Heating and Cooling Systems
EEN-E4002 (5 cr)

Distribution and auxiliary (ancillary) systems

Learning objectives

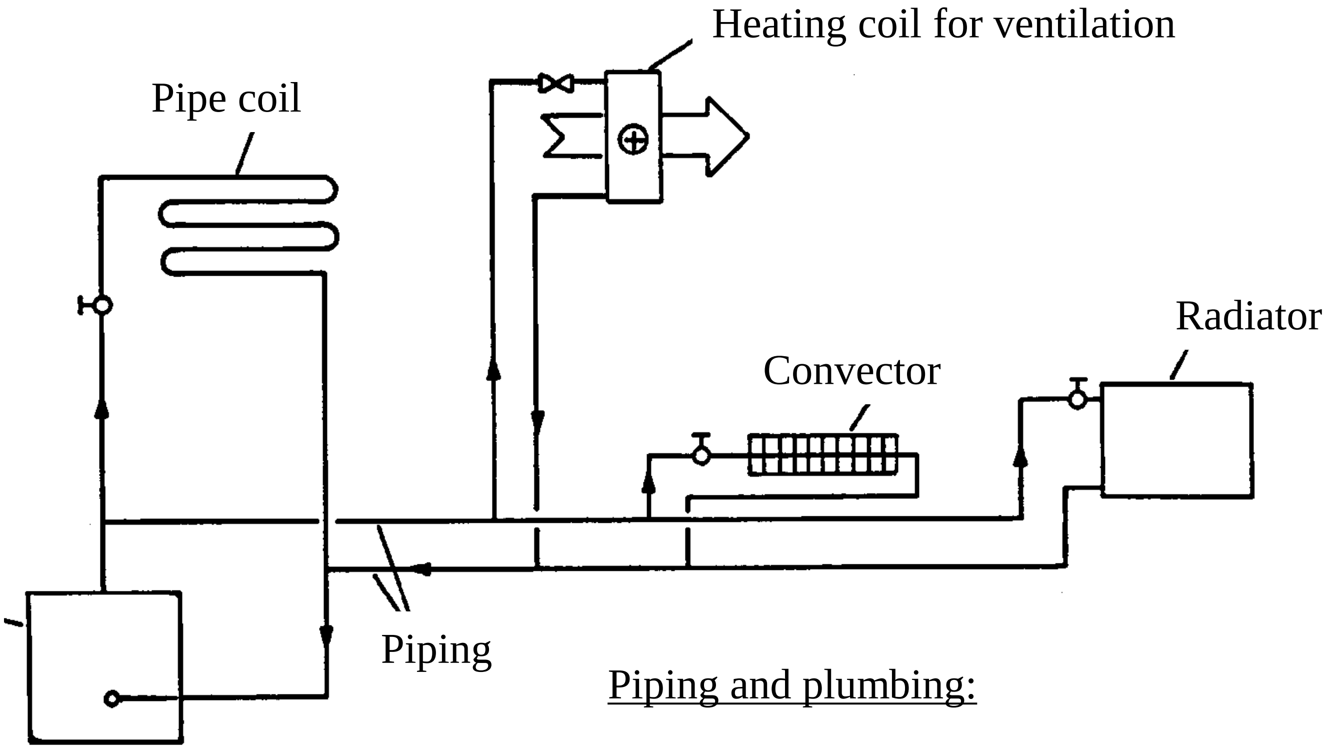
Student will learn to know

- the key terminology, technologies and systems related to heating and cooling energy distribution
- the key terminology and technologies for piping and prime movers (fans, pumps and compressors)

Lesson outline

1. Structure of heat distribution network
   - hydronic heating
   - air heating
   - coupling options for piping
2. Heat distribution systems
   - heat exchangers
   - heat distribution options for hydronic heating
   - heat distribution options for electric heating
3. Cooling energy distribution systems
4. Piping and fittings
5. Auxiliary (ancillary) systems
   - pumps and fans
   - compressors

Structure of heat distribution network – hydronic heating



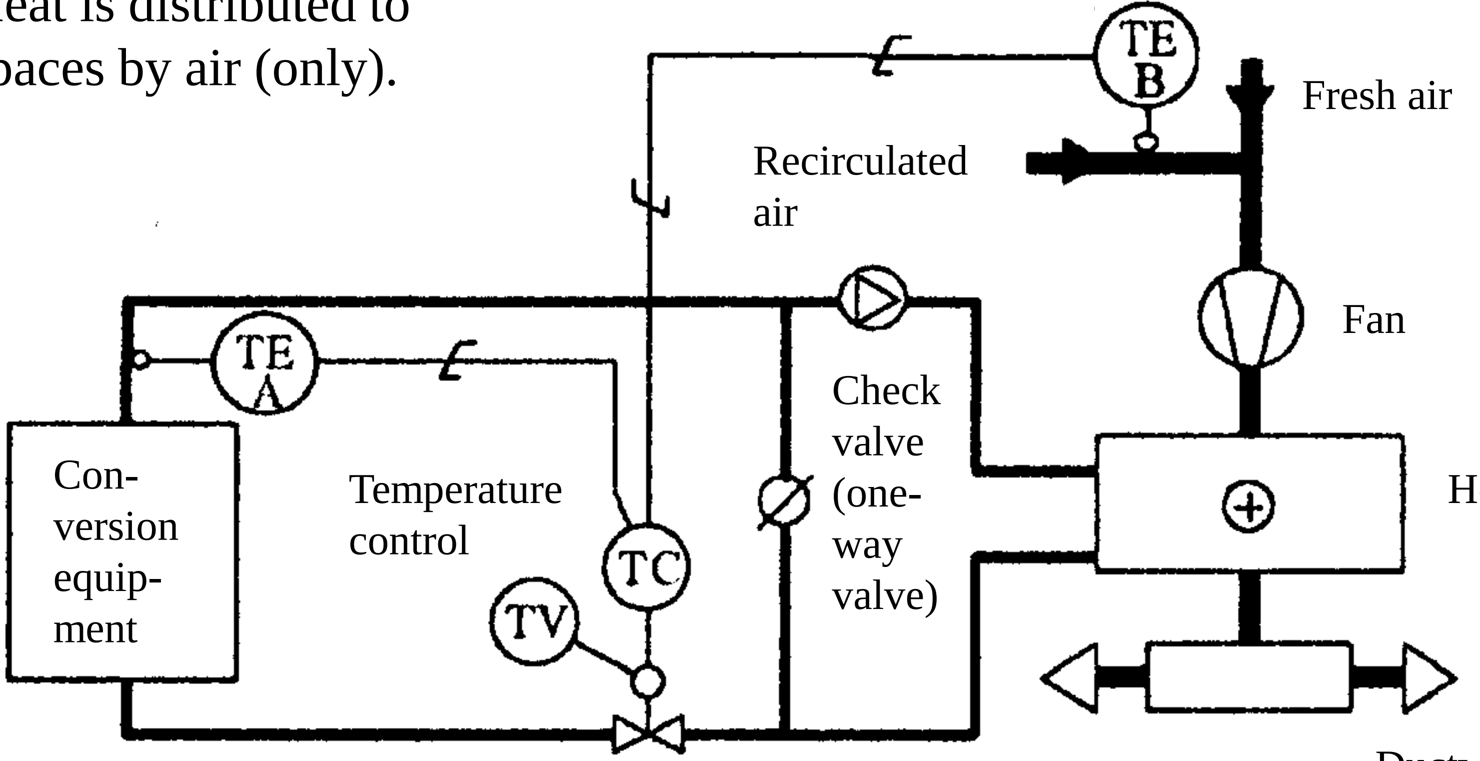
Conversion equipment:
- boiler
- heat exchanger (district heating)
- storage (tank)

<u>Piping and plumbing:</u>

<u>Piping</u> is “the arrangement of pipes in order to transfer the liquids from one area to another area”.
<u>Plumbing</u> is “the job of fixing or fitting the pipes or working with pipes”.
(http://www.differenceall.com/)

Structure of heat distribution network – air heating

<u>Air heating</u>:
Heat is distributed to spaces by air (only).



Recirculated air

Fresh air

Fan

Check valve (one-way valve)

Heating coil

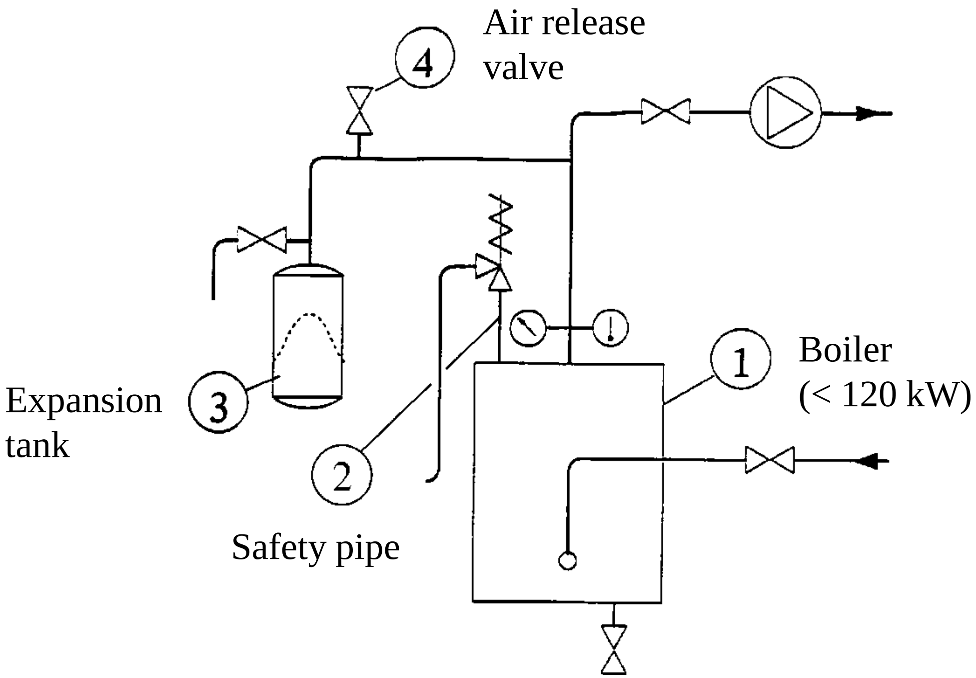
Con-version equip-ment

Temperature control

Ductwork

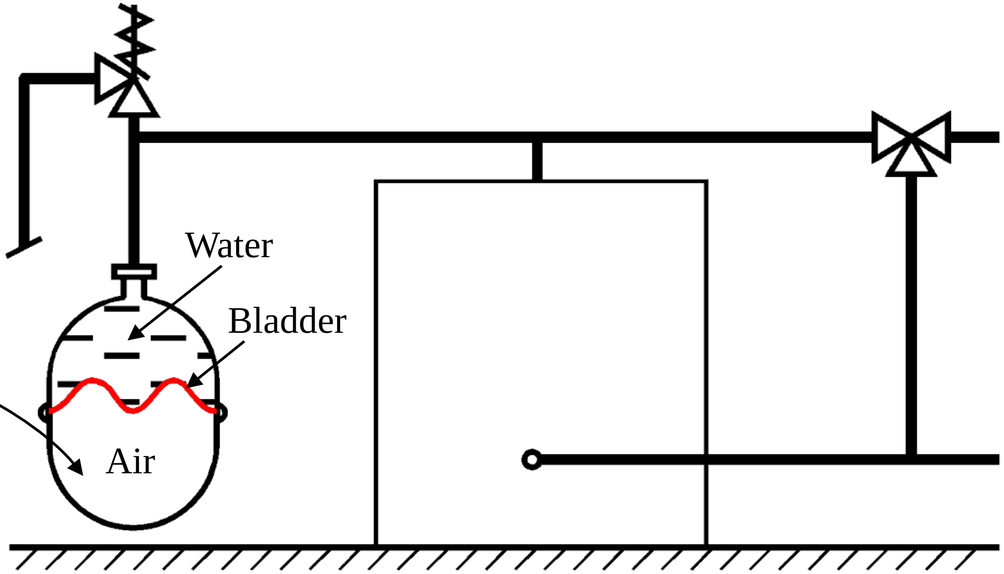
Expansion vessel

- Expansion vessel or tank is required in hydronic heating systems to compensate the expansion of water due to temperature rise. Without an expansion vessel, the system would be exposed to failures.
- For large plants, equipping the system with an expansion tank is defined in the legislation. In Finland:
  - Law 869/1999 for pressure vessels
  - Operational pressures > 0.5 bar over atmospheric pressure
  - Heating systems with water temperatures > 110°C



Bladder expansion tank

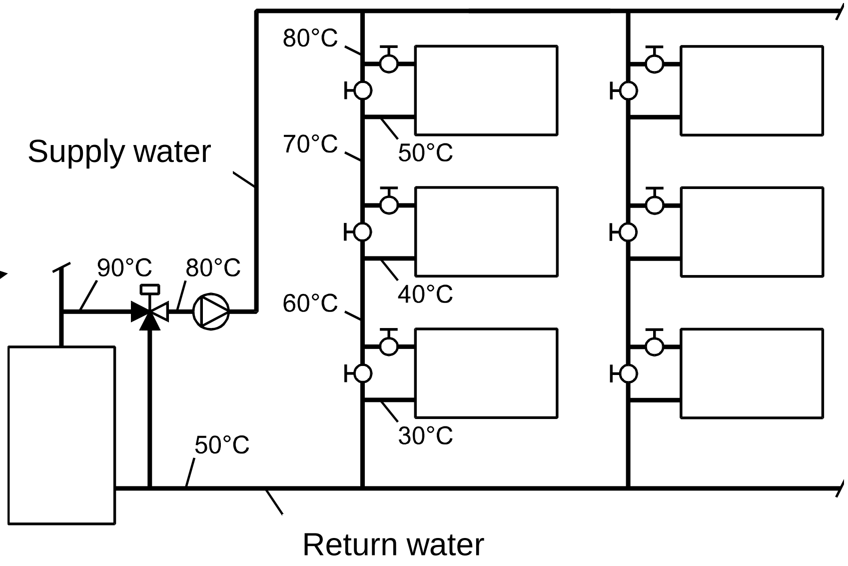
A bladder expansion tank contains pressurized air and water separated by a flexible membrane (bladder). When the static pressure of the heat distribution network rises, the expanded water forces the bladder to move downwards.



Fill pressure > Static pressure of network

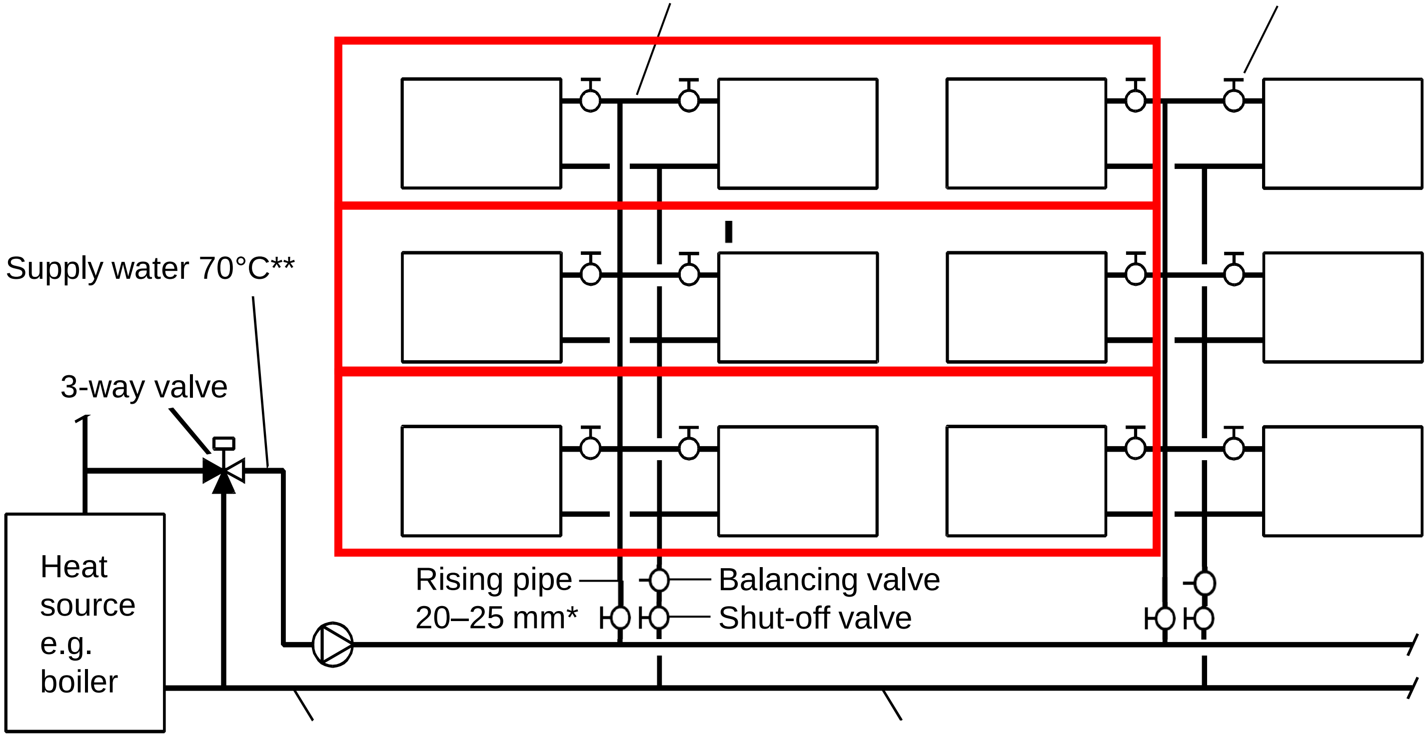
Coupling options for piping

- *Two (double) pipe system*
  - heat exchangers coupled in parallel
  - separate piping for supply and return water
  - all the heat exchangers receive the supply water at equal temperature
  - the most common in Finland
- *One (single) pipe system*
  - heat exchangers in series (Figure)
  - requires high supply water temperatures
- *Supply manifold*
  - apartment (individual) heat distribution
  - allows individual energy metering



Two-pipe system

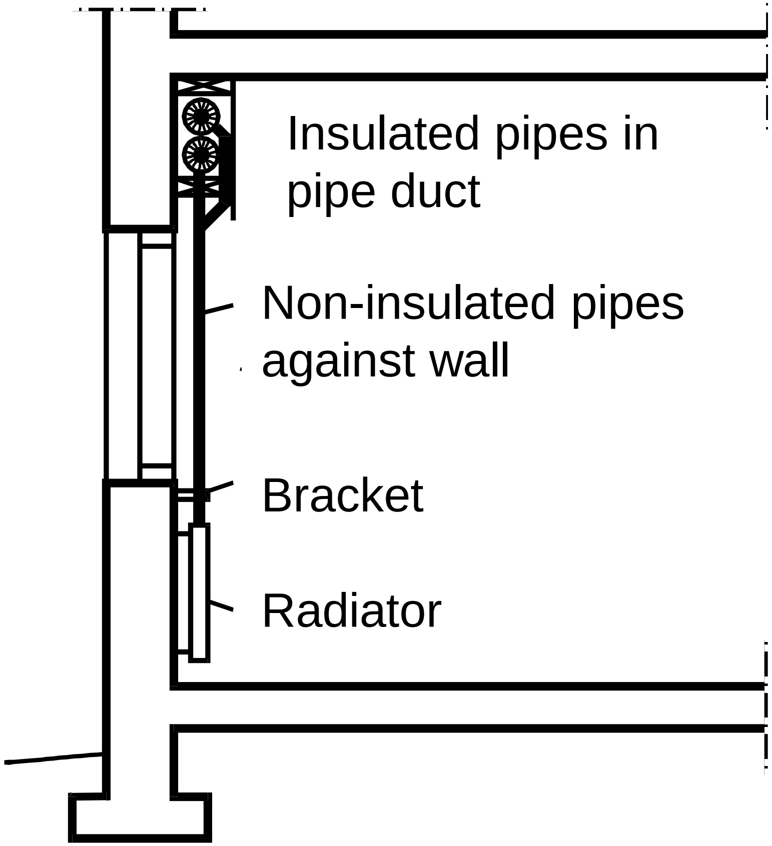
Two rising lines per apartment
⇒ individual (apartment) energy metering impossible



* internal diameter
** design temperatures

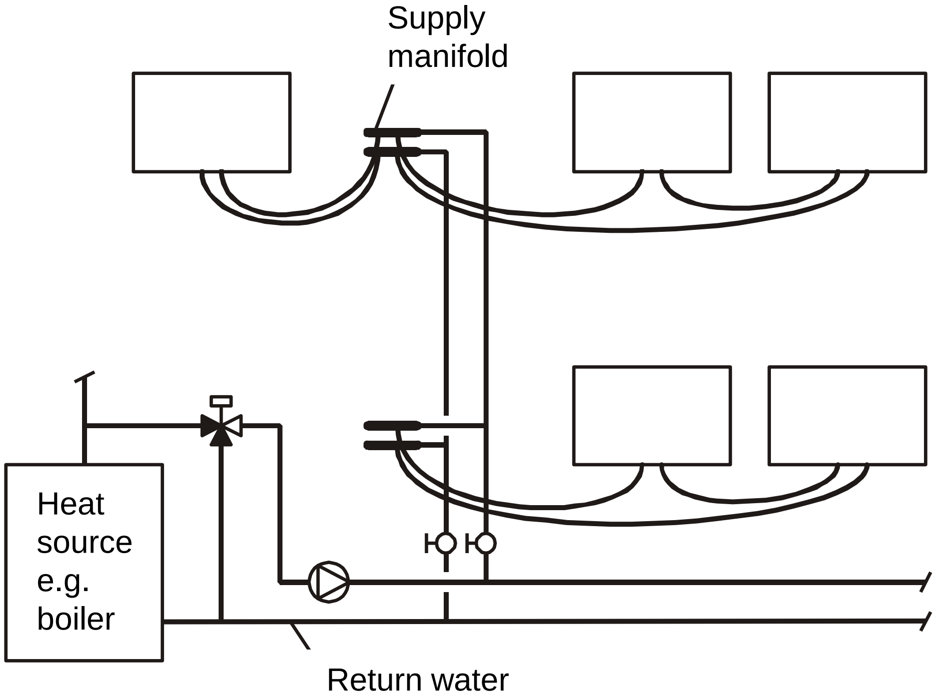
Two-pipe system – installation

- Trunk pipes
  - e.g. ceiling of the cellar
- Rising pipes
  - against the outer wall (non-insulated) or in pipe ducts (insulated)
- Branch pipes
  - example installation in figure



Supply manifold

- Branch pipes (typically made of plastic) are assembled by *supply manifold*.
- One supply manifold serves one apartment, which enables individual heating control and energy metering.
- Radiators can be coupled either in parallel or in series.
- Hydronic floor heating always relies on supply manifold.



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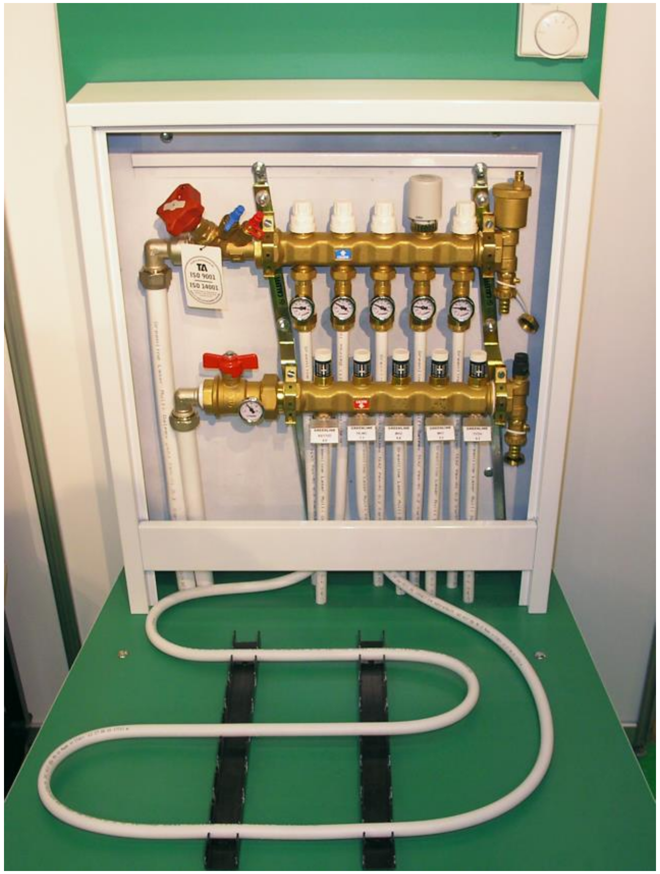
Supply manifold - installation

- Supply manifold cabinet is located in a bathroom or technical area. The cabinet includes
  - supply manifold
  - thermostatic valves
  - equipment to measure water flow and temperature
- The installation of supply manifold presumes that water leaks can be observed.
- In single-family detached houses there must be at least one supply manifold installation for each floor.



Supply manifold cabinet

Heat exchangers

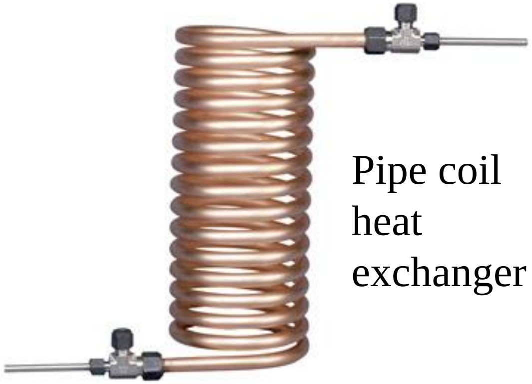
Classifications:

1. Flow pattern
   - counterflow
   - crossflow
   - parallel flow
2. Heat transfer method
   - radiators
   - convectors (including heating/cooling/pipe coils)
3. Heat storage
   - recuperative (heat exchanger does not store heat)
   - regenerative (heat exchanger stores heat)

Radiator

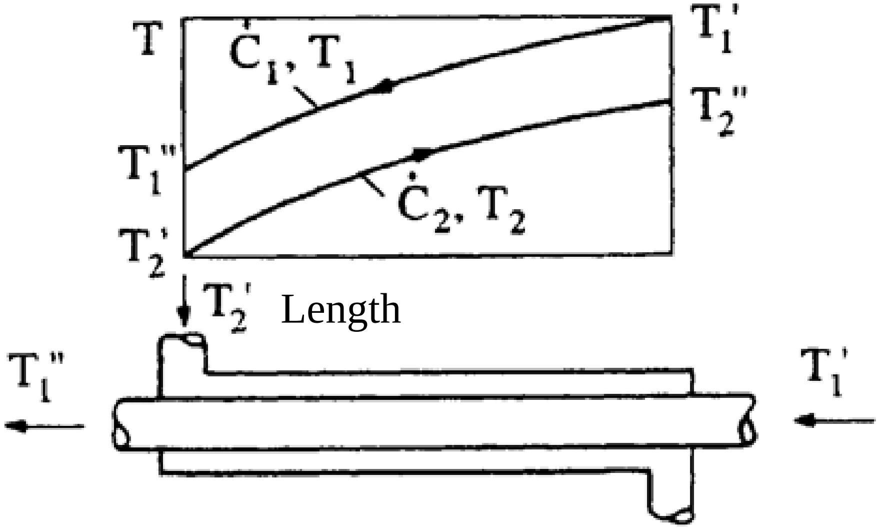
Finned-tube heating/cooling coil

Plate heat exchanger for district heating

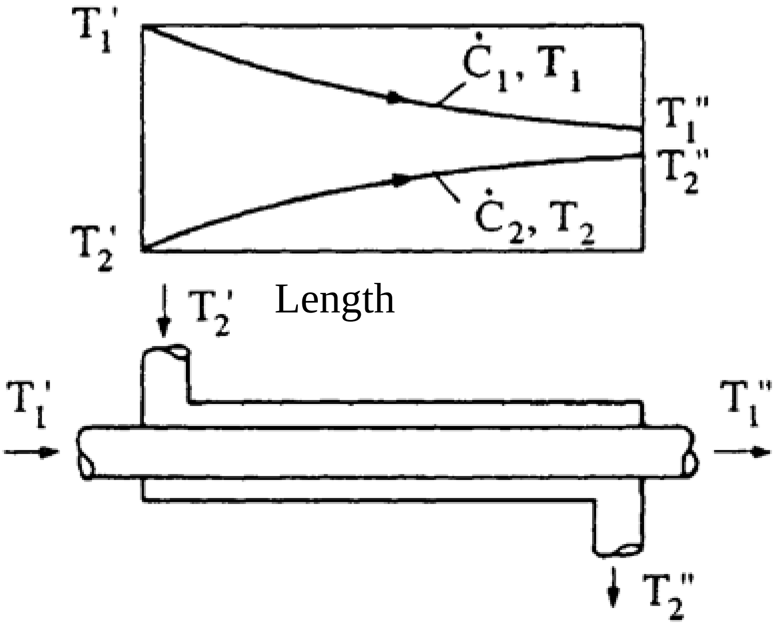


Pipe coil heat exchanger

Impact of flow pattern on heat exchanger temperatures



Counterflow heat exchanger



Parallel flow heat exchanger

Counterflow is more efficient than parallel flow. In practical applications, however, the flow pattern is commonly crossflow (e.g. finned-tube heating/cooling coils).

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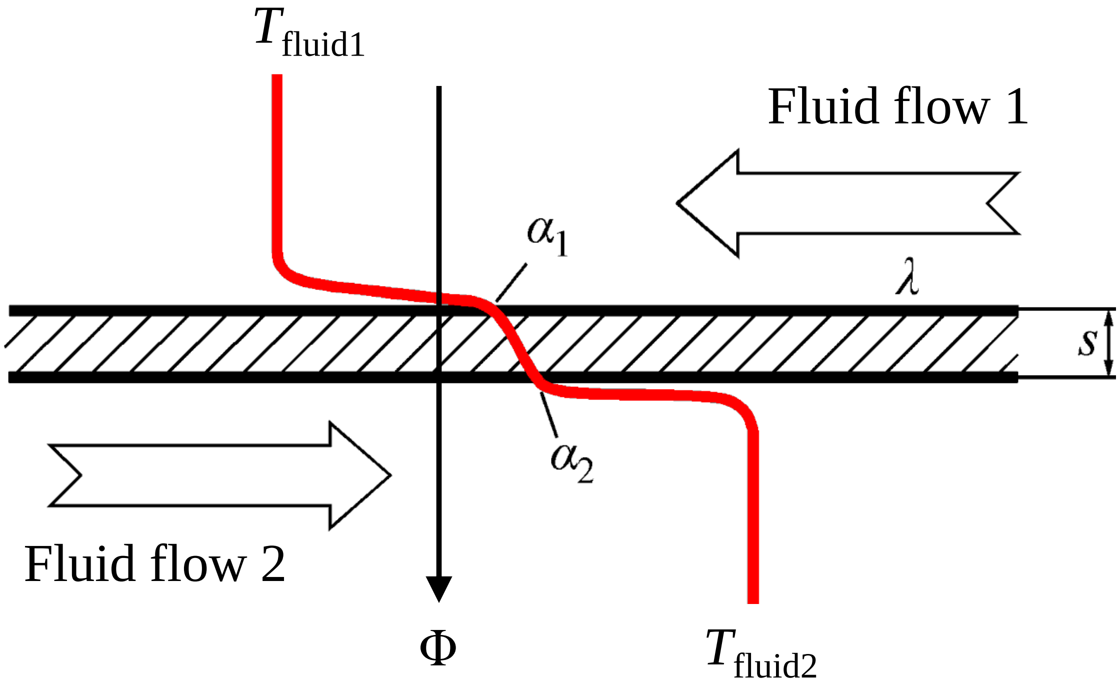
U-value and conductance of heat exchanger

$$R = \frac{1}{\alpha_1} + \frac{s}{\lambda} + \frac{1}{\alpha_2}$$

$$U = \frac{1}{R}$$

$$G = UA$$

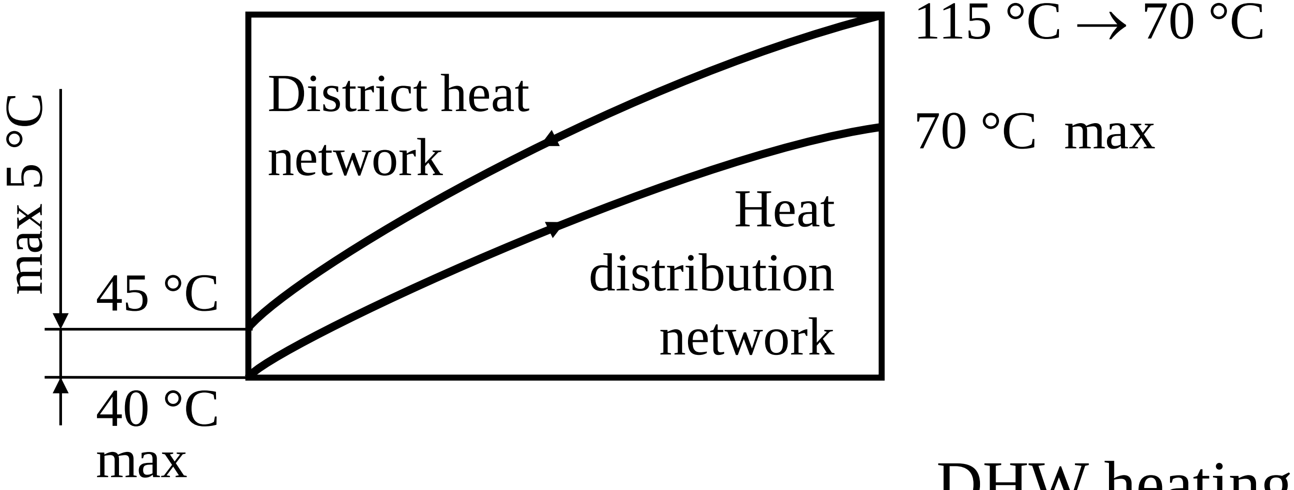
$$\Phi = G\left(T_{fluid1} - T_{fluid2}\right)$$



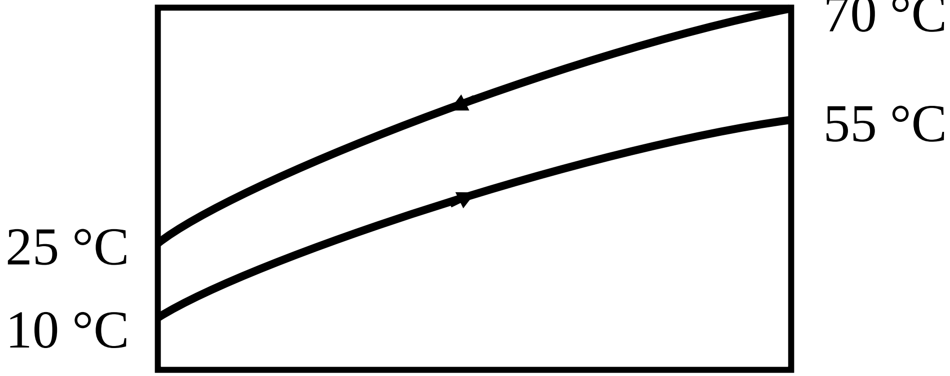
A = heat transfer area

Example: Heat exchanger temperatures

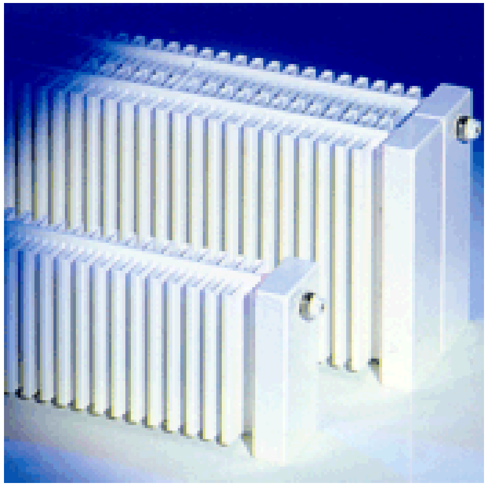
Space heating



DHW heating



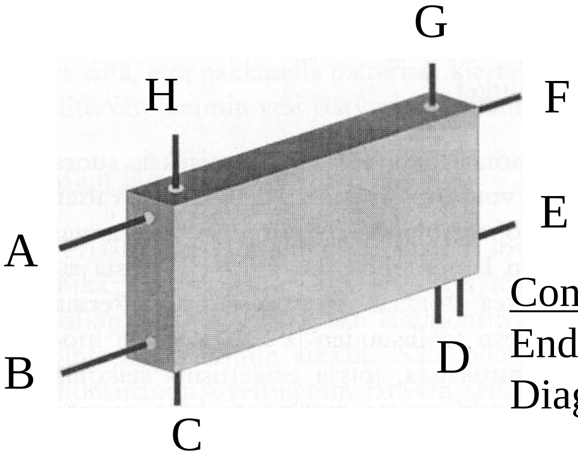
Radiators and convectors



1. Radiators
   - Both radiation and convection occurs, the share of radiation > 50 %
2. Convectors
   - Both radiation and convection occurs, the share of convection > 50 %

Installation of radiators and convectors – I

- The intention is to ensure the largest temperature drop of water (efficient heat transfer).
- Affecting factors:
  - water temperature and mass flow rate
  - structure of radiator
  - installation
  - covering (preferred: no covering!)
  - connection
- Location behind furniture or in a recession decreases the heat transfer, wherefore a larger radiator must be chosen in these cases.

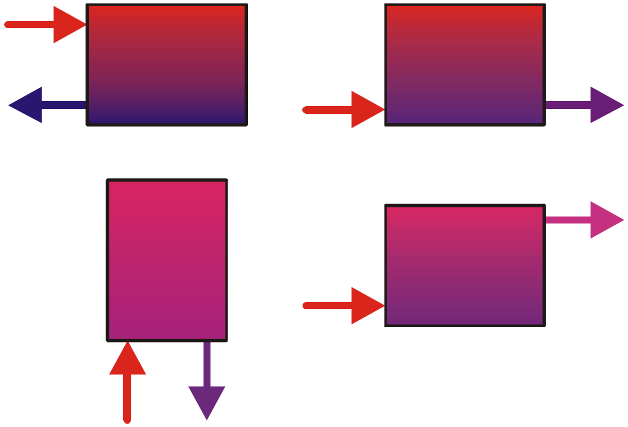


Connection:

End: AB/EF

Diagonal: AE/FB

The impact of connection of the radiators in the radiator network on the temperature drop of water:



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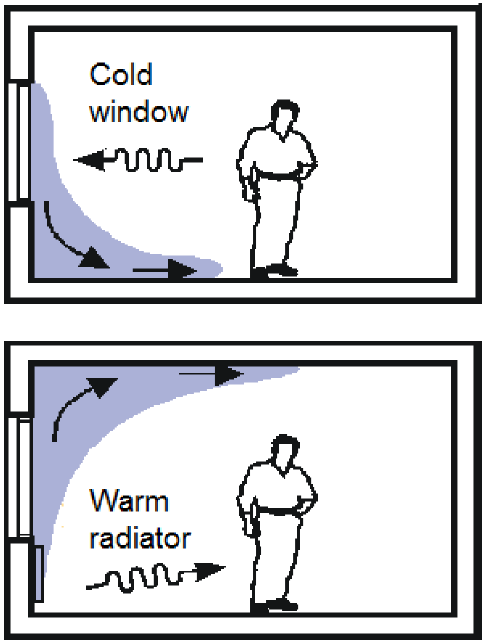
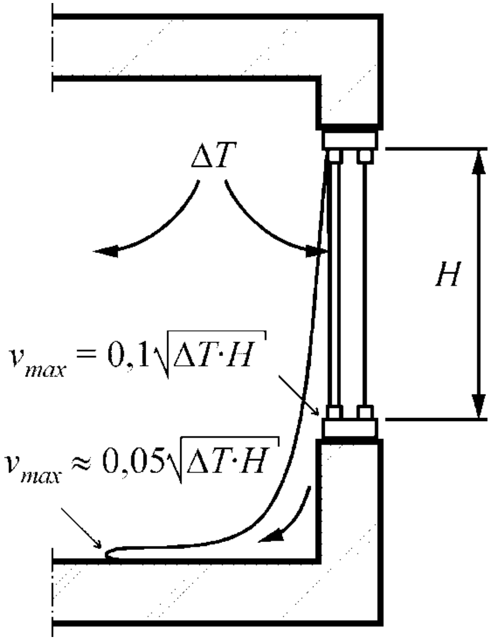
Installation of radiators and convectors – II

- Principle: a radiator/convector is installed in every space
  - Humid spaces (e.g. bathrooms) always have a radiator/convector.
  - Stairwells have a radiator/convector in the entry floor.
  - *Exception*: rooms that are adjacent to heated spaces from all directions
- Installation against outer wall, below windows
- The temperature measurement of the thermostat must be accurate:
  - → No installation behind furnitures/curtains
  - → No installation below ventilation window
  - → Do not cover!



Impact of installing radiator below windows

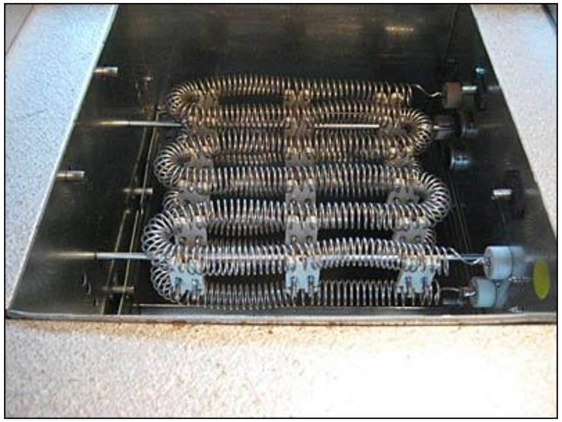


Assessment of air velocity below a cold window

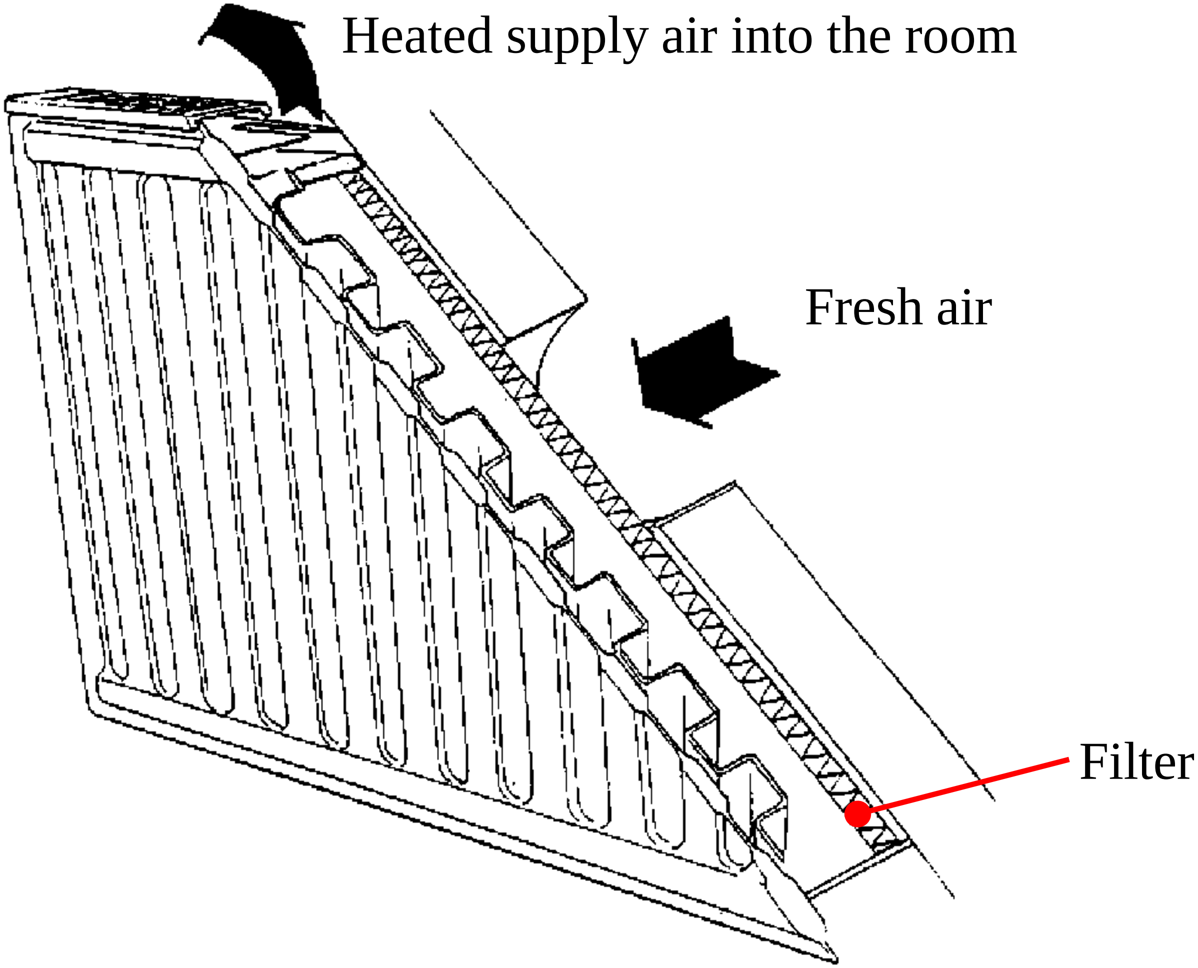
Draught criterion:
$v_{max} < 0.2$ m/s

Heating and cooling coils for ventilation and air-conditioning

1. Hydronic system
    - finned tube heat exchangers
    - water (refrigerant) circulation loop
    - baffles (aka fins, plates, lamellas) made of aluminium (thickness appr. 0.5 mm), finspacing 2…4 mm
    - Heating & cooling coils are commonly counter (or cross)-flow heat exchangers due to optimal heat transfer.
2. Electric heaters
    - resistance heating coils (elements)



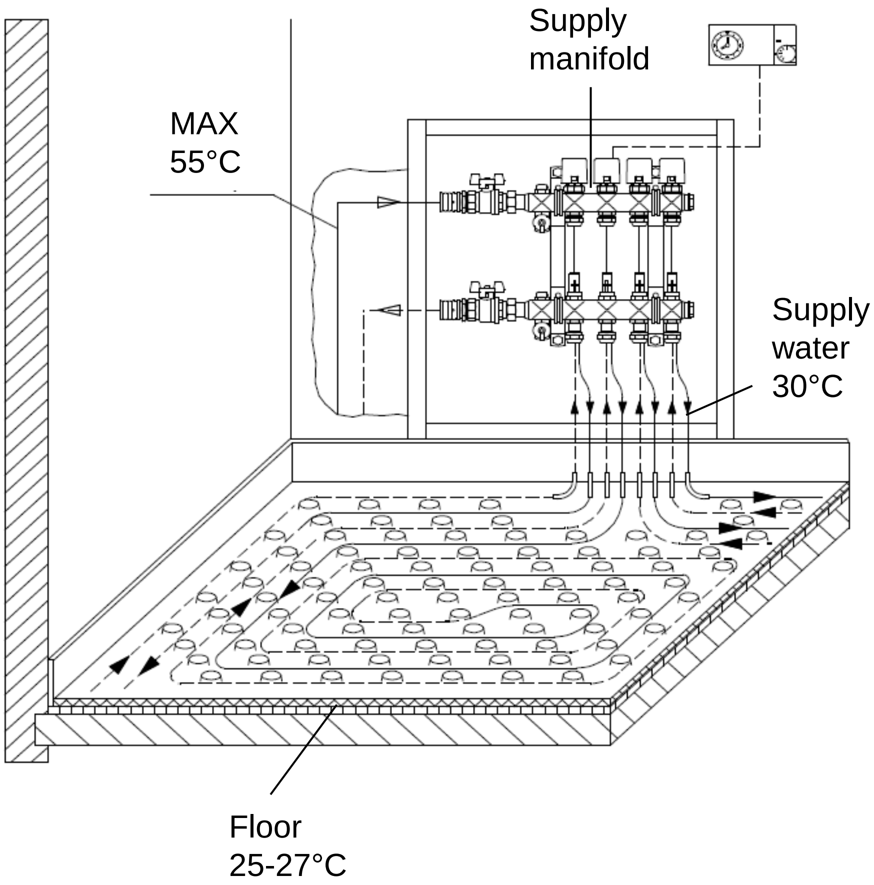
Supply air radiator



Supply air radiator: Supply air is pre-heated by funneling filtered fresh air into the room from behind a radiator.

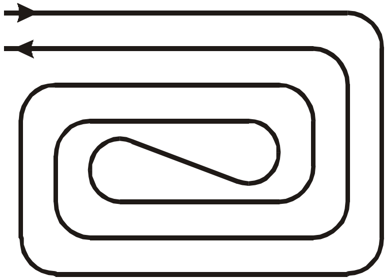
Hydronic floor heating

- The piping is installed in the floor structure, no radiators/convectors
- The main heat transfer mechanism: radiation (share 50-60 %)
- The temperature distribution across the floor is uneven (higher temperatures close to pipes)
- The heat release temperature is low, which makes the floor temperature optimal for the occupants and low-temperature heat sources (e.g. heat pump and solar heating) available.
- Floor is a heat storage (depending on the heat capacity of the structure). For the same reason, the response of floor heating to control actions is delayed.

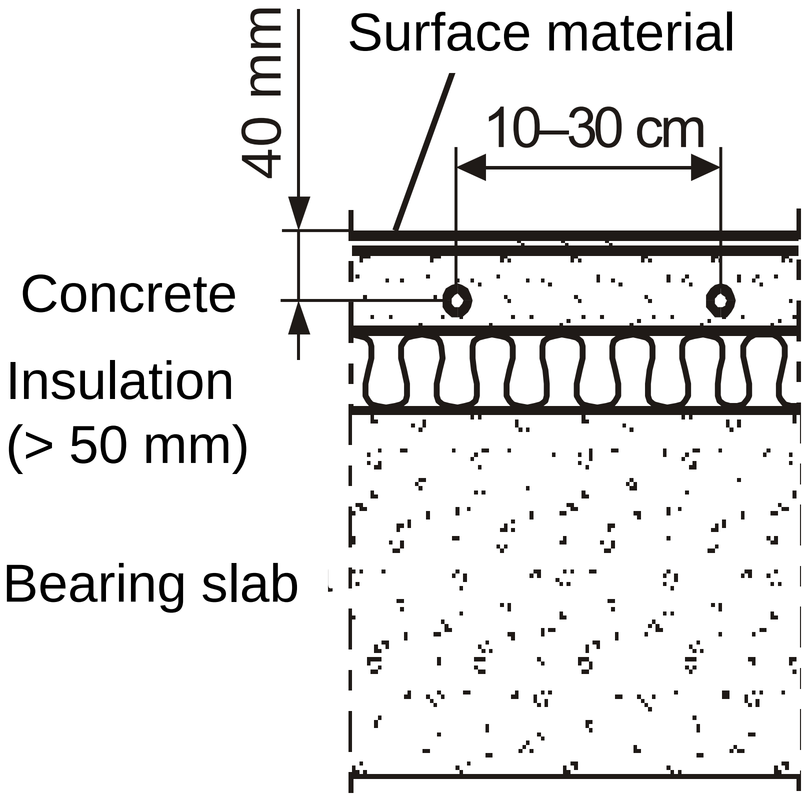


Installation of hydronic floor heating

- Supply and demand pipe are installated as coil:

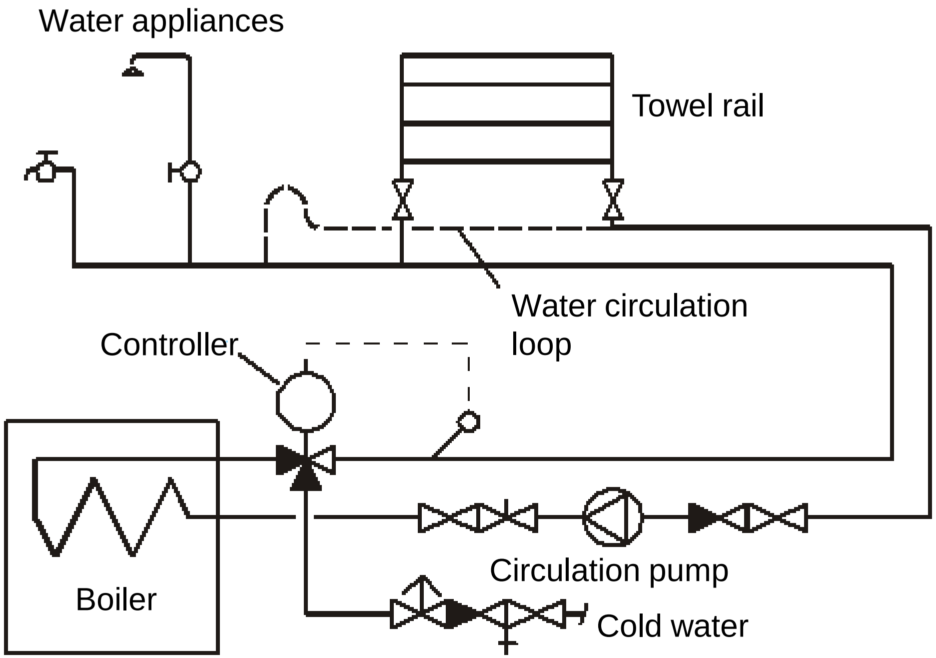


- The larger the space is, the more coils there are installed in parallel.



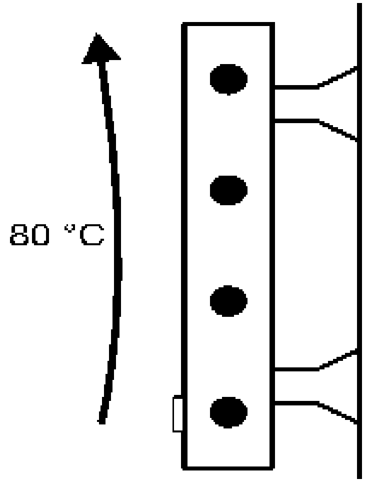
DHW distribution system

- Domestic hot water (DHW) is produced in a centralized heating plant (heat exchanger, boiler or electrically heated thermal storage).
- Water circulation is maintained to ensure the availability of hot water in less than 10 s.
- The minimum temperature of DHW (in Finland) is 50°C (to avoid legionella bacteria) and the maximum temperature 65°C (to avoid burns). The design temperature is 55°C.
- The water temperature is controlled using a 3-way valve.

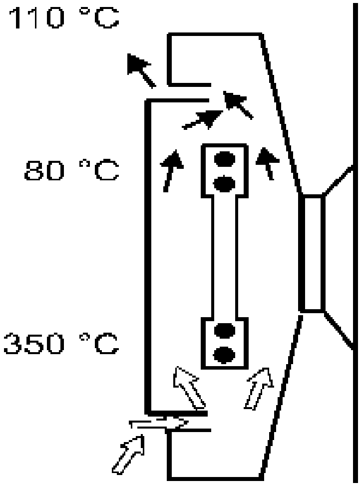


Electric radiators and convectors

- There are electric radiators and electric convectors depending on the dominant heat transfer method from the heater’s outer surface, and *hybrid heaters* (with maximized radiation *and* convection).
- The installation of electric radiators and convectors is similar to that of hydronic ones, but because the internal components (resistors) are hot (up to 350 °C), fire protection must be ensured, e.g. by preventing particles of dust and splash water getting into the heater and avoid covering the heater.



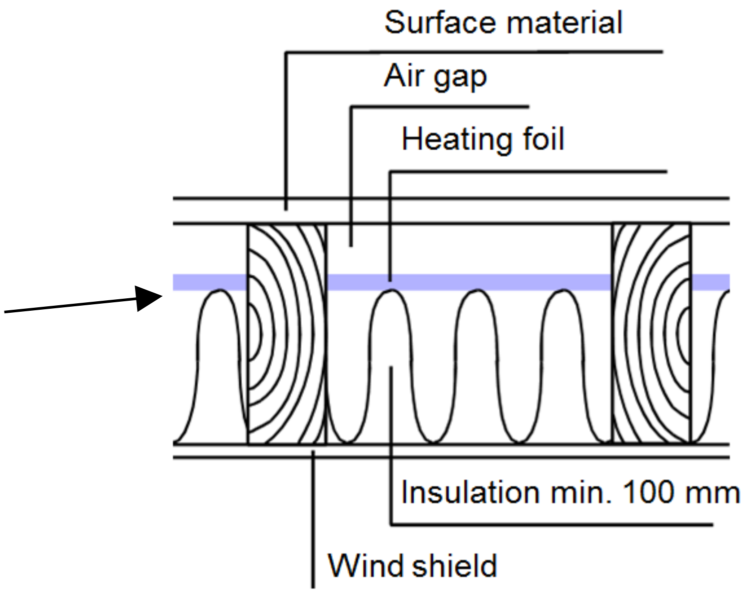
Electric radiator



Hybrid heater

Heating foils

- *<u>Heating foil</u>* is a flexible electric resistance heater surrounded by a foil made of plastic.
- The dominant heat transfer mechanism: radiation (share 50-60 %)
- Suitable to be installed to both floor or ceiling structures as shown in Figure.



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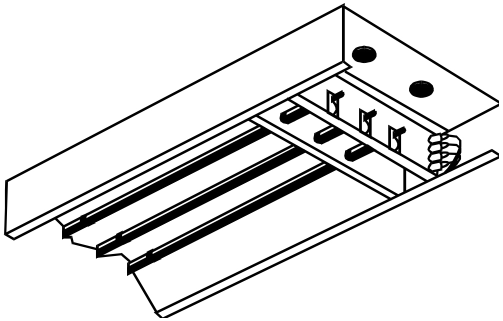
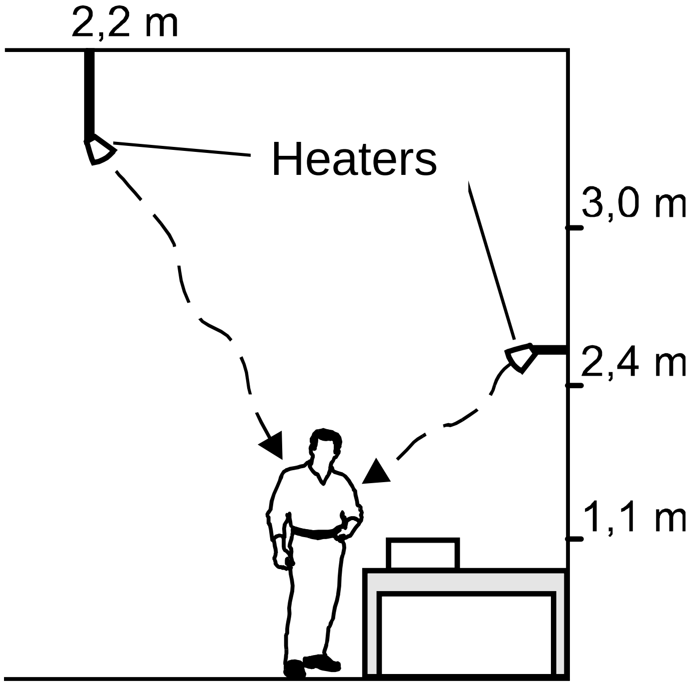
Radiant heaters

- Heat transfer mechanism: radiation 100%
- Enables local heating → thermal comfort without a need to heat the air or structures of the space → energy savings
- Classification on the basis of temperature:

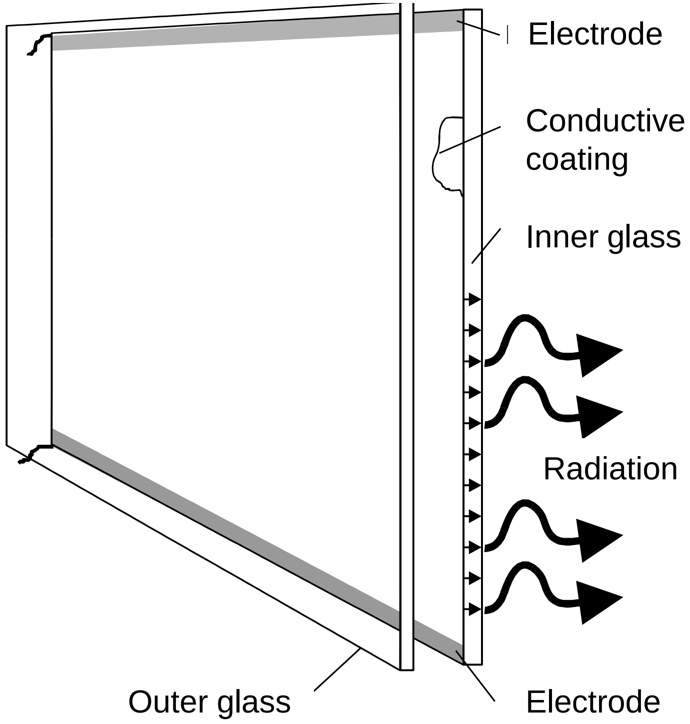
  1. High temperature (temperature > 500°C)
     - equipped with a reflector
     - installation: high spaces, outdoors etc.
  2. Medium temperature (100-500°C)
     - large surface area, even temperature distribution
     - installation: work spaces, stores
  3. Low temperature (< 100°C)
     - local heating
     - installation: close to occupied zone





Heated glass windows

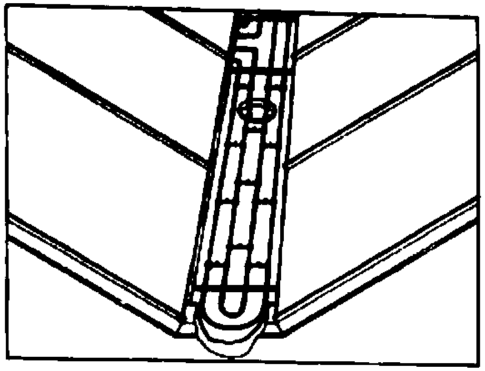
- A resistance heater installed in the coating of a window
- Allows elevated surface temperatures → condensation and draught eliminated
- The dominant heat transfer mechanism: radiation
- Heated glass windows are typically
  - vacuum glass windows, the heated coating installed on the outer surface of the inner glass
  - selective windows → minimum heat loss



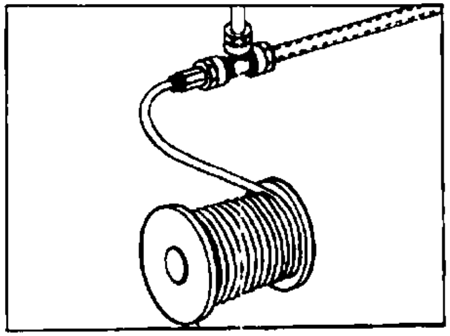
Trace heating

- *Trace heating* (aka *surface heating*) refers to electric heating with an aim to
  - protect equipment and structures from freezing
  - prevent icing in water pipes
  - maintain temperatures above zero (commonly +5…8°C) in certain spaces (e.g. storage rooms)

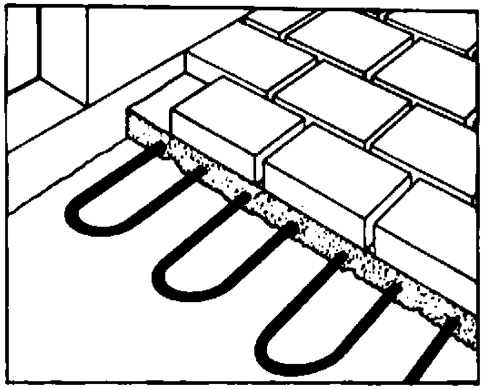
Examples of trace heating applications:



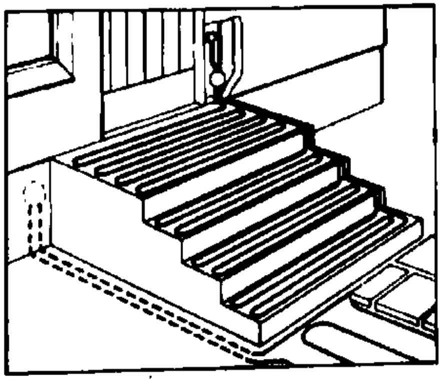
Valley troughs



Along or around pipe



Walkways, patios etc.

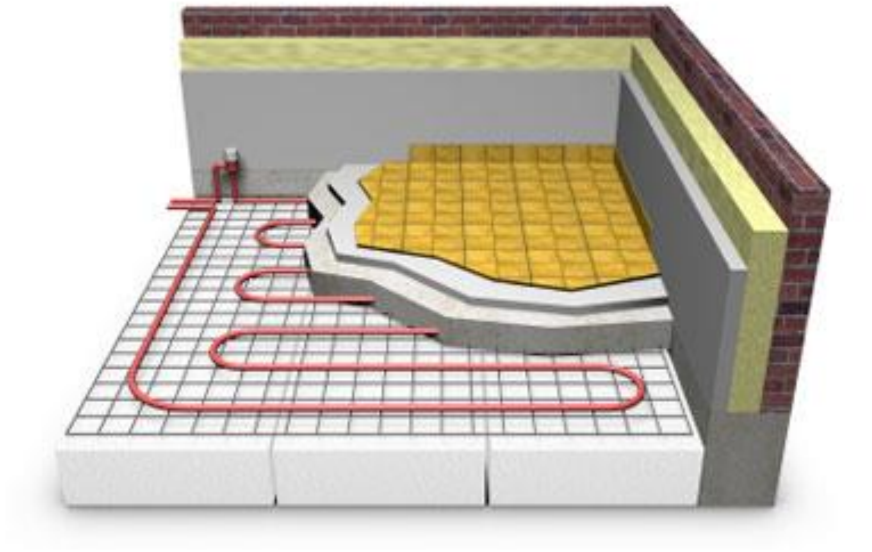


Stairways

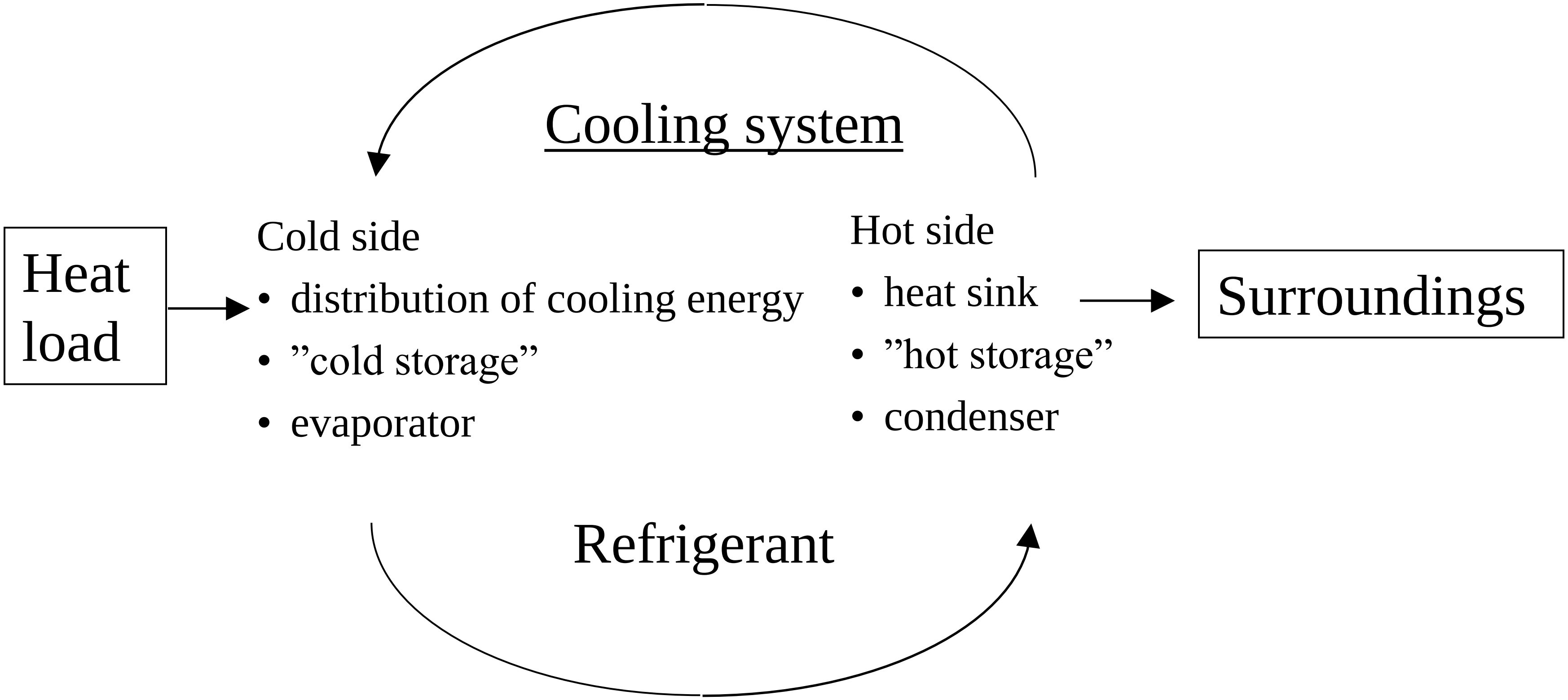
Electric floor heating

- The operational principle and characteristics are similar to hydronic floor heating.
- Installation: electric cables are embedded into a concrete slab with the thickness of 100 mm and spacing 150–250 mm.
- Storage heating: the highest temperature occurs in the morning and the highest demand in the evening

  → requires auxiliary heaters to maintain thermal comfort



The ”path” of cooling energy



Cooling system

Heat load

Cold side

- distribution of cooling energy
- ”cold storage”
- evaporator

Hot side

- heat sink
- ”hot storage”
- condenser

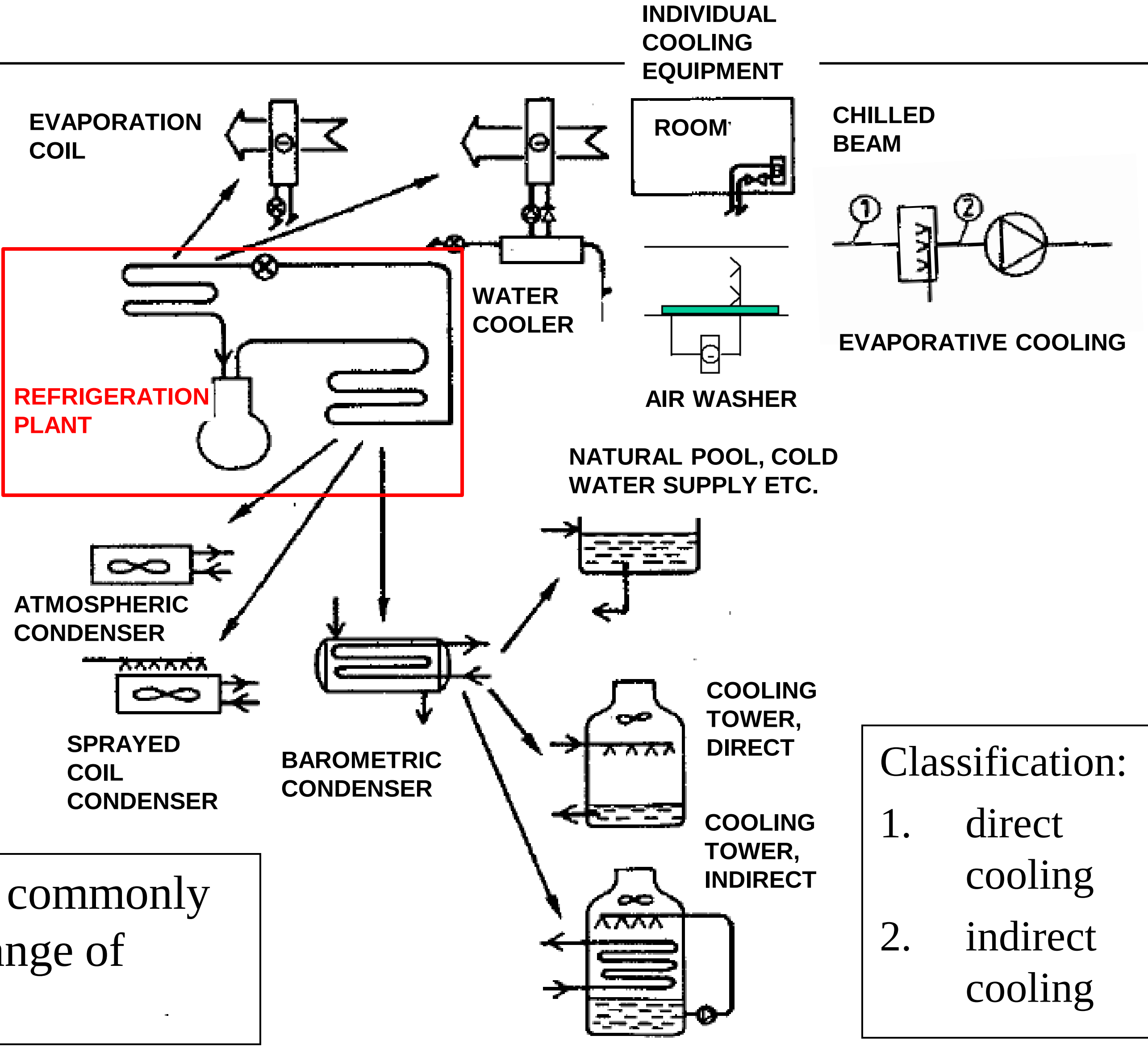
Surroundings

Refrigerant

Cooling as a psychrometric process will be treated in the course ”EEN-4003 Ventilation and Air-Conditioning Systems”

Cooling energy distribution

- Cold side
  - distribution of cooling energy
  - ”cold storage”
  - evaporator
- Hot side
  - heat sink
  - ”hot storage”
  - condenser



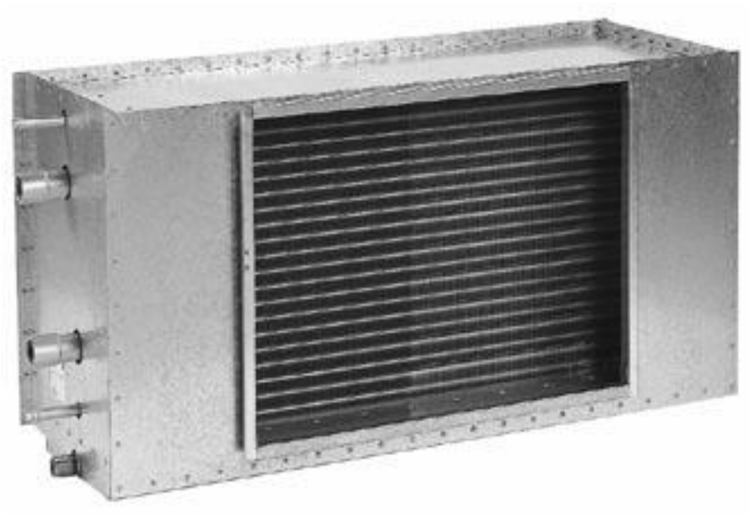
The cooling process is commonly based on the phase change of refrigerant.

Classification:

1. direct cooling
2. indirect cooling

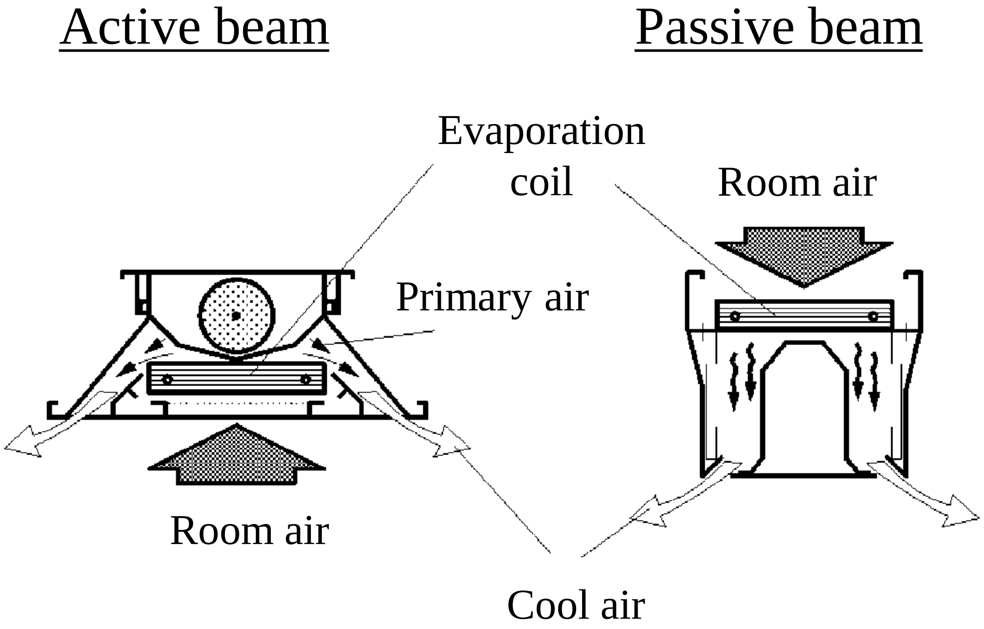
Evaporation coils

- Evaporation takes place in a finned tube heat exchanger, which is directly contacted with the air flow to be cooled.
- A system may contain several units.
- The surface temperature is constant.
- Direct evaporation is common in small air-conditioning systems.



Chilled beams

- Equipment for individual cooling
- Air is expelled to room through a ceiling-mounted cooling coil (cool air drops downwards).
- *Active beam*: Forced air flow (fan) through cooling coil, consists of primary (supply) air and recycled room air
- *Passive beam*: Cool room air flows through the cooling coil naturally (due to gravity).

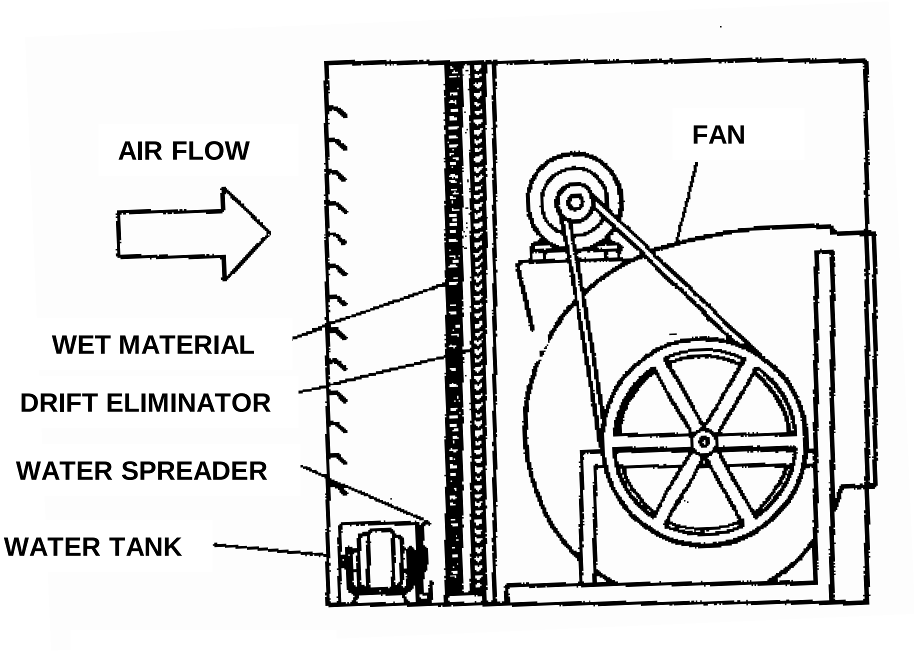


Active beam

Passive beam

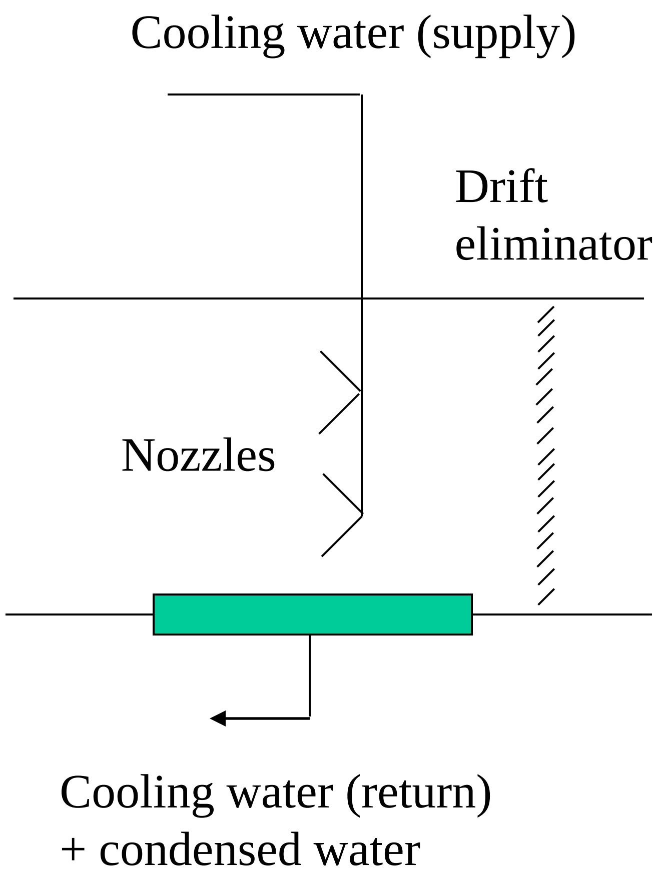
Evaporative cooling

- Principle:
  - The evaporation of a refrigerant (commonly water) removes heat from the air to be cooled.
- Structural options:
  - Water is sprayed into the supply air flow or directly to the room to be conditioned.
  - Supply air passes through moistened material.
- Applicability:
  - hot and dry climate
  - industry



Hydronic cooling

- Water is cooled separately (evaporator).
- Classification into direct and indirect systems:
    1. Indirect (finned tube coils)
        - indirect contact between the source of cooling energy and air
        - large, centralized systems
    2. Direct (”air washer”)
        - direct contact between the source of cooling energy and air
        - several industrial applications
        - Cold water is sprayed into the air at a temperature lower than the dew point temperature.
        - Vapour condenses onto the water droplets and air is cleaned.
- Cooling water temperature: 5…10 ºC

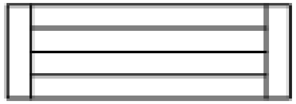


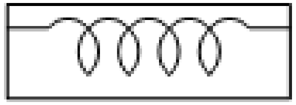
Also known as ”*air washer*”

Heat sinks

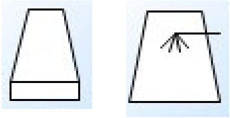
- Heat sinks receive the heat removed from air by the cooling system.
- Condensers
  - atmospheric condenser
  - sprayed coil condenser
  - barometric condenser
- Cooling towers
  - direct
  - indirect
- Other
  - natural pool
  - cold water supply

More drawing symbols for condensers:





More drawing symbols for cooling towers:



Condensers

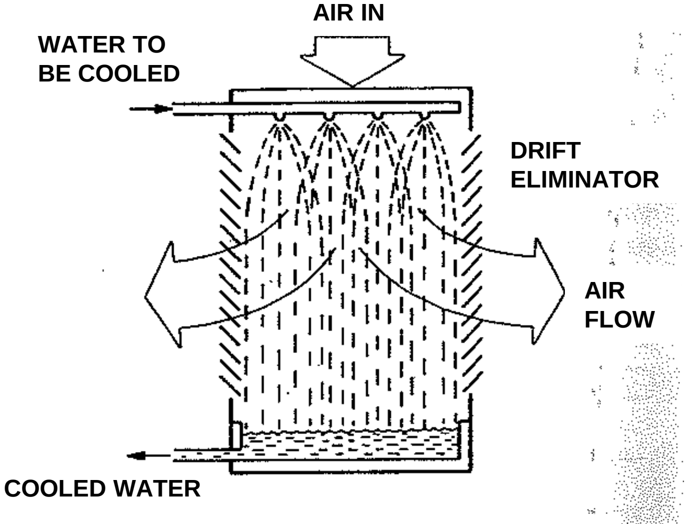
- Heat exchanger, where vapour is condensed into liquid by removing latent heat into a fluid or into surroundings
- Atmospheric condenser
  - Latent heat is transferred into air flow.
  - required fan energy appr. 2-4 % of cooling energy
  - high condensing temperature, appr. +10 ºC to the outdoor temperature
- Barometric condenser
  - Latent heat is transferred into water flow.
  - no fan required
  - low condensing temperature

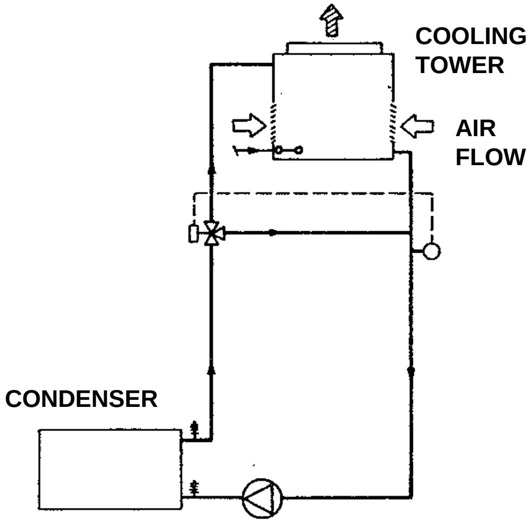
Atmospheric condenser
(Source: Recair)

- Sprayed coil condenser
  - Latent heat is transferred into air flow that is moistened by spraying water into it.
  - Latent heat of water is utilized.
  - Condensing temperature is close to the wet-bulb outdoor temperature.
  - small-sized

Cooling towers – I

- *Cooling tower* is a device applied to transfer heat from a cooling process to surroundings through evaporation.
- Classification: direct (upper) and indirect (lower picture)
- Cooling power:
  - min. 10 kW
  - commonly: > 500 kW
- Water can be cooled to appr. 5 ºC higher temperature than is the *wet-bulb temperature* (i.e. reading of a thermometer wrapped in a wet cloth).





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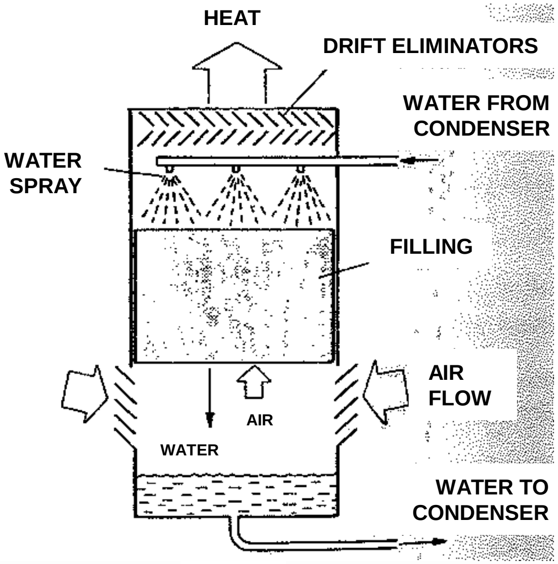
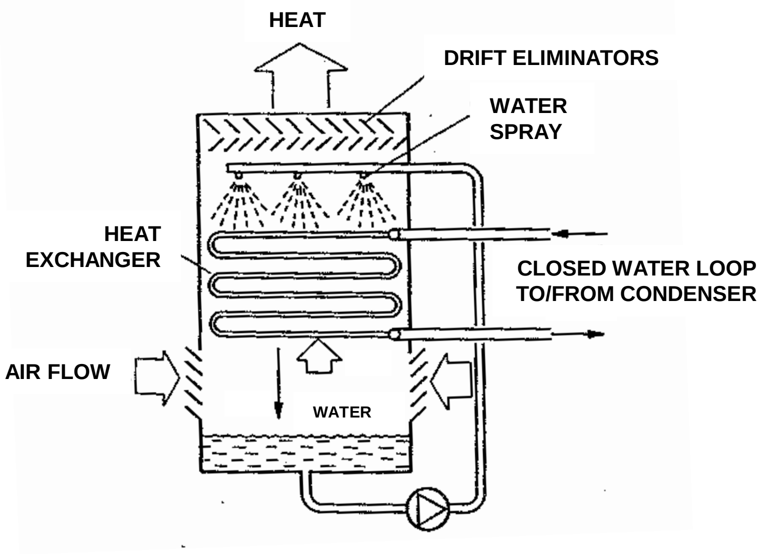
Cooling towers – II

- ***Direct***
  - Water from condenser contacts the air directly.
  - efficient cooling
  - Water may become polluted by impurities.



- ***Indirect***
  - Water from condenser circulates through heat exchanger.
  - inefficient cooling
  - Water remains clean.



Choosing a cooling system

- Evaporation (air bound system)
  - cooling power < 300 kW
  - short distances for cooling energy transfer
  - limited use of water (e.g. safety reasons)
- Hydronic cooling
  - cooling power > 300 kW
  - several air-conditioning plants in the building
  - complicated cooling distribution network
  - accurate power control required

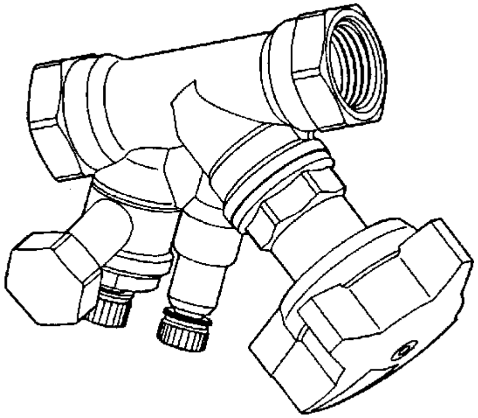
Pipes: materials and sizes

- Available materials:
  - steel
  - copper
  - plastic
  - composite
- Standard sizes for steel pipes:
  - *Nominal Diameter (DN)* (Europe)
  - *Nominal Pipe Size (NPS)* (North America)
  - DN and NPS are *approximately* equal to the inside diameter.
  - The inside diameter varies slightly depending on the wall thickness and *pipe thread*.
  - The outside diameter is always the same (to ensure the compatibility of pipes with *equipment* and *fittings*).
  - Useful DN-sizes:
    DN 10,15,20,25,32,40,50,65,80,100

Nominal Diameter (DN)	Outer diameter [mm]	Wall thickness (medium) [mm]	Wall thickness (thick) [mm]
10	17.2	2.35	2.90
15	21.3	2.65	3.25
20	26.9	2.65	3.25
25	33.7	3.25	4.05
32	42.4	3.25	4.05
40	48.3	3.25	4.05
50	60.3	3.65	4.50

Self-studying: Familiarize yourself with the temperature and installation requirements for different piping materials.

Examples of fittings and equipment



Balancing valve

Threaded pipe (male)

Threaded elbow (female)

Copper fittings for soldered joints

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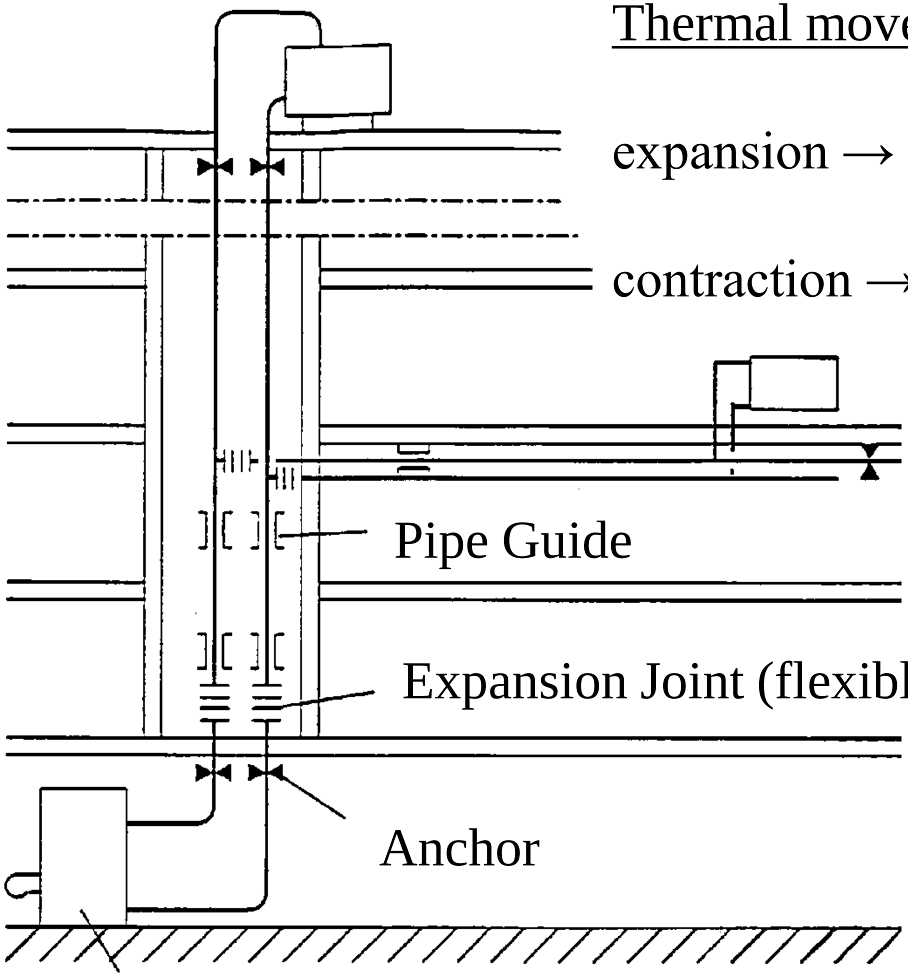
Fittings for compensating the thermal movement



Pipe Guide

Expansion Joint (flexible pipe couplings)

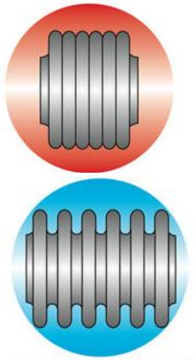
Anchor

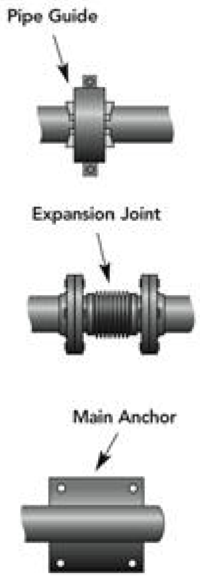
Boiler

Thermal movement:

expansion → compression

contraction → expansion

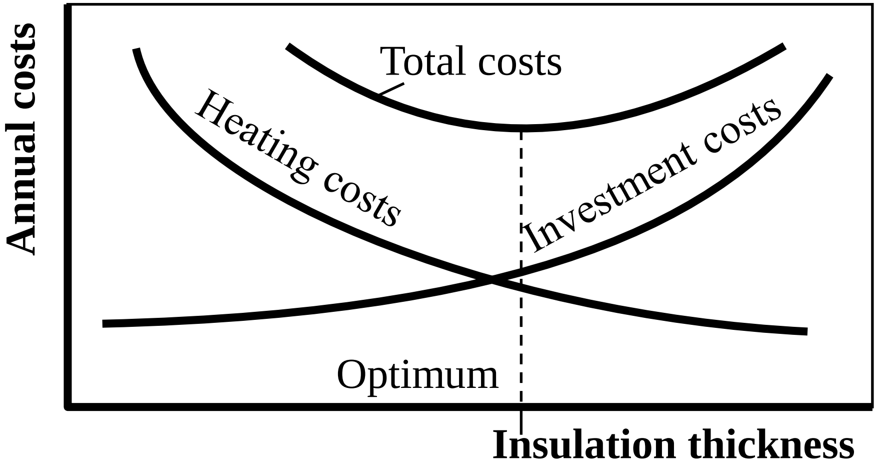


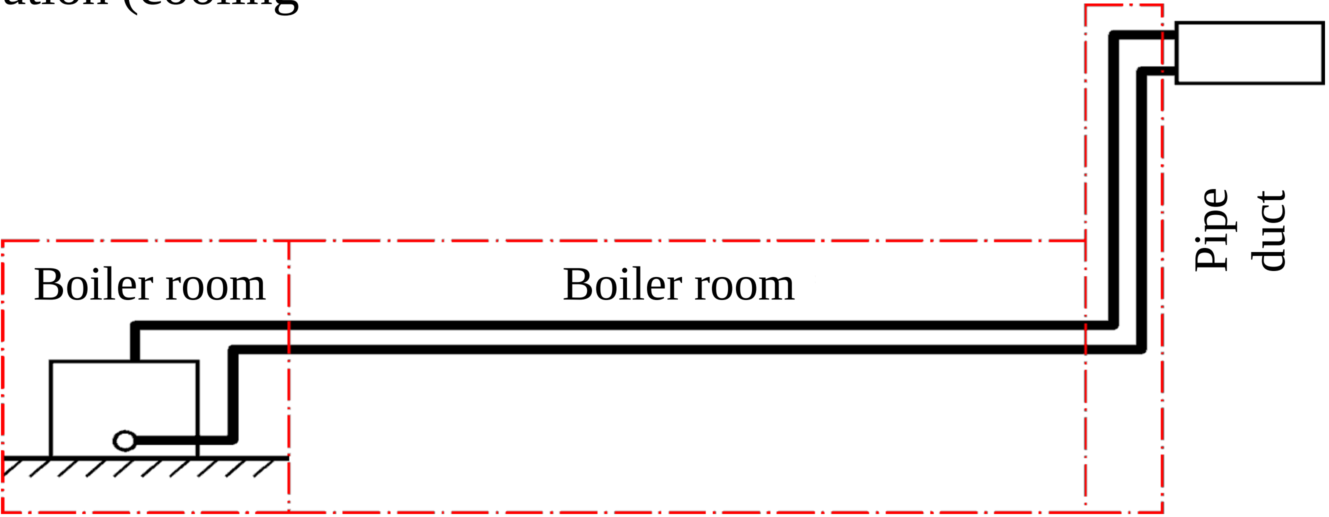


Insulation of pipes

Insulation is required

- to prevent heat loss of the distribution system
- to prevent DHW from cooling down
- to improve safety (reduce risk of burn injury)
- to prevent condensation (cooling pipes)





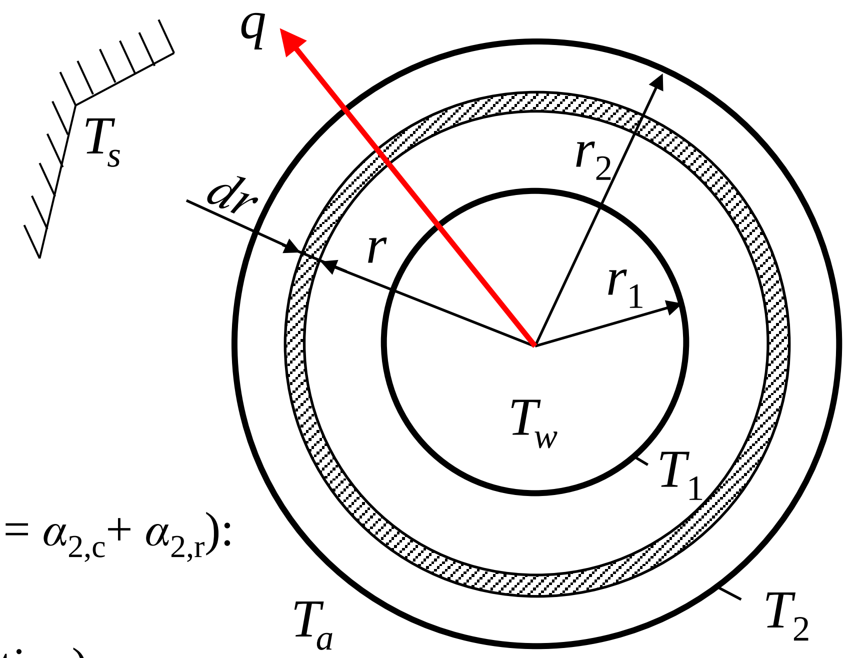
Heat loss of pipe

Conduction per *one meter of pipe* [W/m]:

$$q = -\lambda 2\pi r \frac{dT}{dr} \Leftrightarrow q = \frac{T_2 - T_1}{\frac{1}{2\pi\lambda}\ln\frac{d_2}{d_1}}$$

Convection + conduction (+ radiation) [W/m]:

$$q = \pi d_1 \alpha_1 (T_w - T_1) = \frac{T_2 - T_1}{\frac{1}{2\pi\lambda}\ln\frac{d_2}{d_1}} = \pi d_2 \alpha_2 (T_2 - T_a)$$



External (= dominant) heat transfer coefficients ($\alpha_2 = \alpha_{2,c} + \alpha_{2,r}$):

$$\alpha_{2,c} = 1.21\left(\frac{T_2 - T_a}{d_2}\right)^{0.25}$$ Laminar flow (natural convection)

$$\alpha_{2,c} = 4.16 v^{0.8} d_2^{-0.2}$$ Turbulent (forced convection)

U'-value $\left[\frac{\mathrm{W}}{\mathrm{mK}}\right]$: $\frac{1}{U'} = \frac{1}{2\pi\lambda}\ln\frac{d_2}{d_1} + \frac{1}{\pi d_2 \alpha_2}$

$$\alpha_{2,r} = \frac{4\sigma\left(\frac{T_2 + T_s}{2}\right)^3}{1/\varepsilon_a + 1/\varepsilon_2 - 1}; \quad T_s = \text{temperature of surrounding surfaces}$$

Note: The internal heat transfer coefficient is of the magnitude 1000...10000 W/m^{2}K, wherefore it has been omitted from the equation of the U-value.

Example

Calculate the reduction of heat loss, when the insulation thickness of a pipe (d_1 = 100 mm) is increased from 50 mm to 100 mm.

λ = 0.046 W/mK, $T_w - T_a$ = 85 °C, α_2 = 10 W/m²K

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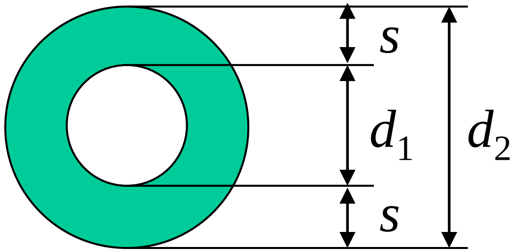
Solution

1. Pipe diameters with insulation:
   - $d_1 = 100\text{ mm} = 0.1\text{ m}$
   - $d_{2(50\text{ mm})} = d_1 + 2s = (100 + 2\cdot 50)\text{ mm} = 200\text{ mm} = 0.2\text{ m}$
   - $d_{2(100\text{ mm})} = (100 + 2\cdot 100)\text{ mm} = 300\text{ mm} = 0.3\text{ m}$



2. U'-values:

$$U'_{50\text{ mm}} = \frac{1}{\frac{1}{2\pi\lambda}\ln\frac{d_2}{d_1} + \frac{1}{\pi d_2 \alpha_2}} = \frac{1}{\frac{1}{2\pi\cdot 0.046\frac{\text{W}}{\text{mK}}}\ln\frac{0.2\text{ m}}{0.1\text{ m}} + \frac{1}{\pi\cdot 0.2\text{ m}\cdot 10\frac{\text{W}}{\text{m}^2\text{K}}}} = 0.39\frac{\text{W}}{\text{mK}}$$

$$U'_{100\text{ mm}} = 0.26\frac{\text{W}}{\text{mK}}$$

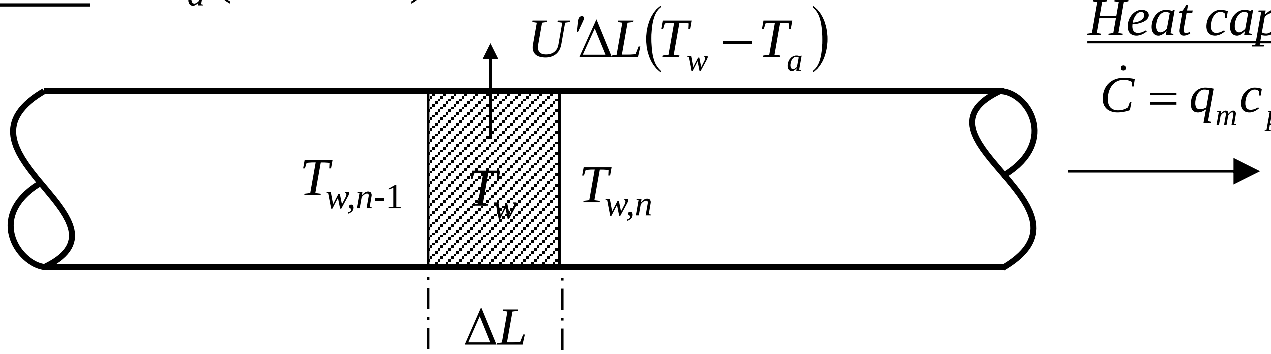
3. Reduction of heat loss (in [W/m], length L = constant = 1 m):

$$\left.\begin{aligned} q_{50\text{ mm}} &= U'_{50\text{ mm}}(T_w - T_a) \\ q_{100\text{ mm}} &= U'_{100\text{ mm}}(T_w - T_a) \end{aligned}\right\} \Rightarrow \text{Reduction} = \frac{q_{50\text{ mm}} - q_{100\text{ mm}}}{q_{50\text{ mm}}} = \frac{(U'_{50\text{ mm}} - U'_{100\text{ mm}})(T_w - T_a)}{U'_{50\text{ mm}}(T_w - T_a)}$$

$$= \frac{U'_{50\text{ mm}} - U'_{100\text{ mm}}}{U'_{50\text{ mm}}} = \frac{(0.39 - 0.26)\frac{\text{W}}{\text{mK}}}{0.39\frac{\text{W}}{\text{mK}}} = \underline{\underline{0.35\,(35\%)}}$$

Temperature drop of water in pipe

Illustration: T_a (constant)



Heat capacity flow

$\dot{C} = q_m c_{pw}$

Energy conservation for ΔL: $\dot{C}\left(T_{w,n-1} - T_{w,n}\right) = U'\Delta L\left(T_w - T_a\right)$

Cooling law: $\dfrac{T_{w,n} - T_a}{T_{w,n-1} - T_a} = e^{-\frac{U'\Delta L}{\dot{C}}}$

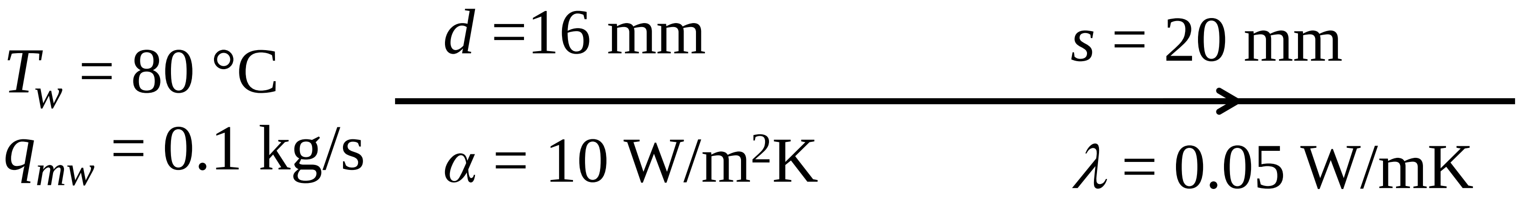
Analytical solution of the energy conservation equation applying infinitesimal dL and dT.

Discretization: $T_{w,n} = T_{w,n-1} - \dfrac{U'\Delta L}{\dot{C}}\left(T_{w,n-1} - T_a\right)$

The accuracy of the discretized calculation is the better the shorter ΔL is chosen. Discretized calculation can be also applied, when $T_{w,n\text{-}1} - T_{w,n}$ is small.

Example

Calculate the temperature drop in the pipe described below using both the cooling law and the discretized method (choose $\Delta L = L$). What is the magnitude of the error made when using the discretized calculation?



$T_w = 80$ °C

$q_{mw} = 0.1$ kg/s

$d = 16$ mm

$\alpha = 10$ W/m^{2}K

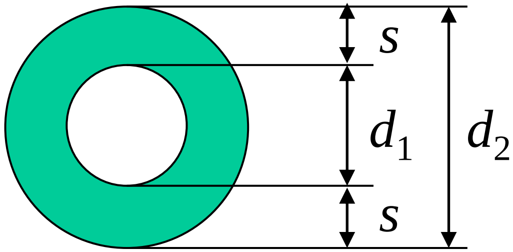
$s = 20$ mm

$\lambda = 0.05$ W/mK

$L = 50$ m

$T_a = 10$ °C

Solution – I



1. Pipe diameter with insulation:
   - $d_1 = 16$ mm = 0.016 m
   - $d_2 = d_1 + 2s = (16 + 2\cdot20)$ mm = 56 mm = 0.056 m

2. U'-value:

$$U' = \frac{1}{\frac{1}{2\pi\lambda}\ln\frac{d_2}{d_1} + \frac{1}{\pi d_2 \alpha_2}} = \frac{1}{\frac{1}{2\pi\cdot 0.05\,\frac{\mathrm{W}}{\mathrm{mK}}}\ln\frac{0.056\,\mathrm{m}}{0.016\,\mathrm{m}} + \frac{1}{\pi\cdot 0.056\,\mathrm{m}\cdot 10\,\frac{\mathrm{W}}{\mathrm{m^2K}}}} = 0.22\,\frac{\mathrm{W}}{\mathrm{mK}}$$

3. Heat capacity flow:
   - Specific heat capacity of water: $c_{pw} = 4.186$ kJ/kgK
   - Heat capacity flow: $\dot{C} = q_m c_{pw} = 0.1\,\frac{\mathrm{kg}}{\mathrm{s}}\cdot 4.186\,\frac{\mathrm{kJ}}{\mathrm{kgK}} = 419\,\frac{\mathrm{W}}{\mathrm{K}}$

Solution – II

4. Final temperature and the error due to discretization:

- Cooling law:

$$\frac{T_{w,n}-T_a}{T_{w,n-1}-T_a}=e^{-\frac{U'\Delta L}{\dot{C}}}\Leftrightarrow T_{w,n}=T_a+e^{-\frac{U'\Delta L}{\dot{C}}}\cdot\left(T_{w,n-1}-T_a\right)=10^{\circ}\mathrm{C}+e^{-\frac{0.22\cdot 50}{419}}\cdot(80-10)^{\circ}\mathrm{C}=\underline{\underline{78.19^{\circ}\mathrm{C}}}$$

- Discretized calculation:

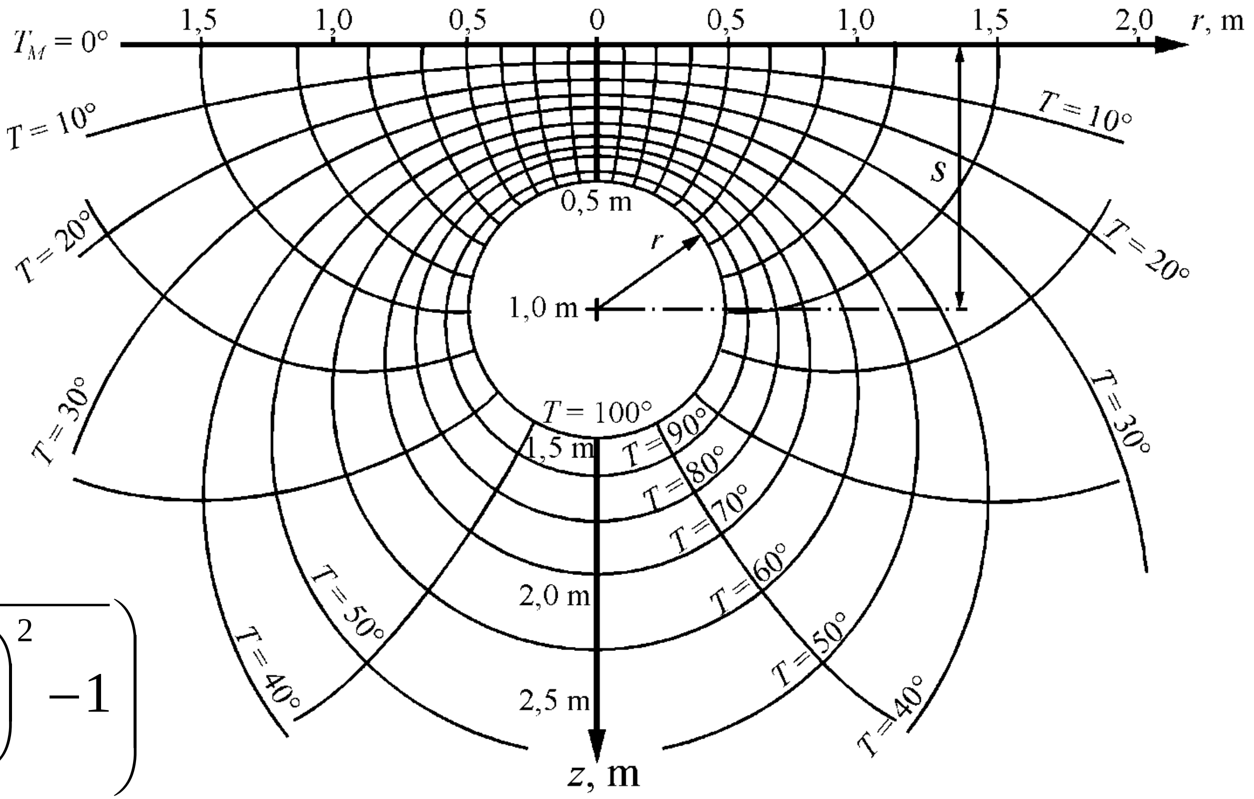
$$T_{w,n}=T_{w,n-1}-\frac{U'\Delta L}{\dot{C}}\left(T_{w,n-1}-T_a\right)=80^{\circ}\mathrm{C}-\frac{0.22\,\frac{\mathrm{W}}{\mathrm{mK}}\cdot 50\,\mathrm{m}}{419\,\frac{\mathrm{W}}{\mathrm{K}}}\cdot(80-10)^{\circ}\mathrm{C}=\underline{\underline{78.16^{\circ}\mathrm{C}}}$$

- Conclusion: In the present application the difference is negligible (0.3 ‰).

Thermal resistance of underground pipe

The total thermal resistance of an underground pipe is the sum of thermal resistances of

- insulation layer (I)
- ground layer (G)



$$\frac{1}{U}=\frac{1}{U_I}+\frac{1}{U_G}$$

where

$$\frac{1}{U_I}=\frac{1}{2\pi\lambda_I}\ln\frac{d_1}{d_2}$$

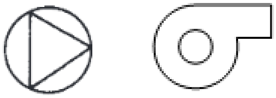
$$\frac{1}{U_G}=\frac{1}{2\pi\lambda_G}\ln\left(\frac{s}{r}+\sqrt{\left(\frac{s}{r}\right)^2-1}\right)$$

Prime movers in HVAC technology

Prime movers:

- Pumps

- Fans



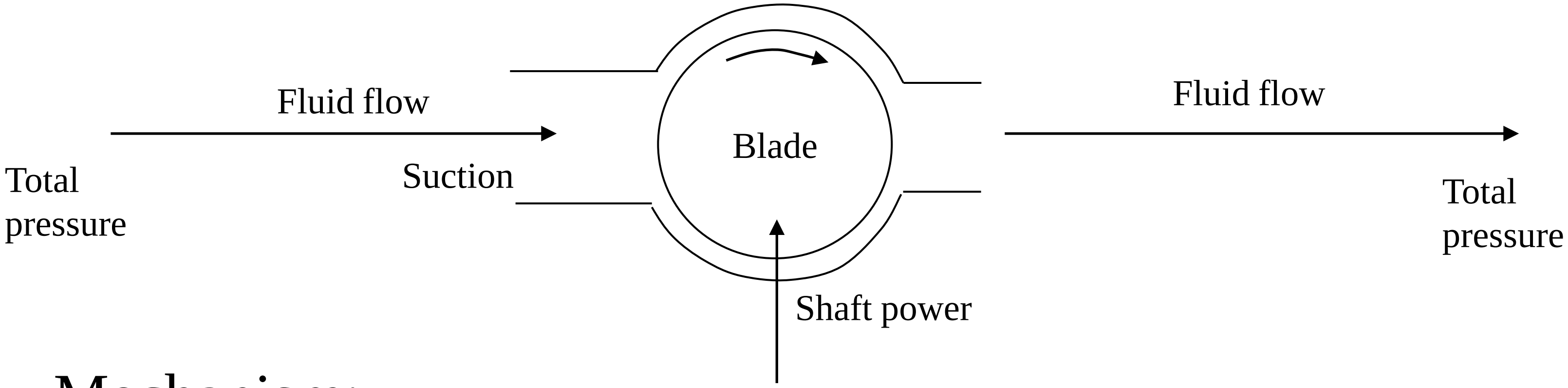
- Compressors

Applications in heating and cooling:

- Circulation pumps
- DHW circulation pumps
- Pressure elevation pumps
- District heating
- Fan coils
- Refrigeration compressors

Operational philosphy of pumps and fans

- The purpose of prime movers is to balance pressure losses in fluid flow systems.



Fluid flow

Total pressure

Suction

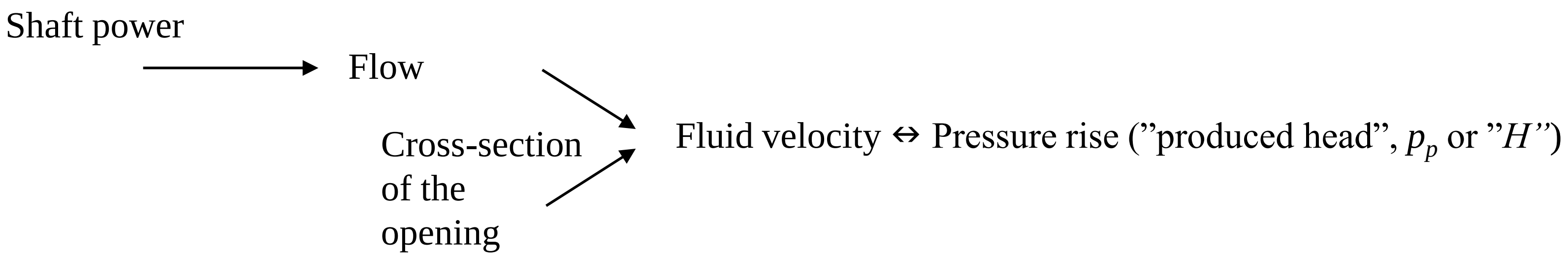
Blade

Shaft power

Fluid flow

Total pressure

- Mechanism:



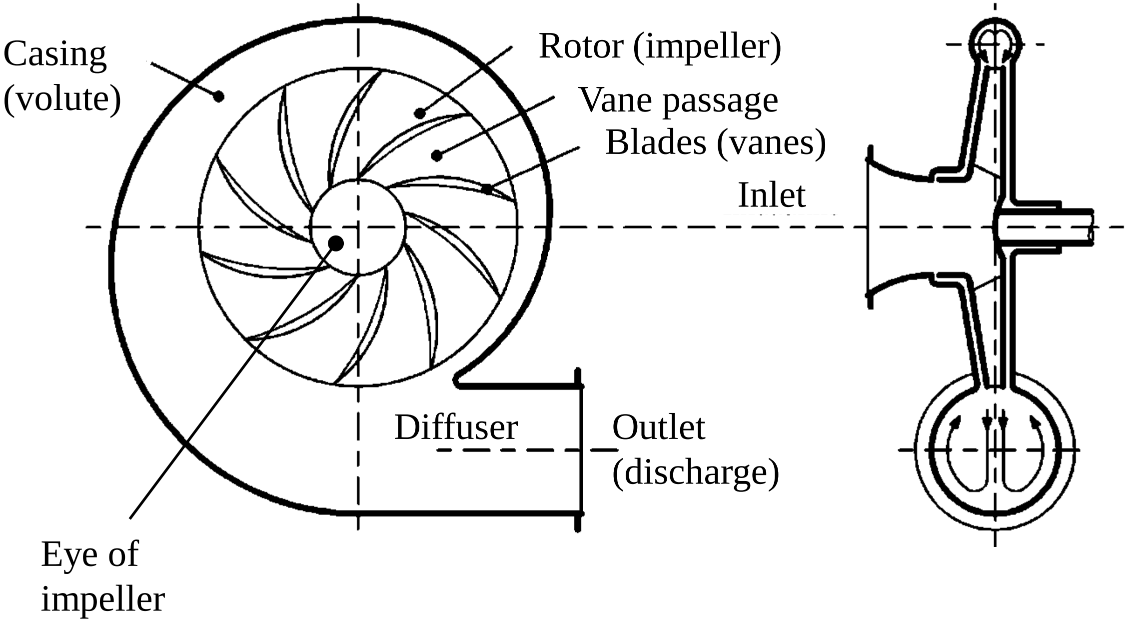
Shaft power

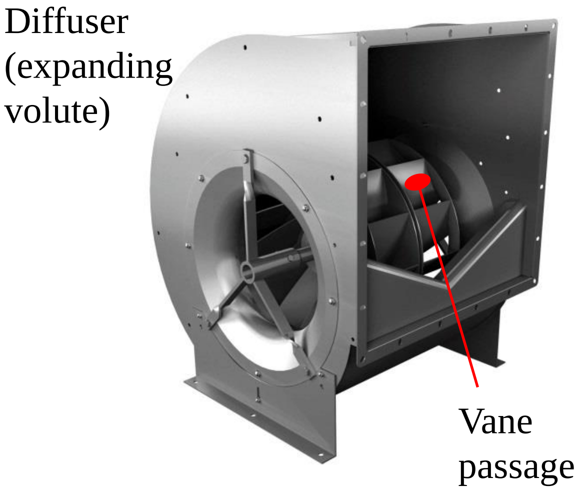
Flow

Cross-section of the opening

Fluid velocity ⇔ Pressure rise (”produced head”, p_p or ”H”)

Structure of centrifugal pumps and fans





Centrifugal fan

Pressure rise in pumps and fans

- Energy conservation:

$$p_1 + \rho g z_1 + \frac{1}{2}\rho v_1{}^2 + p_{tp} = p_2 + \rho g z_2 + \frac{1}{2}\rho v_2{}^2$$

$$z_1 = z_2$$

$$\rightarrow p_1 + \frac{1}{2}\rho v_1{}^2 + p_{tp} = p_2 + \frac{1}{2}\rho v_2{}^2$$

- Pressure rise (total pressure):

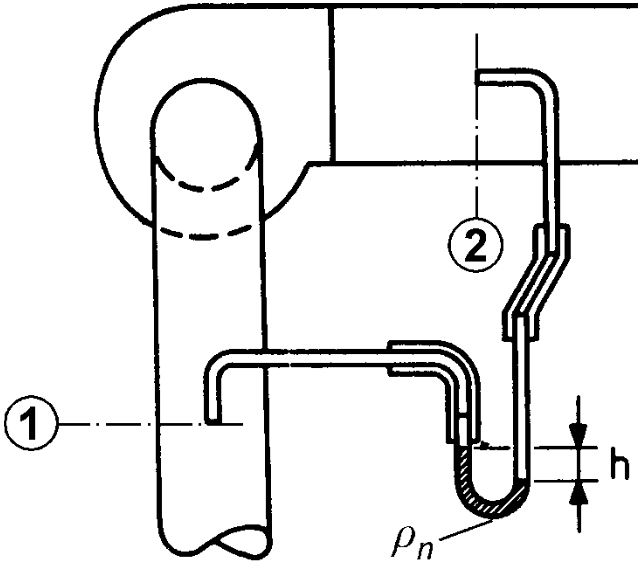
$$p_{tp} = \underbrace{p_2 - p_1}_{= p_{sp}} + \underbrace{\frac{1}{2}\rho\left(v_2{}^2 - v_1{}^2\right)}_{= p_{dp}}$$

- Pressure rise (static pressure):

$$p_{sp} = p_2 - p_1$$

- Pressure rise (dynamic pressure):

$$p_{dp} = \frac{1}{2}\rho\left(v_2{}^2 - v_1{}^2\right)$$



$$p_{tp} = \rho_n g h$$

Pressure generation in centrifugal pumps and fans

Static pressure rise due to the acceleration of fluid flow:

$$\Delta p_u = \frac{1}{2}\rho\left(u_2^2 - u_1^2\right) \quad \text{increase of the peripheral speed } u_2 > u_1$$

Static pressure regain due to slow-down of fluid flow:

$$\Delta p_w = \frac{1}{2}\rho\left(w_1^2 - w_2^2\right) \quad \text{expansion of the vane passage } A_2 > A_1, w_2 < w_1$$

Static pressure rise:

$$p_{sp} = \Delta p_u + \Delta p_w = p_2 - p_1$$

Energy conservation for vane passage:

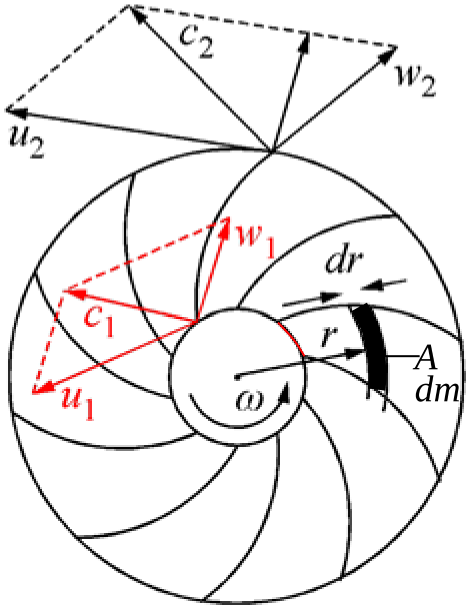
$$p_1 + \frac{1}{2}\rho c_1^2 + p_{tp} = p_2 + \frac{1}{2}\rho c_2^2$$

c is the resultant velocity (i.e. absolute velocity), implicitly defined on the basis of *u* and *w*.

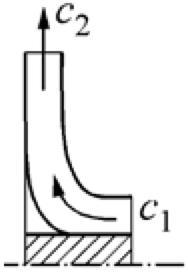
Generated total pressure:

$$\Leftrightarrow p_{tp} = p_2 - p_1 + \frac{1}{2}\rho\left(c_2^2 - c_1^2\right) = p_{sp} + \frac{1}{2}\rho\left(c_2^2 - c_1^2\right) = \Delta p_u + \Delta p_w + \frac{1}{2}\rho\left(c_2^2 - c_1^2\right)$$

<u>Velocity diagram:</u>

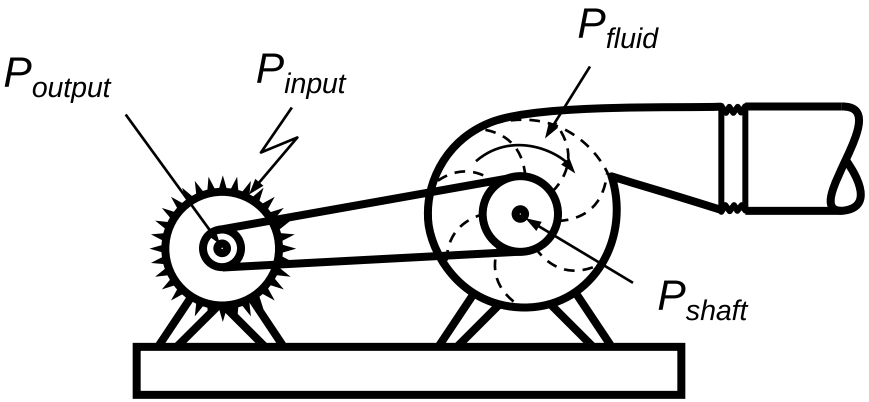


A = area of vane passage



Self-studying: Derive the static pressure rise due to the acceleration of fluid flow from the centrifugal force for the mass element $dm = Adr$. The centrifugal force is defined as $F_c = dm \cdot \omega^2 r$ and $p = F_c/A$.

Efficiency of pumps and fans



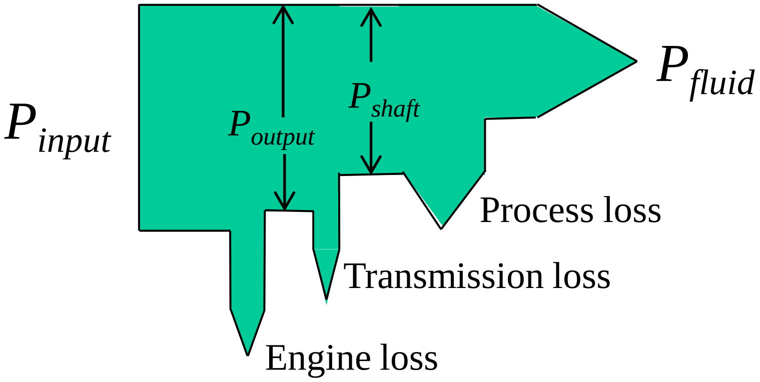
Origin of losses:

- blading and casing
- bearing
- transmission
- engine

Fluid power (effective output) $P_{fluid} = q_V \cdot p_{tp} = q_m \cdot \dfrac{p_{tp}}{\rho}$

Total efficiency $\eta_{tot} = \dfrac{P_{fluid}}{P_{input}}$

Prime mover efficiency
(provided by manufacturer) $\eta_p = \dfrac{P_{fluid}}{P_{shaft}}$



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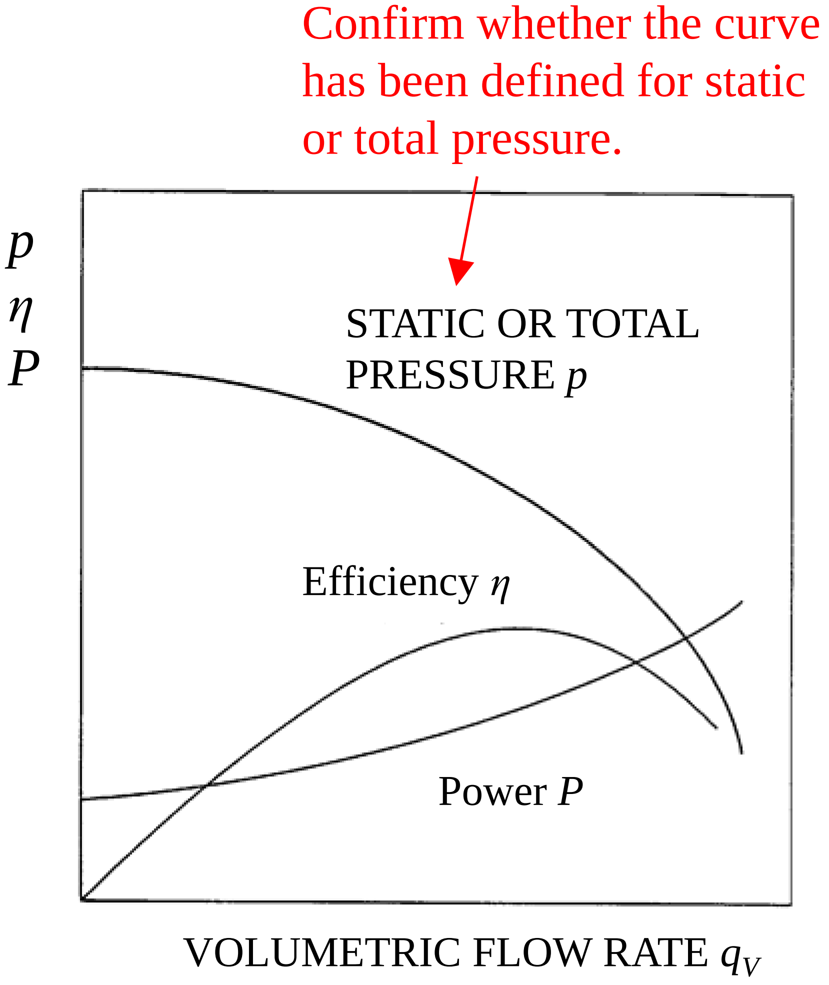
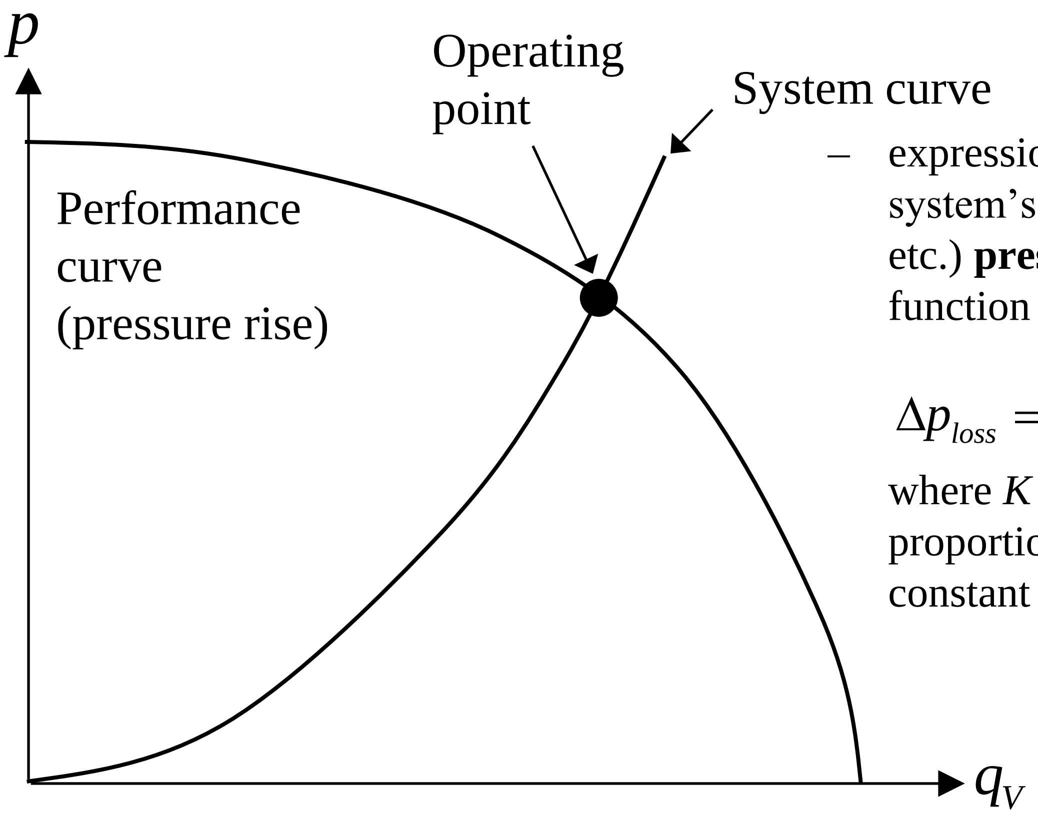
Performance curve

- Performance curve
  - relationship between pressure rise (static or total pressure) and flow rate
  - individual for each equipment
  - defined for ideal flow conditions
- Total pressure increases, if
  - density increases
  - rotational speed increases
  - diameter increases



System curve and operating point



- expression of the system's (pipework etc.) **pressure loss** as a function of flow rate

$$\Delta p_{loss} = K \cdot \dot{q}_V^{\,2}$$

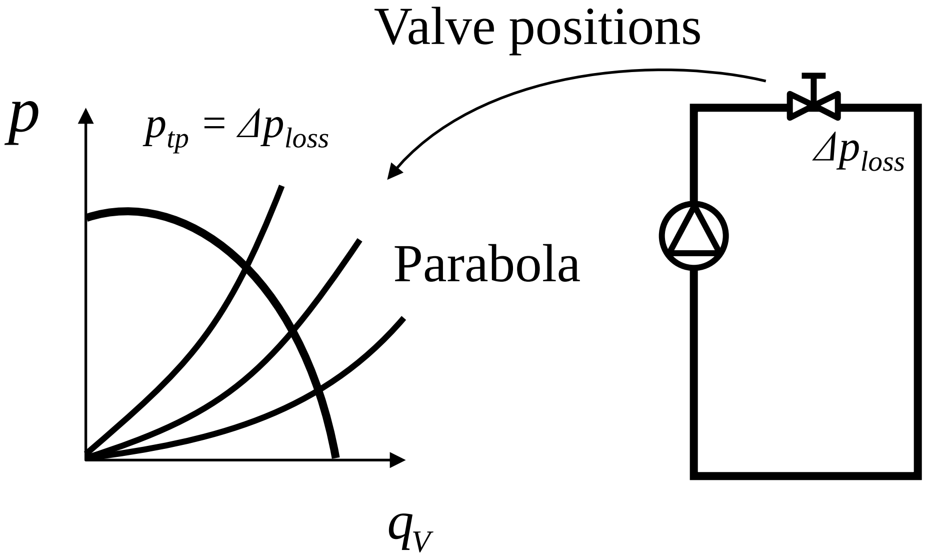
where K is a proportionality constant

A workable system presumes that the pressure rise of the prime mover is equal to the sum of frictional and minor losses of the pipe-/ductwork:

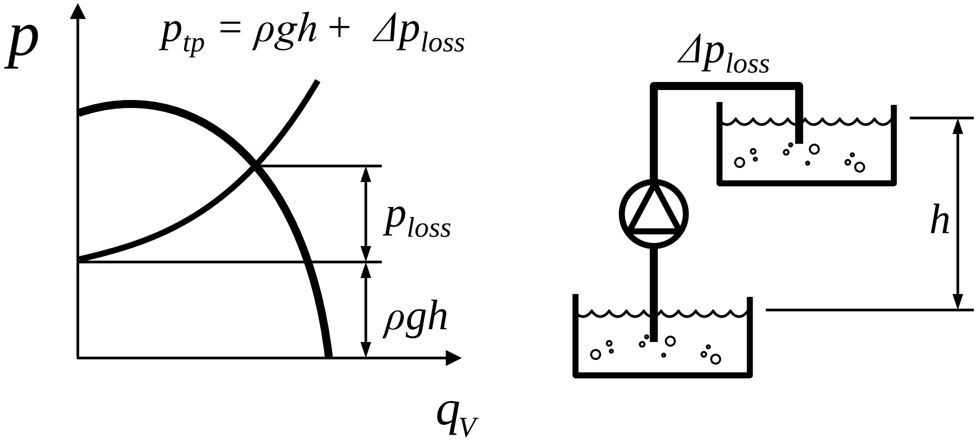
$$p_{tp} = \Delta p_{loss} = \Delta p + \Delta p_f$$

System curve & operating point – Open vs. closed loop system

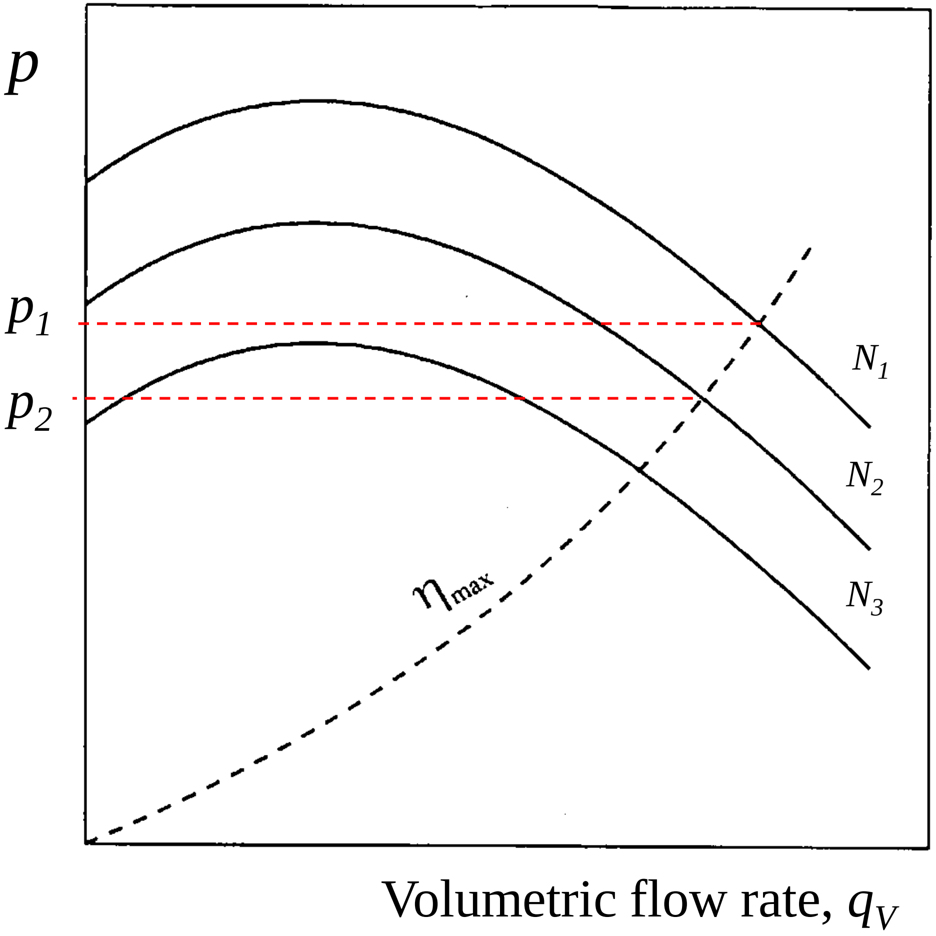
Closed loop system



Open loop system



System curve & operating point – Impact of rotation speed



$$q_{v2} = \frac{N_2}{N_1} q_{V1}$$

$$p_2 = \left(\frac{N_2}{N_1}\right)^2 p_1$$

Aalto University

Affinity Laws

- Affinity – ”a quality that makes things suited to each other” (Merriam-Webster)
- Affinity laws determine the relationship between the variables of performance (static *or* total pressure, flow rate, power demand, rotation speed, diameter) for pumps and fans.
- Subscript 1 stands for an initial operation; subscript 2 the operation after a change
- The key affinity laws:

→ Rotation speed change *N***:**

$$\boxed{\frac{q_{V2}}{q_{V1}} = \frac{N_2}{N_1} \qquad \frac{p_2}{p_1} = \left(\frac{N_2}{N_1}\right)^2 \qquad \frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3}$$

→ Diameter change *D***:**

$$\boxed{\frac{q_{V2}}{q_{V1}} = \left(\frac{D_2}{D_1}\right)^3 \qquad \frac{p_2}{p_1} = \left(\frac{D_2}{D_1}\right)^2 \qquad \frac{P_2}{P_1} = \left(\frac{D_2}{D_1}\right)^5}$$

Example

The volumetric flow rate is increased by 20 %. How many percent will the pressure rise change?

Solution

Let it be q_{V1} = 100 % → q_{V2} = (100 + 20) % = 120 % = 1.2.

From the affinity laws:

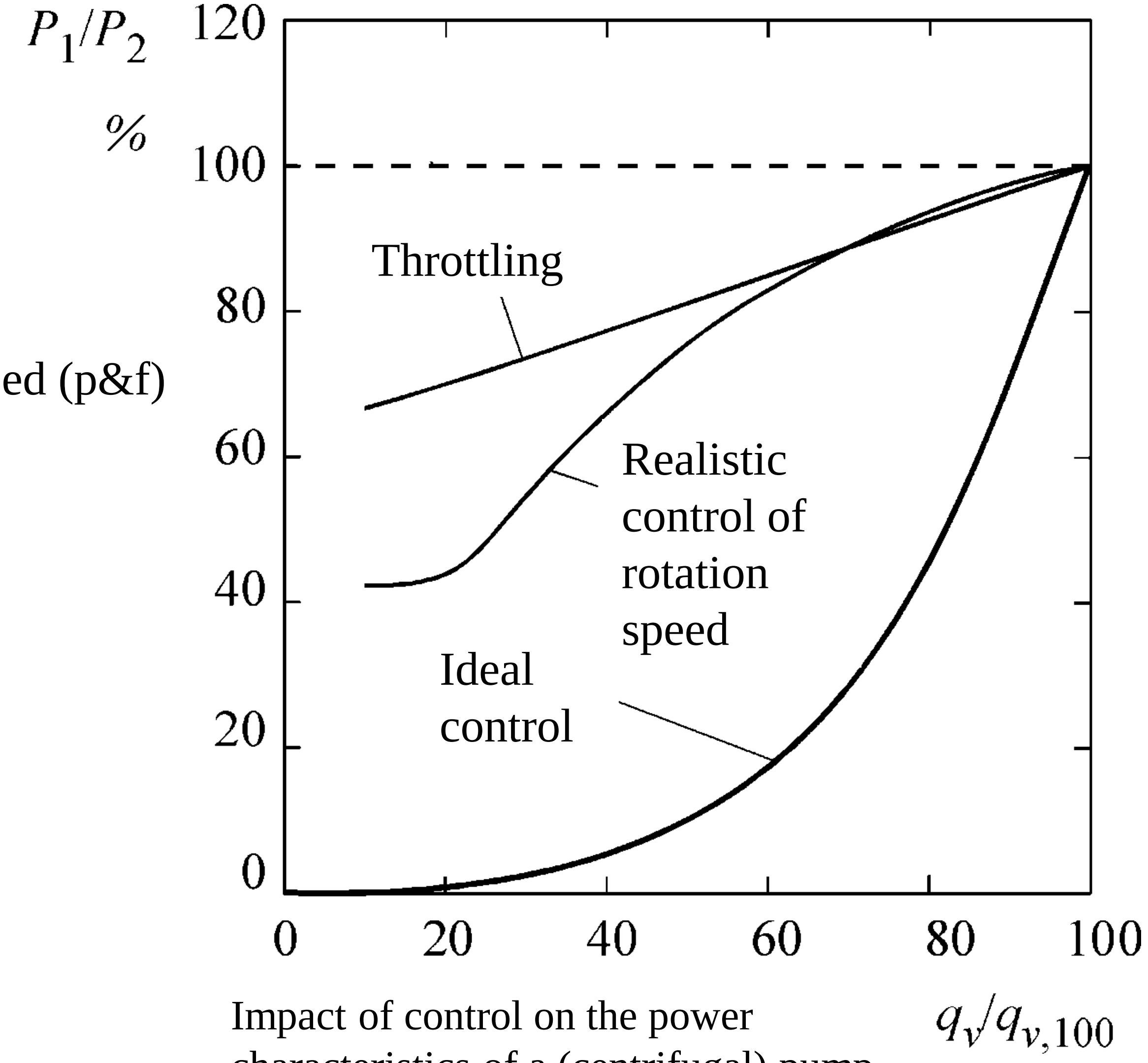
$$\frac{q_{V2}}{q_{V1}} = \frac{N_2}{N_1} = 1.2$$

$$\Rightarrow \frac{p_2}{p_1} = (1.2)^2 = 1.44$$

$$\Rightarrow \underline{\underline{\text{The pressure rise increases by 44\%.}}}$$

Control of prime movers

1. Ideal control (pumps & fans)
2. Realistic control of rotation speed (p&f)
3. Blade pitch adjustment (fans)
4. Vane control (fans)
5. Throttling (pumps & fans)

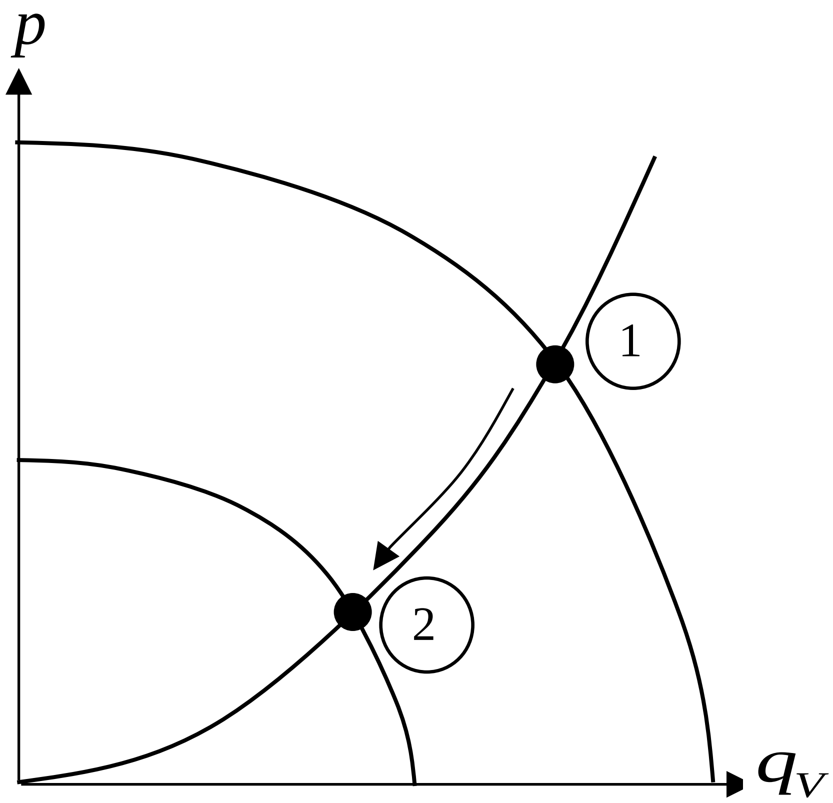


Impact of control on the power characteristics of a (centrifugal) pump

Ideal control

- Rotational speed changes → Performance curve moves towards new operating point (2).
- Implementation (near ideal control):

1. multi-pole induction motor
2. V-belt drive pulleys
3. gearing
4. hydraulic switch
5. inverter + induction motor
6. thyristor control + DC motor



Example

At the rotation speed 1400 r/min the volumetric air flow rate of a fan (free inlet, no duct) is 3 m^3/s, the static pressure rise is 1200 Pa, and the fluid velocity 10 m/s. What is the theoretical power demand of the fan and how does it behave, when the air flow rate is reduced to half using an ideal control? What is the new rotation speed?

Solution – I

1. Theoretical power demand (= fluid power) at 1400 r/min:
   - Assumption: ρ = 1.2 kg/m^3

Free inlet:
$\rightarrow p_{d1} = 0$

$$P_{fluid} = q_V\, p_{tp} = q_V \cdot \left(p_{sp} + p_{dp}\right) = q_V \cdot \left(p_{sp} \boxed{+ \frac{1}{2}\rho v^2} \right)$$

$$= 3\,\frac{\mathrm{m}^3}{\mathrm{s}} \cdot \left(1200\ \mathrm{Pa} + \frac{1}{2} \cdot 1.2\,\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot \left(10\,\frac{\mathrm{m}}{\mathrm{s}} \right)^2 \right) = \underline{\underline{3780\ \mathrm{W}}}$$

Solution – II

2. Reduced rotation speed:

$$\text{Affinity law}: \frac{q_{V2}}{q_{V1}} = \frac{N_2}{N_1}$$

$$\Rightarrow N_2 = \frac{q_{V2}}{q_{V1}} \cdot N_1 = \frac{3\,\frac{\text{m}^3}{\text{s}}}{(1-0.5)\cdot 3\,\frac{\text{m}^3}{\text{s}}} \cdot 1400\,\frac{\text{r}}{\text{min}} = \underline{\underline{700\,\frac{\text{r}}{\text{min}}}}$$

Solution – III

3. Theoretical power demand at 700 r/min:

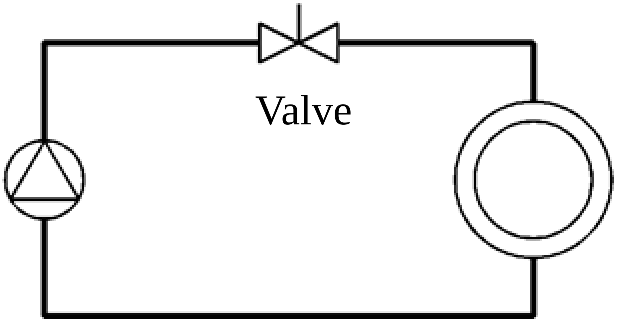
$$\text{Fan law}: \frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3$$

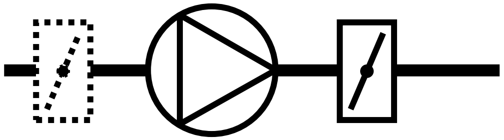
$$\Rightarrow P_2 = \left(\frac{N_2}{N_1}\right)^3 \cdot P_1 = \left(\frac{700\ \dfrac{\text{r}}{\text{min}}}{1400\ \dfrac{\text{r}}{\text{min}}}\right)^3 \cdot 3780\ \text{W} = \underline{\underline{473\ \text{W}}}$$

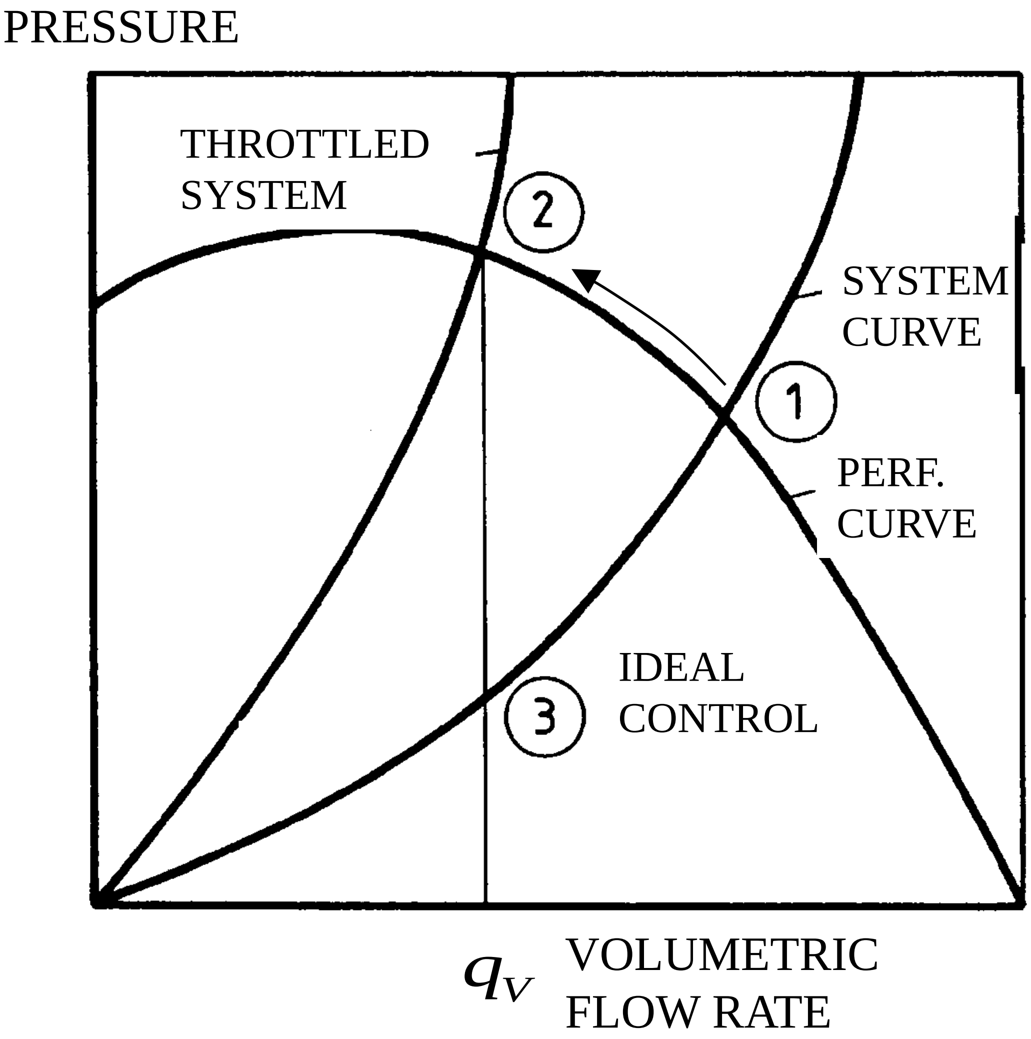
$$\left(\text{Reduction - \%}: \frac{3780 - 473}{3780} \cdot 100\% = 87\%\right)$$

Throttling

- System curve changes (1 → 2).





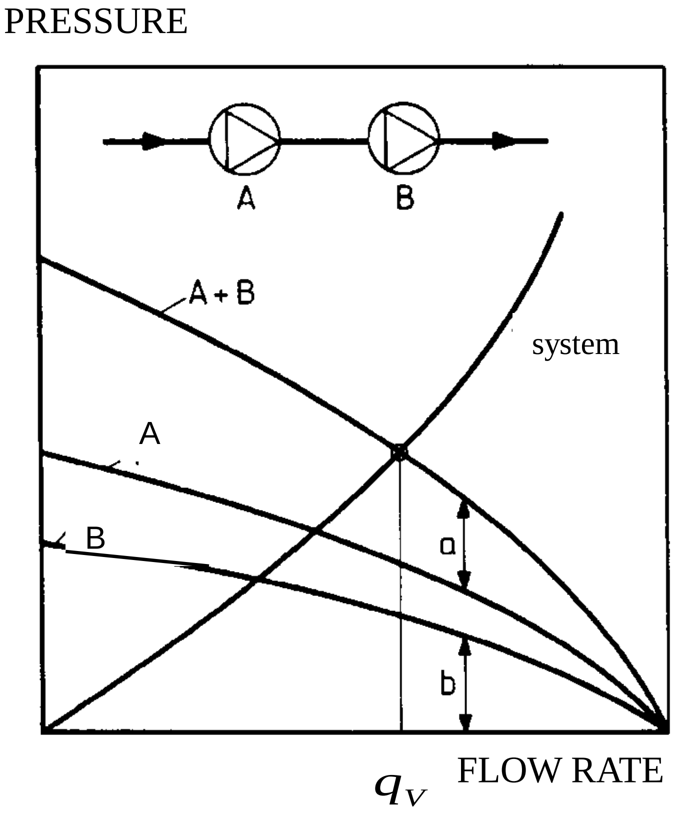


Vane control and blade pitch adjustment for fans

- Vane control
  - The fluid is driven to rotation using inlet guide vanes (IGV).
  - The flow rate is proportional to the rotation speed.
- Blade pitch adjustment
  - In axial fans, the adjustment of the blade pitch results in the change of flow rate and pressure.
  - Minimal losses

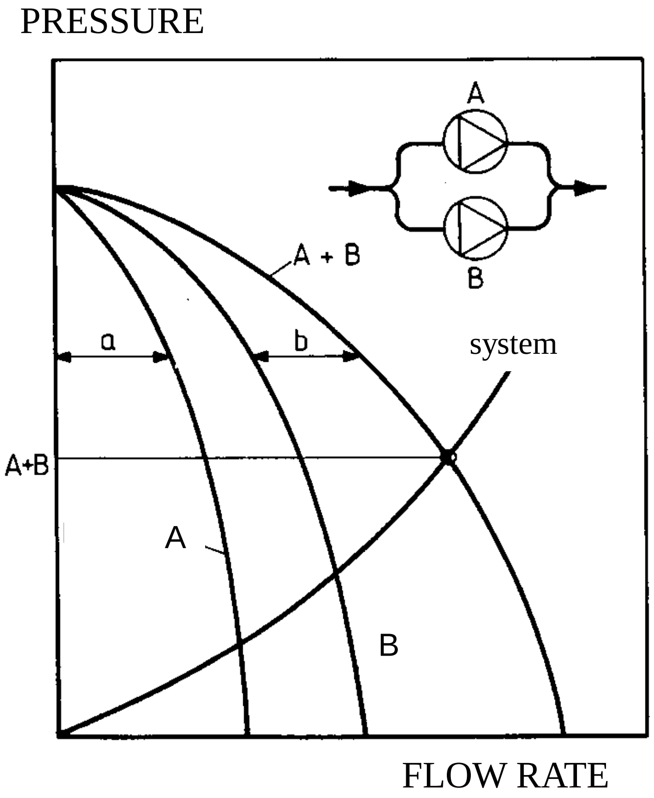
Impact of coupling

In series



- – volumetric flow rate constant
- – pressures are added together

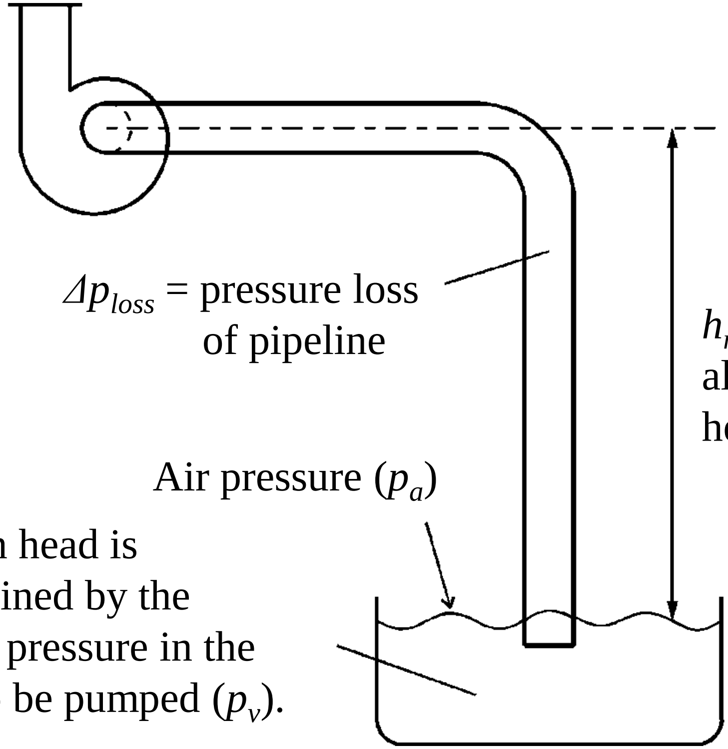
In parallel



- – flow rates are added together
- – constant pressure

Cavitation

- *Cavitation* is the formation of vapor cavities in a liquid due to evaporation caused by low pressures (*flashing*) and shock waves due to implosion of the vapor cavities due to condensation as a consequence of pressure rise.
- Cavitation is harmful for pumps and therefore the *suction head* is constrained.

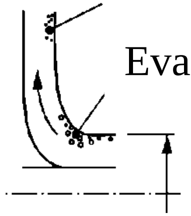


Δp_{loss} = pressure loss of pipeline

h_{max} = maximum allowable suction head

Air pressure (p_a)

Suction head is constrained by the vapour pressure in the fluid to be pumped (p_v).

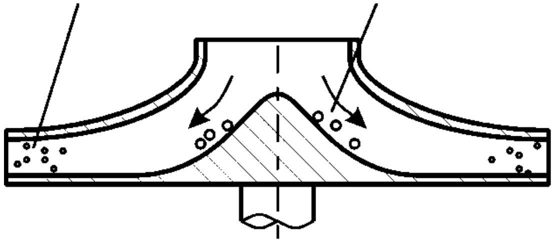


Condensation

Evaporation

h_{max}

Evaporation and condensation in the impeller



Condensation

Evaporation

Net Positive Suction Head (NPSH)

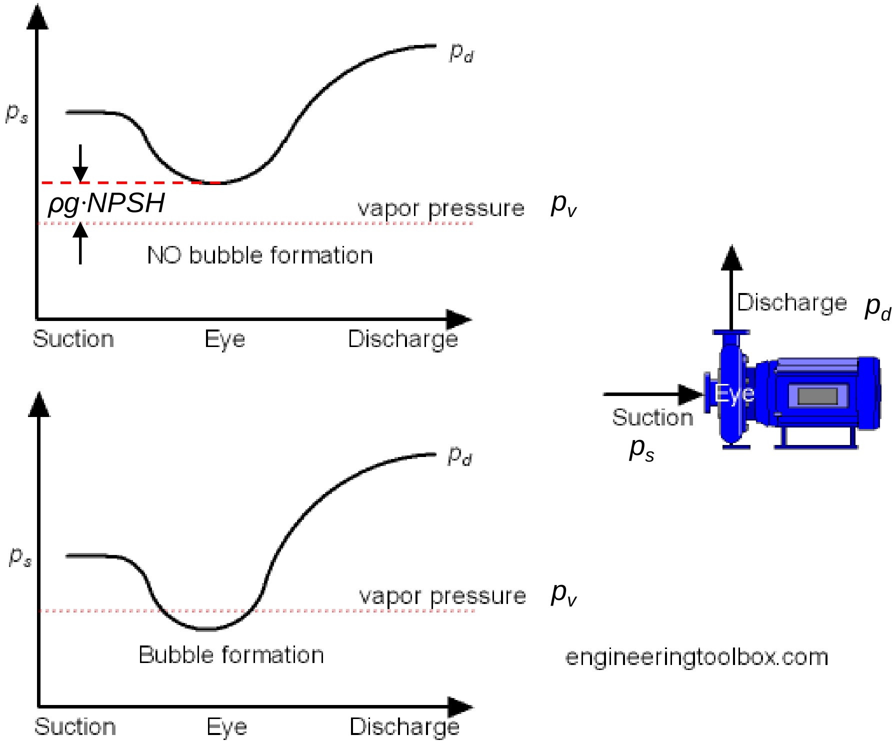
NET POSITIVE SUCTION HEAD (NPSH)

- determines the condition to keep the fluid to be pumped from cavitation
- is defined by manufacturer for each impeller through structural parameters (λ_1 and λ_2), velocities (w_1 and c_1) and the standard gravity (g):

$$NPSH = \frac{1}{g}\left(\lambda_1 \frac{w_1^2}{2} + \lambda_2 \frac{c_1^2}{2}\right)$$

The condition to avoid cavitation:

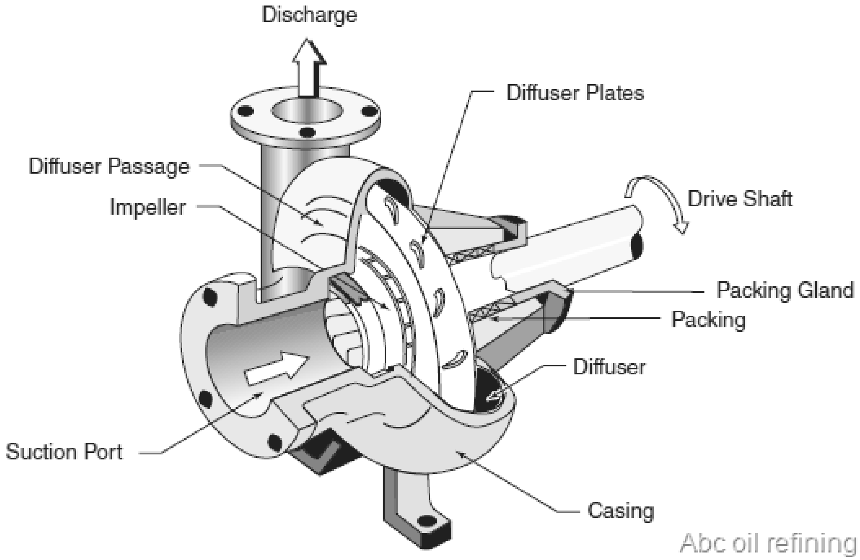
$$p_v = p_a - \Delta p_{loss} - \rho g h_{\max} - \rho g \cdot NPSH$$



engineeringtoolbox.com

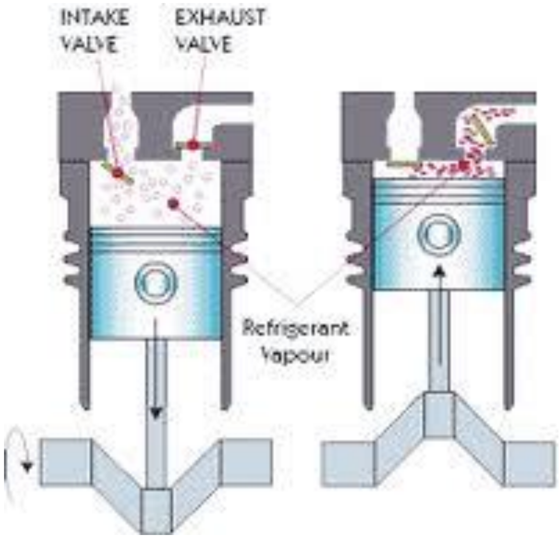
Compressors – types

1. Centrifugal compressors

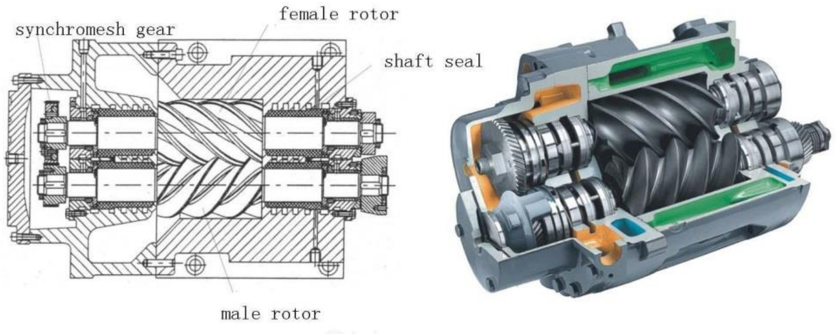


Abc oil refining

2. Reciprocating compressors



3. Screw compressors

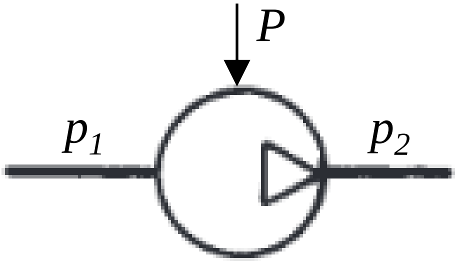


Screw Compressor Structure

Compressors – ideal gas processes

Compressors:

- method to pressurize/transport gases
- $p_2/p_1 > 1.15$ (typically)



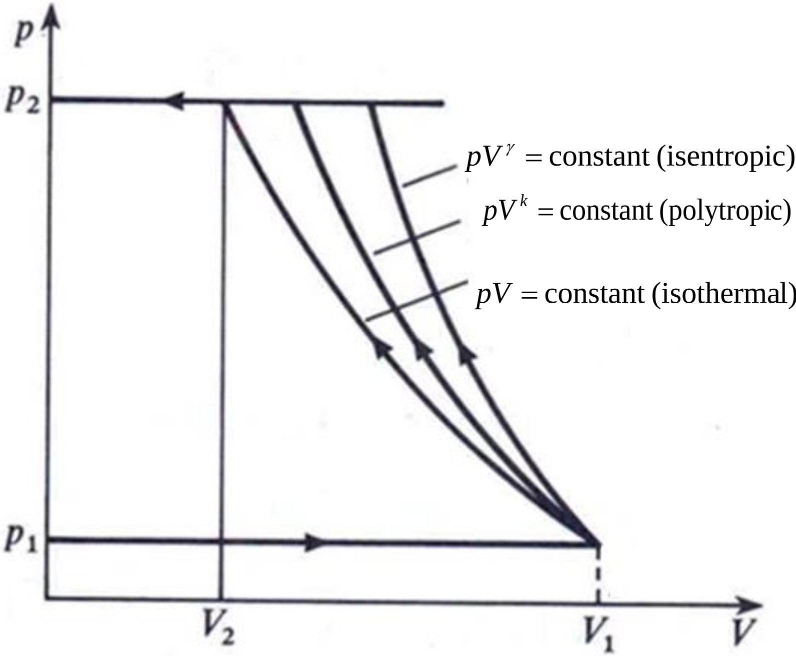
For ideal gas: polytropic process from 1 to 2:

$$pV^k = \text{constant}$$

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}}$$

$$P = q_m \frac{k}{k-1} RT_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right]$$

where n = polytropic exponent
R = universal gas constant (8.314 J/molK)
T = temperature in [K]



$k = \gamma = 1.4$ (isentropic)

$k = 1$ (isothermal)

Compressors – real gas processes

For the compression of real gases (e.g. refrigerants), the ideal gas law is not accurate. Here, the process is modeled by way of the *isentropic efficiency*.

$$\eta_s = \frac{h_{2s} - h_1}{h_2 - h_1}$$

$$P = q_m \left(h_2 - h_1 \right)$$

where η_s = isentropic efficiency