure drop of rising I}: \Delta p = \sum_{i=7}^{12} \Delta p_i = 369 + 226 + 116 + 150 + 2000 + 43 = 2904 \text{ Pa}$$

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Summary

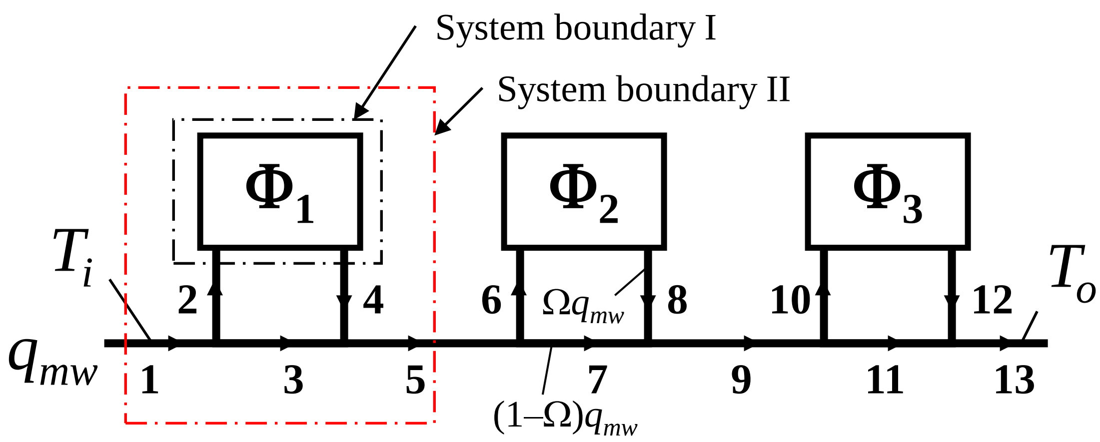
- The rest of the distribution network is sized and balanced in a corresponding manner. Because risings II...VI are identical to rising I, their pipe sizes and balancing values are the same as with rising I.
- The balancing valves are adapted to provide the network with the total pressure drop 6477 Pa. Their sizes are chosen as identical with the pipe diameter. In the present example, the volumetric flow rate and the pressure drop of the balancing valve of rising VI are 0.063 L/s and 1765 Pa, respectively.
- The pressure drops of the boiler loop and the mixing valve are calculated in a corresponding manner and added to the total pressure for the selection of circulation pump. The mixing valve should represent ca. 50 % of the pressure drop of the boiler loop.
- The present example does not include the impact of pressure difference due to difference of temperature (density) between supply and return water (aka *natural circulation*).

Tools for sizing one-pipe systems – I

<u>Tool 1:</u>
Fixed proportion of passage (Ω)

$$\text{Flow rate}: q_{mw} = \frac{\Phi}{c_{pw}(T_i - T_o)}$$

$$\text{where } \Phi = \sum_i \Phi_i$$



Return water temperature after radiator/convector:

Balance I:

$$\Omega q_{mw} c_{pw}(T_2 - T_4) = \Phi_1 \Leftrightarrow T_4 = T_2 - \frac{\Phi_1}{\Omega q_{mw} c_{pw}} = T_2 - \frac{\Phi_1}{\Omega \Phi}(T_i - T_o)$$

Supply water temperature before radiator/convector:

Balance II:

$$q_{mw} c_{pw}(T_1 - T_5) = \Phi_1 \Leftrightarrow T_5 = T_1 - \frac{\Phi_1}{q_{mw} c_{pw}} = T_1 - \frac{\Phi_1}{\Phi}(T_i - T_o)$$

Tools for sizing one-pipe systems – II

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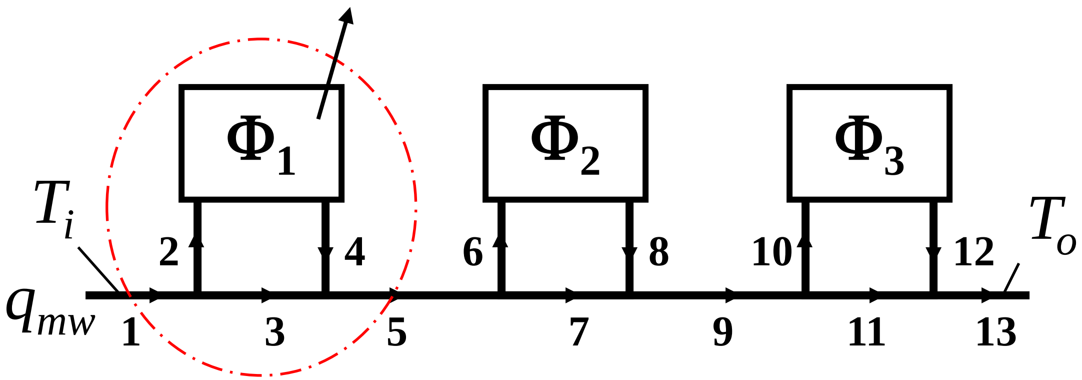
Tool 2:

Fixed temperature drop (ΔT)

$$T_1 = T_2 = T_3\,,$$
$$T_4 - T_2 = \Delta t = \text{const}$$
$$\Rightarrow T_4 = T_1 - \Delta T$$



$$\text{Flow rate}: q_{mw} = \frac{\Phi}{c_{pw}(T_i - T_o)}, \quad \text{where } \Phi = \sum_i \Phi_i$$

Balance:

$$\Phi_1 = q_{mw} c_{pw}\left(T_1 - T_5\right) \Rightarrow T_6 = T_5 = T_1 - \frac{\Phi_1}{q_{mw} c_{pw}} = T_1 - \frac{\Phi_1}{\Phi}\left(T_i - T_o\right)$$

$$T_8 = T_6 - \Delta T = T_1 - \frac{\Phi_1}{\Phi}\left(T_i - T_o\right) - \Delta T$$

$$T_9 = T_5 - \frac{\Phi_2}{\Phi}\left(T_i - T_o\right) = T_1 - \frac{\Phi_1 + \Phi_2}{\Phi}\left(T_i - T_o\right)$$

Etc.

Self-learning: Reflect on the consequences of coupling the heat exchangers in parallel/series (one pipe vs. two pipe systems). Specifically: What is the impact on the heat release (physical size) of heat exchangers and what are the consequences for sizing the radiator/convector network?

Gravity heating system

- Based on the utilization of natural circulation. The driving force is defined as

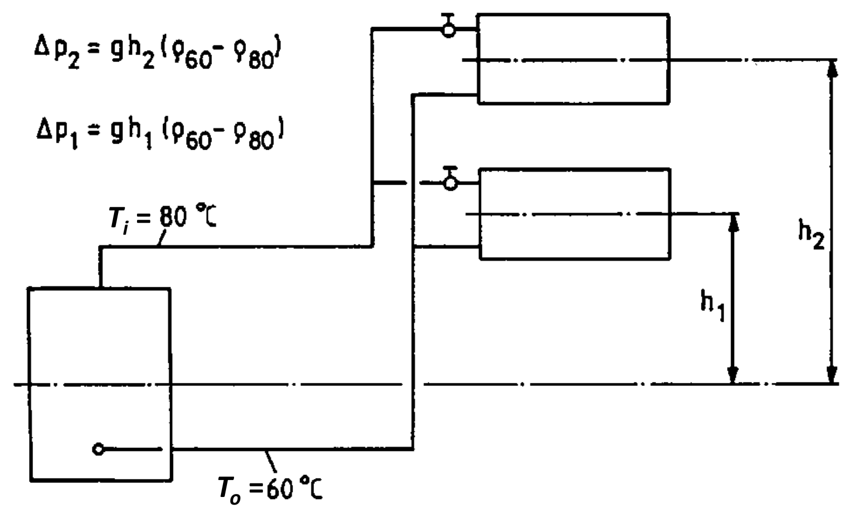
$$\Delta p = gh(\rho_o - \rho_i); \quad \rho_o > \rho_i$$

where h = elevation between radiator (centerline) and boiler (centerline), m

+ Works without electrical power input

− Weak driving force $\Rightarrow$ large pipes

- Sizing and balancing:
  - The driving force is calculated separately for each radiator loop.
  - The pipe diameters are chosen so that the total pressure drop does not exceed the driving force of the target loop.
  - The driving force and the pressure drop are set equal by adjusting radiator valve.



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Sizing of bladder expansion tank

Sizing = choosing such a tank size (V_1) that is sufficient to compensate the expansion of water due to temperature rise.

Sizing equations (ideal gas law):

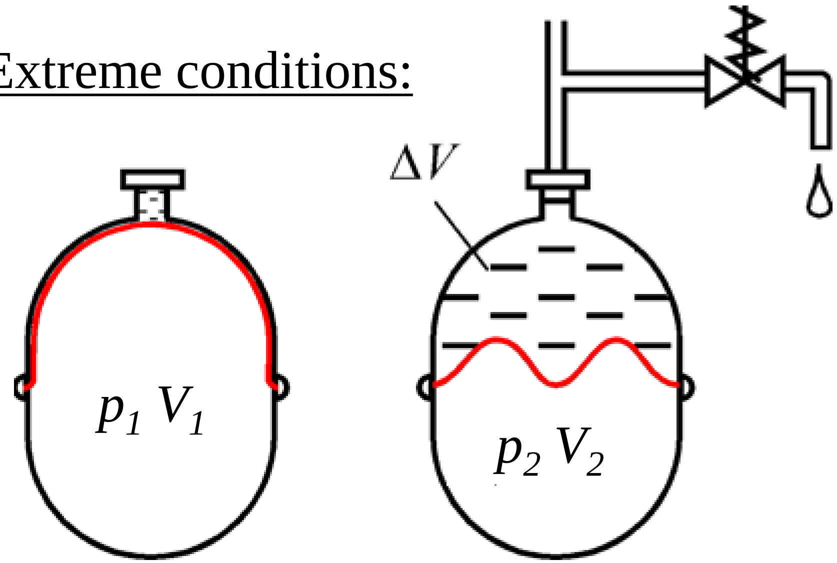
$$p_1 V_1 = p_2 V_2 \Rightarrow \frac{V_1}{V_2} = \frac{p_2}{p_1}$$

$$\Delta V = V_1 - V_2 = \text{Effective expansion volume}$$

$$\eta = \frac{\Delta V}{V_1} = \frac{V_1 - V_2}{V_1} = 1 - \frac{V_2}{V_1} = \frac{p_2 - p_1}{p_2} = \frac{\Delta p}{p_2}$$

$$V_1 = \frac{\Delta V}{\eta}$$

<u>Extreme conditions:</u>



Tank filled with air (minimum operational temperature e.g. 10°C, fill pressure e.g. 1.5 bar).

Both water and air within the tank volume (maximum operational temperature e.g. 90°C, maximum operational pressure e.g. 2.5 bar).

Rules of thumb (L/capacity of the heating plant in kW):

- 15 L/kW (general default)
- 12...13 L/kW (boiler plane)
- 9...12 L/kW (district heating)
- 4...5 L/kW (ventilation loop)

Example

Choose the size of bladder expansion tank with the following information:

- Water volume of the heat distribution network: 300 L
- Fill conditions: 10°C/1.5 bar
- Extreme operational conditions: 90°C/2.5 bar

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Solution

1. Water densities and specific volumes in extreme conditions:
   - $\rho_1 = \rho(10°C) = 999.7\ kg/m^3 \rightarrow\ v_1 = 1.0003\ m^3/kg$
   - $\rho_2 = \rho(90°C) = 965.3\ kg/m^3 \rightarrow\ v_2 = 1.0361\ m^3/kg$

2. Effective expansion volume:
   - proportional change of volume (the absolute tank size is to be chosen)

$$\frac{v_2 - v_1}{v_1} = \frac{(1.0361 - 1.0003)\frac{\mathrm{m}^3}{\mathrm{kg}}}{1.0003\frac{\mathrm{m}^3}{\mathrm{kg}}} = 0.036$$

$\rightarrow$ effective expansion volume $\Delta V = 0.036 \cdot 300\ \mathrm{L} = 10.8\ \mathrm{L}$

3. Tank size:
   - from sizing equations: $\eta = \frac{p_2 - p_1}{p_2} = \frac{(2.5 - 1.5)\,\mathrm{bar}}{2.5\,\mathrm{bar}} = 0.4$

$$\Rightarrow V_1 = \frac{\Delta V}{\eta} = \frac{10.8\,\mathrm{L}}{0.4} = \underline{\underline{27\,\mathrm{L}}}$$