FACULTY
OF MECHANICAL
ENGINEERING
CTU IN PRAGUE

Environmental Engineering

Heating Systems

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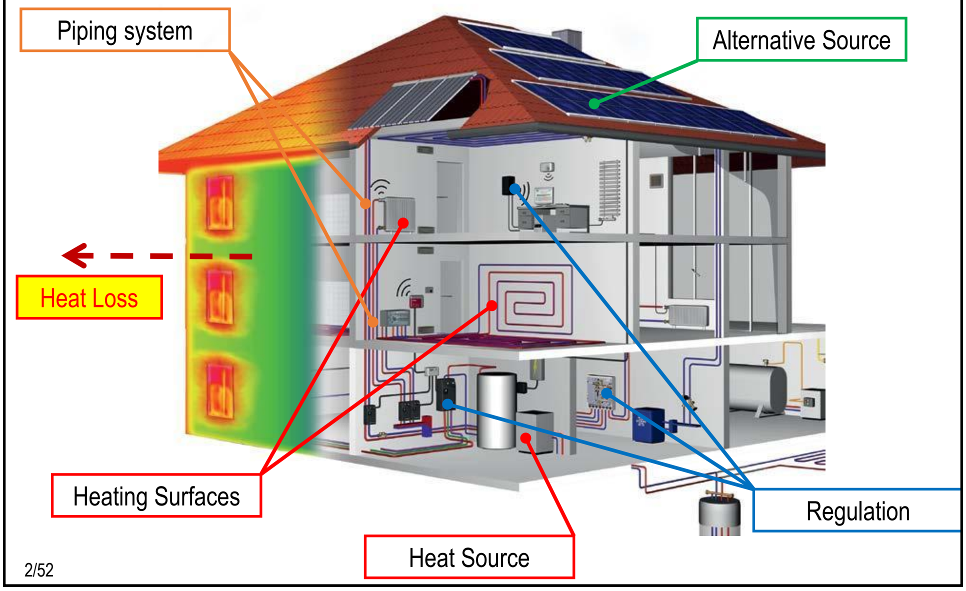
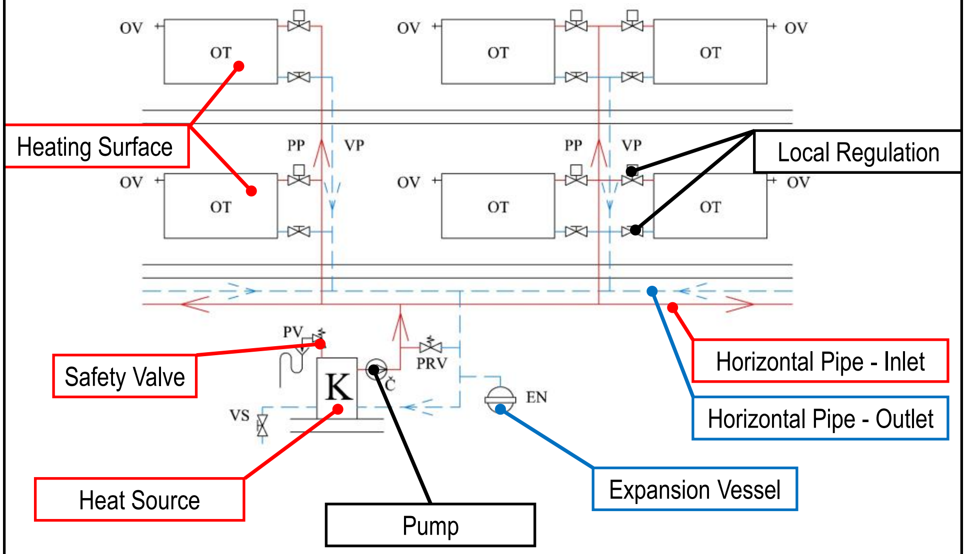
Heating Systems – Basic Elements



Heating Systems – Typical Elements - Drawing



Heating Surface

Local Regulation

Safety Valve

Horizontal Pipe - Inlet

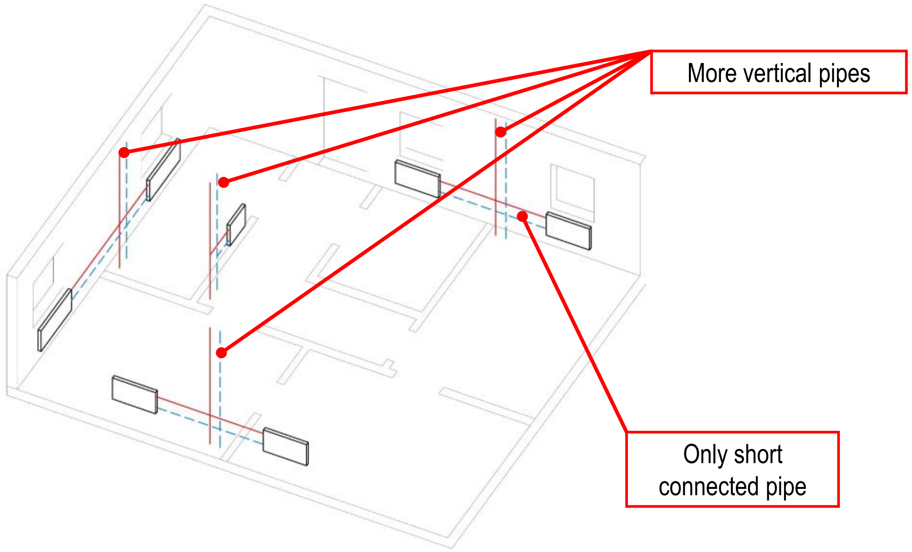
Horizontal Pipe - Outlet

Heat Source

Pump

Expansion Vessel

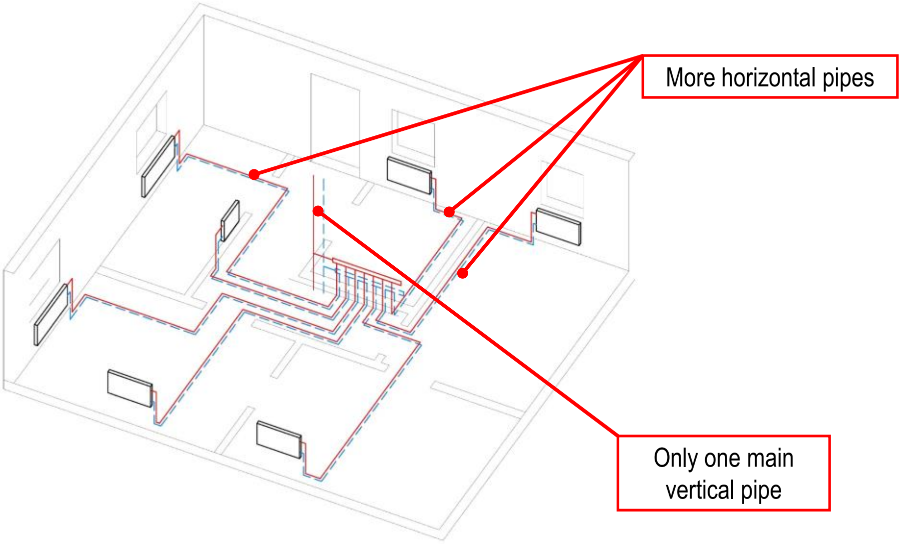
Vertical Heating Systems



More vertical pipes

Only short connected pipe

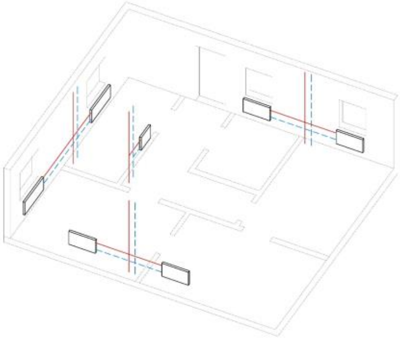
Horizontal Heating Systems

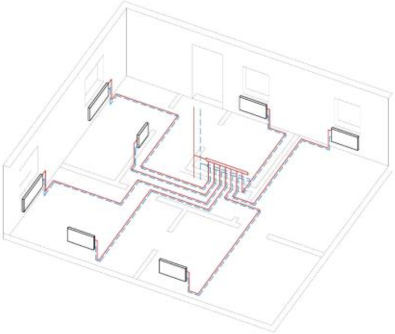


More horizontal pipes

Only one main vertical pipe

Horizontal vs. Vertical Heating Systems





Less Pipe (shorter pipe lengths)

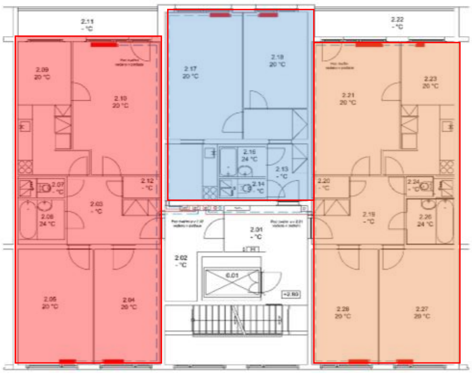
Exactly measurement of heat consumption

Horizontal vs. Vertical Heating Systems

ONE CENTRAL SOURCE

ONE CENTRAL SOURCE

or possibility of own heat source in the each apartments - INDEPENDENTLY



Heating Systems – Pipe materials

Copper - *Cu*

Advantages:

- ✓ high corrosion resistance,
- ✓ low weight of 1 m of pipe = easier installation,
- ✓ lower pressure losses (compared to steel)

Soldering - burner

Pressing – special pliers

Disadvantages:

- ✓ higher price,
- ✓ greater thermal expansion (compared to steel by about 40 %)

Heating Systems – Pipe materials

Plastic

Advantages:
- ✓ corrosion resistance,
- ✓ low pressure drop (compared to all metallic materials),
- ✓ electrical non-conductivity and hygienic safety

Butt welding

Pressing – special pliers

Disadvantages:
- ✓ more higher values of thermal expansion (10 times more than with metallic materials),
- ✓ lower heat and pressure resistance,
- ✓ ***flammability !!!!!!!***

Heating Systems – Pipe materials

Steel - *Fe*

Advantages:
- ✓ lower price,
- ✓ high variability of connection

Thick-walled pipes – threaded joints

Thick-walled pipes - welding

Thin-walled pipes – pressing special pliers

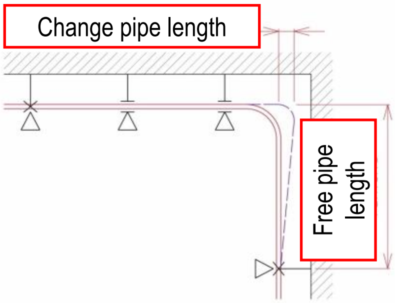
Disadvantages:
- ✓ low corrosion resistance,
- ✓ weight (for thick-walled pipes)

Heating Systems – Pipe materials – Thermal Expansion

$$\Delta l = l_0 \cdot \alpha \cdot \Delta t$$

Δl – change pipe length [mm]
l_0 - pipe length [m]
α - coefficient of thermal particle expansion [mm/m·K]
Δt - temperature difference [K]

Pipe Material	Coefficient of thermal particle expansion *α* [mm/m·K]
Steel	0,012
Copper	0,017
Aluminium	0,0238
Plastic (PVC)	0,026
Plastic (PEX)	0,08



Heating Systems – Pipe materials – Thermal Expansion

$$\Delta l = l_0 \cdot \alpha \cdot \Delta t$$

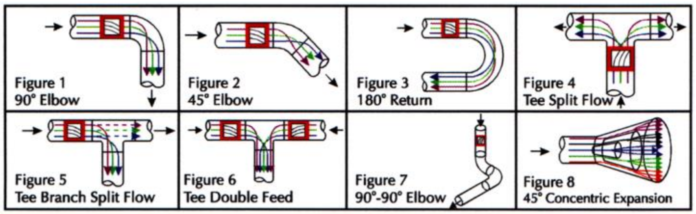
Example 1:

Pipe length is 10 m for pipe DN 15, when heated by 50 K.

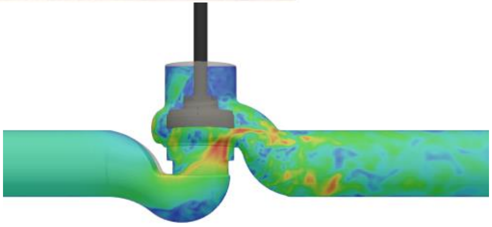
Pipe Material	Coefficient of thermal particle expansion *α* [mm/m·K]	Change pipe length Δ*l* [mm]
Steel	0,012	
Copper	0,017	
Aluminium	0,0238	
Plastic (PVC)	0,026	
Plastic (PEX)	0,08	

Heating Systems – Pressure Equations

Local Loss



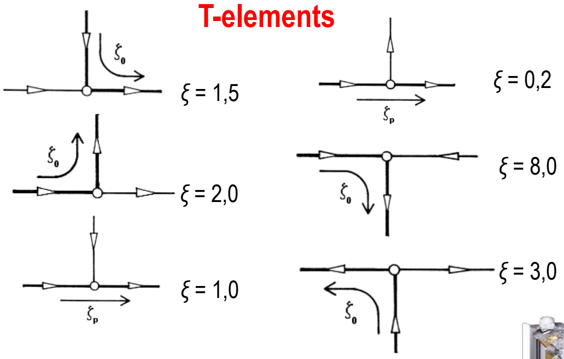
- ✓ Elbows, Tee-Elements, Expansion, etc.
- ✓ Valves, Check Valve, Radiators, etc.



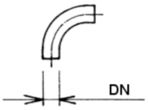
Heating Systems – Pressure Equations

Local Loss

T-elements



Elbow - Bend



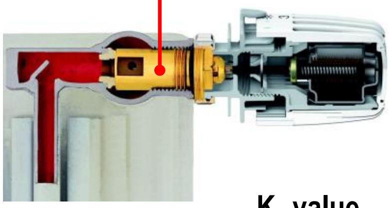
DN	ξ [-]
10-15	2,0
20-25	1,5
32-40	1,0
50 and more	0,5

Main parts	ξ [-]
Boiler cast iron	2,50
Boiler steel	2,00
Element radiator	2,50
Panel radiator	8,50

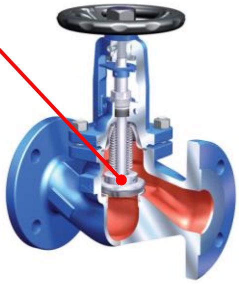
Heating Systems – Pressure Equations

Local Loss - Valves

Thermostatic valve



Control valve



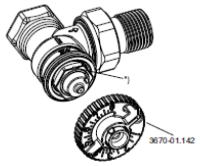
K_v value – nominal flow [m³/h]

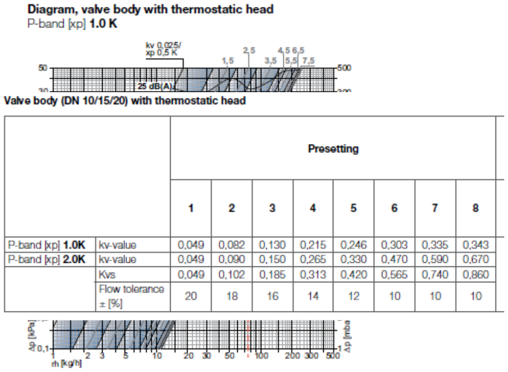
$$k_v = \dot{V}\cdot\sqrt{\frac{100}{\Delta p_{Valve}}}\cdot\sqrt{\frac{\rho}{1000}} \Rightarrow \Delta p_{Valve} = \left(\frac{\dot{V}}{k_v}\right)^2\cdot\frac{\rho}{10}$$

Heating Systems – Pressure Equations

Local Loss - Valves

Thermostatic valve





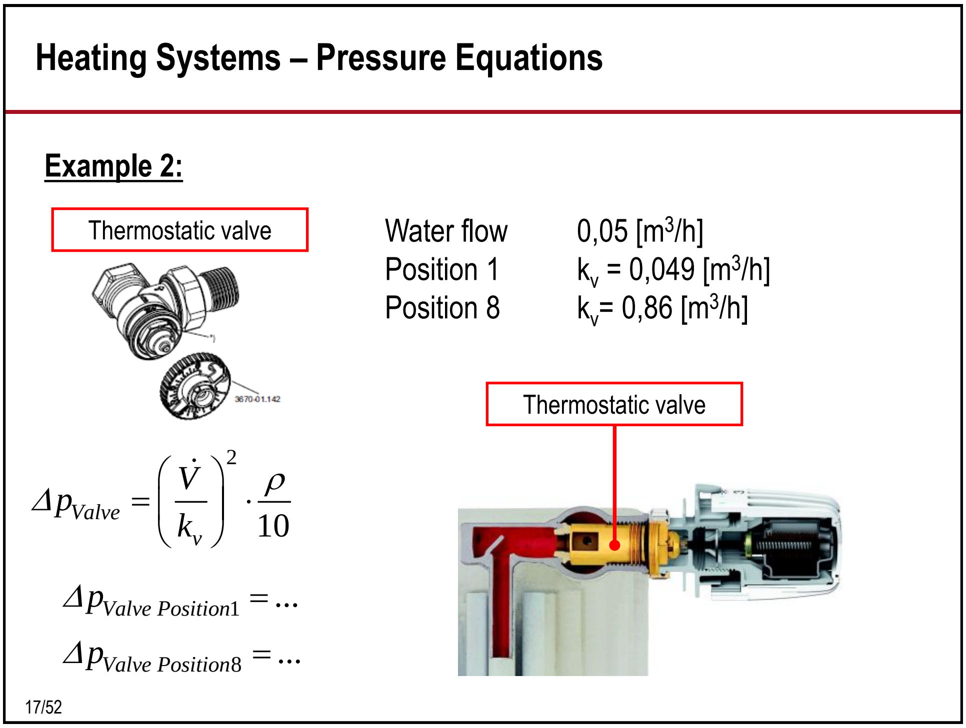
Diagram, valve body with thermostatic head
P-band [xp] **1.0 K**

Valve body (DN 10/15/20) with thermostatic head

		Presetting							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
P-band [xp] **1.0K**	kv-value	0,049	0,082	0,130	0,215	0,246	0,303	0,335	0,343
P-band [xp] **2.0K**	kv-value	0,049	0,090	0,150	0,265	0,330	0,470	0,590	0,670
	Kvs	0,049	0,102	0,185	0,313	0,420	0,565	0,740	0,860
	Flow tolerance ± [%]	20	18	16	14	12	10	10	10

K_v value – nominal flow [m³/h]

$$k_v = \dot{V}\cdot\sqrt{\frac{100}{\Delta p_{Valve}}}\cdot\sqrt{\frac{\rho}{1000}} \Rightarrow \Delta p_{Valve} = \left(\frac{\dot{V}}{k_v}\right)^2\cdot\frac{\rho}{10}$$



Heating Systems – Pressure Equations

Example 2:

Thermostatic valve

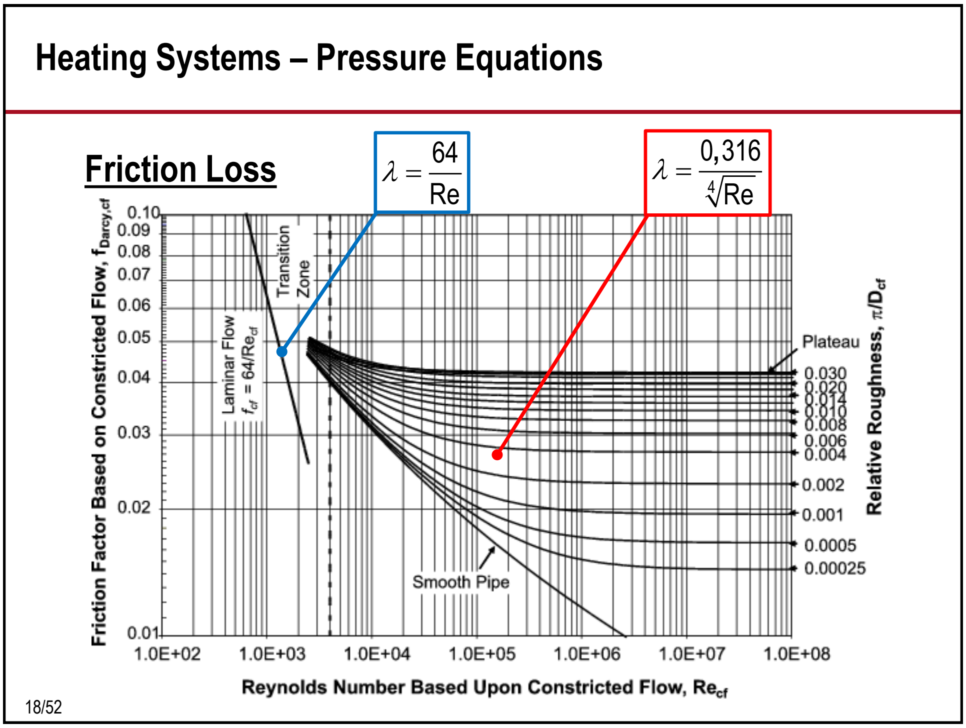
Water flow	0,05 [m^3/h]
Position 1	k_v = 0,049 [m^3/h]
Position 8	k_v= 0,86 [m^3/h]

Thermostatic valve

$$\Delta p_{Valve} = \left(\frac{\dot{V}}{k_v}\right)^2 \cdot \frac{\rho}{10}$$

$$\Delta p_{Valve\ Position1} = \dots$$

$$\Delta p_{Valve\ Position8} = \dots$$



Heating Systems – Pressure Equations

Friction Loss

$$\lambda = \frac{64}{\mathrm{Re}}$$

$$\lambda = \frac{0{,}316}{\sqrt[4]{\mathrm{Re}}}$$

Heating Systems – Pressure Equations

Total Pressure Loss

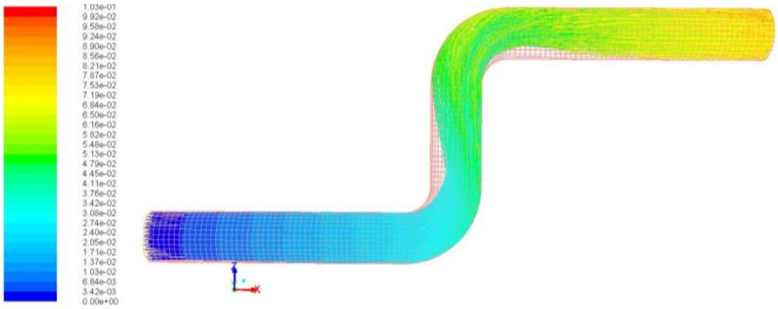
$$\Delta p_{Total} = \Delta p_{Friction} + \Delta p_{Local} = \lambda \cdot \frac{L}{d} \cdot \frac{w^2}{2} \cdot \rho + \sum \xi \cdot \frac{w^2}{2} \cdot \rho = \left(\lambda \cdot \frac{L}{d} + \sum \xi \right) \cdot \frac{w^2}{2} \cdot \rho$$

λ - friction coefficient [-]
d - inner pipe diameter [m]
L - pipe length [m]
w - velocity [m/s]
ρ - density [kg/m^3]
ξ - local loss coefficient [-]

Heating Systems – Pressure Equations

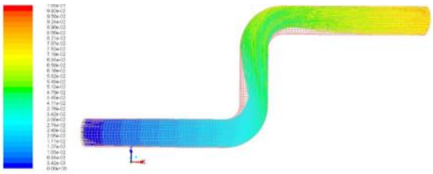
Example 3:

Total pipe length	5 [m]
Elbow local loss coefficient	2,0 [-]
Inner diameter	15 [mm]
Water flow	0,4 [m^3/h]



Heating Systems – Pressure Equations

Example 3:



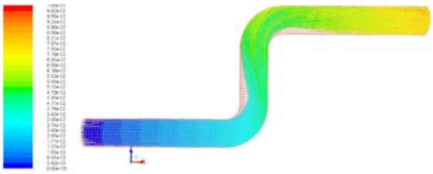
$$\dot{V} = \frac{\pi \cdot d^2}{4} \cdot w \Rightarrow w = \frac{4 \cdot \dot{V}}{\pi \cdot d^2} = \ldots$$

$$\mathrm{Re} = \frac{w \cdot d}{\nu} = \ldots$$

v - kinematic viscosity [m^2/s] (for 50 °C is $0{,}553 \cdot 10^{-6}$)

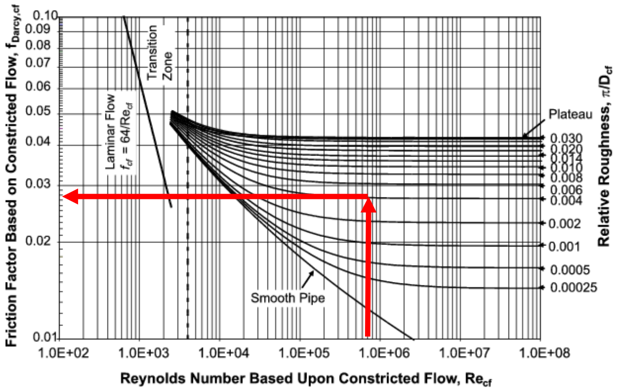
Heating Systems – Pressure Equations

Example 3:



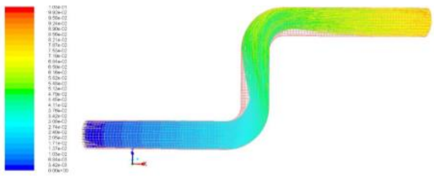
$$\lambda = \ldots$$

$$\boxed{\lambda = \frac{0{,}316}{\sqrt[4]{\mathrm{Re}}}}$$



Heating Systems – Pressure Equations

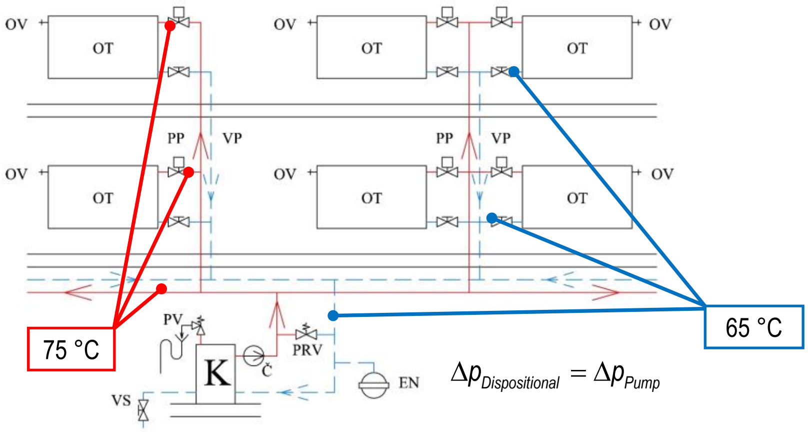
Example 3:



$$\Delta p_{Total} = \Delta p_{Friction} + \Delta p_{Local} = \lambda \cdot \frac{L}{d} \cdot \frac{w^2}{2} \cdot \rho + \sum \xi \cdot \frac{w^2}{2} \cdot \rho = \left(\lambda \cdot \frac{L}{d} + \sum \xi\right) \cdot \frac{w^2}{2} \cdot \rho$$

$$\Delta p_{Total} = \left(\ldots \cdot \frac{5}{0{,}015} + \sum 2 \cdot 2{,}0\right) \cdot \frac{\ldots^2}{2} \cdot 1000 = \ldots$$

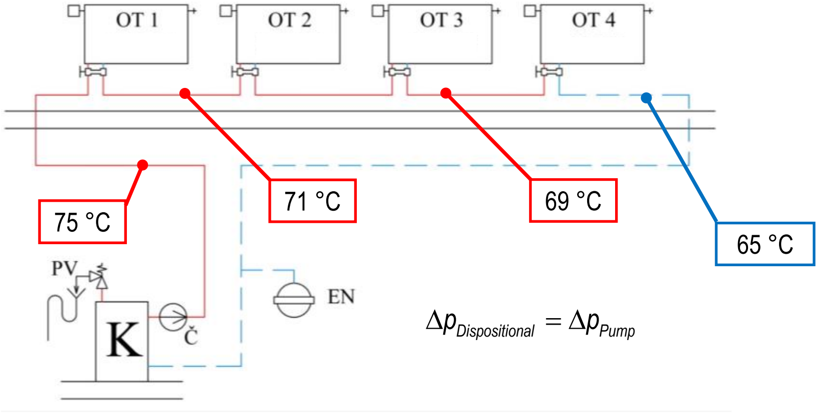
Heating Systems – Pipe Design



$$\Delta p_{Dispositional} = \Delta p_{Pump}$$

Two-pipe systems with pump (forced) is **optimal velocity** of **0,6 m/s.**

Heating Systems – Pipe Design



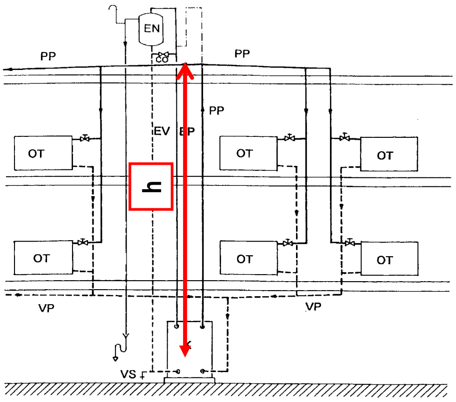
$$\Delta p_{Dispositional} = \Delta p_{Pump}$$

One-pipe systems with pump (forced) is **optimal velocity** of **1,0 m/s.**

Heating Systems – Pipe Design

Gravity heating systems

The boiler is located at the lowest point in the system. The **warm** water has a lower density (it is lighter) than the **cooled** return water. Therefore, water in the system automatically starts circulate due to buoyant pressure. There is no need for a pump. As there is only a small differential pressure, wide-diameter pipes are required.

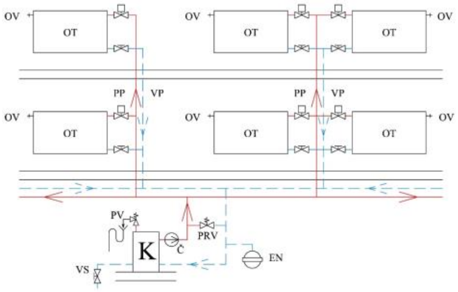


Two-pipe gravity systems is **optimal velocity** of **0,2 m/s.**

$$\Delta p_{Dispositional} = \Delta \rho \cdot g \cdot h$$

Heating Systems – Pipe Design

Mass flow rate is determined from basic calorimetric equation (output for chosen radiator)



Q	real heat output of the radiator [W]
c	specific thermal capacity [4187 J/kg·K]
t_{w1}	flow water temperature (inlet) [°C]
t_{w2}	return water temperature (outlet) [°C]

$$\dot{Q} = \dot{m} \cdot c \cdot (t_{w1} - t_{w2}) \Rightarrow \dot{m} = \frac{\dot{Q}}{c \cdot (t_{w1} - t_{w2})}$$

Heating Systems – Pipe Design

Internal (optimal) diameters are designed according to the selected optimal (i.e. economic) velocity:

$$\dot{m} = \dot{V} \cdot \rho = S \cdot w_{opt} \cdot \rho = \frac{\pi \cdot d_{opt}^{\ 2}}{4} \cdot w_{opt} \cdot \rho \Rightarrow d_{opt} = \sqrt{\frac{4 \cdot \dot{m}}{\pi \cdot \rho \cdot w_{opt}}}$$

After calculation diameter you have to select the nearest nominal diameter from real production line and subsequently **you have to calculate real velocity!** (and real pressure drop of course)

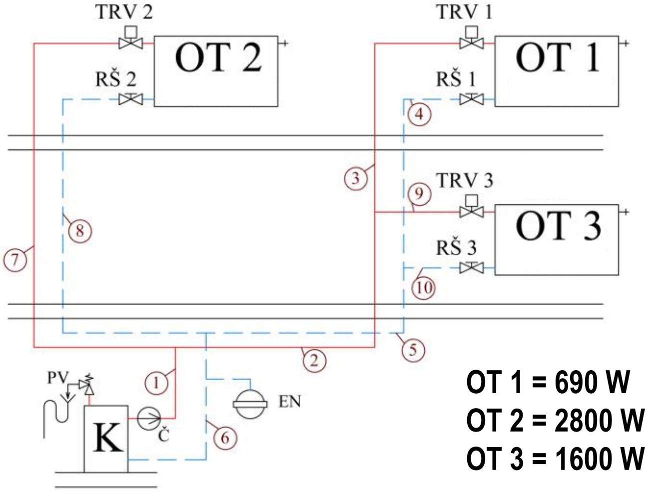
d_{opt} => d_{real}

$$w_{real} = \frac{4 \cdot \dot{m}}{\pi \cdot \rho \cdot d_{real}^{\ 2}}$$

Heating Systems – Pipe Design

Example 4:

60/50 °C

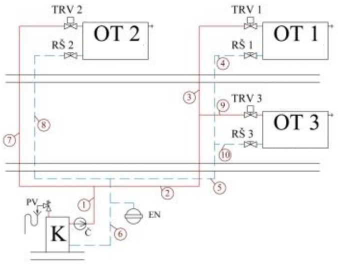


OT 1 = 690 W
OT 2 = 2800 W
OT 3 = 1600 W

Heating Systems – Pipe Design

Example 4:

60/50 °C
OT 1 = 690 W
OT 2 = 2800 W
OT 3 = 1600 W



Determine mass flow rate for each radiator (in kg/h)

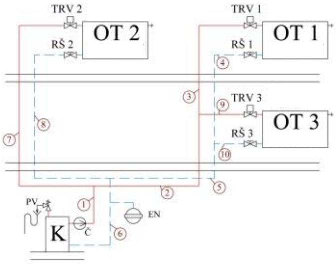
i	Q [W]	m_i [kg/s]	m_i [kg/h]
1	690		
2	2800		
3	1600		

$$\dot{m} = \frac{\dot{Q}}{c \cdot (t_{w1} - t_{w2})}$$

Heating Systems – Pipe Design

Example 4:

Determine mass flow rates in each section

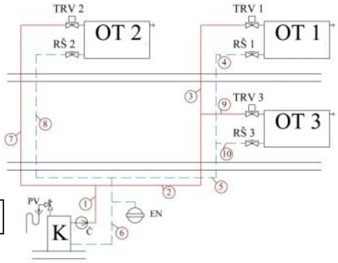


Section	m [kg/s]	m [kg/h]
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Heating Systems – Pipe Design

Example 4:

Select the nearest real diameter from real line according to calculated optimal (internal!) diameter. Calculate real velocity according chosen (inner) diameters of individual sections.



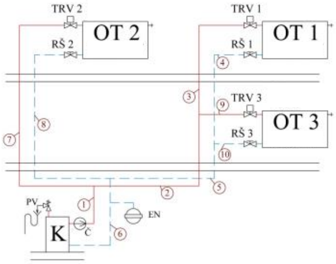
$d_{i,\,real}$ [mm]	4	6	8	10	13	16	20

Section	m [kg/s]	d_{opt} [mm]	d_{real} [mm]	w_{real} [m/s]
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Recommendation (practical note):
If possible, never use diameters smaller than 8 mm (pipes with this diameters are expensive and causes big pressure loss…)

Heating Systems – Pressure Loss

Example 4:



$$\Delta p_{Total} = \Delta p_{Friction} + \Delta p_{Local} = \lambda \cdot \frac{L}{d} \cdot \frac{w^2}{2} \cdot \rho + \sum \xi \cdot \frac{w^2}{2} \cdot \rho = \left(\lambda \cdot \frac{L}{d} + \sum \xi \right) \cdot \frac{w^2}{2} \cdot \rho$$

$$\Delta p_{Total} = \Delta p_{Friction} + \Delta p_{Local} = R \cdot L + Z$$

$$R = \lambda \cdot \frac{w^2}{2 \cdot d} \cdot \rho \quad [Pa/m] \qquad Z = \sum \xi \cdot \frac{w^2}{2} \cdot \rho \quad [Pa]$$

Heating Systems – Pressure Loss

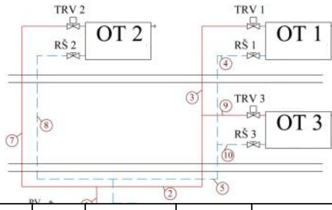
Example 4:

$$R = \lambda \cdot \frac{w^2}{2 \cdot d} \cdot \rho \quad [Pa/m]$$

Cu pipes	8 x 1 (d_i = 6 mm)		10 x 1 (d_i = 8 mm)		12 x 1 (d_i = 10 mm)		15 x 1 (d_i = 13 mm)		18 x 1 (d_i = 16 mm)		22 x 1 (d_i = 20 mm)	
M [kg/h]	***R*** [Pa/m]	***w*** [m/s]	***R*** [Pa/m]	***w*** [m/s]	***R*** [Pa/m]	***w*** [m/s]	***R*** [Pa/m]	***w*** [m/s]	***R*** [Pa/m]	***w*** [m/s]	***R*** [Pa/m]	***w*** [m/s]
50	805	0,50	155	0,28	43,5	0,18	13,0	0,11	5,70	0,07	2,35	0,04
71	1475	0,71	375	0,40	120	0,25	24,5	0,15	8,25	0,10	3,30	0,06
100			680	0,56	235	0,36	68,0	0,21	19,5	0,14	5,40	0,09
140			1225	0,80	420	0,50	120	0,30	45,0	0,19	14,5	0,12
200			2300	1,10	790	0,71	225	0,42	83,5	0,28	29,0	0,18
250					1170	0,90	330	0,53	125	0,34	42,5	0,22
320					1810	1,10	515	0,67	190	0,45	65,5	0,28
360					2235	1,30	630	0,75	235	0,50	80,5	0,32
400							760	0,85	280	0,56	97,0	0,36
450							940	0,95	345	0,63	120	0,40
500							1130	1,00	415	0,71	145	0,45

Heating Systems – Pressure Loss

Example 4:

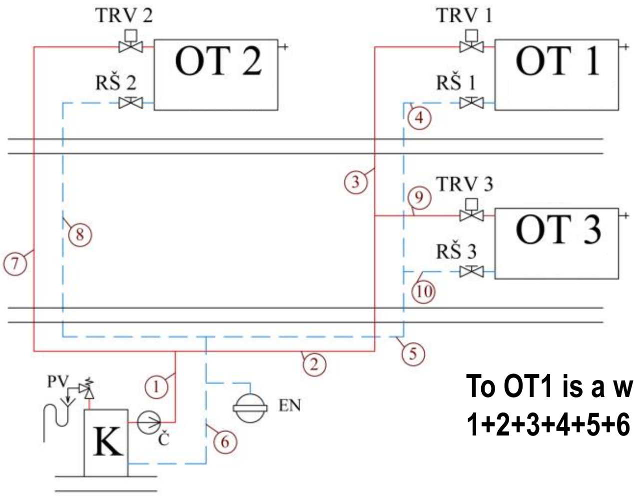


Section	m [kg/h]	d_{opt} [mm]	d_{real} [mm]	w_{real} [mm]	L [m]	R [Pa/m]	ξ [-]	R·L [Pa]	Z [Pa]	R·L+Z [Pa]
1					2		4,1			
2					5		2,5			
3					3		1,0			
4					3		2,5			
5					5		2,5			
6					2		0,6			
7					8		2,0			
8					8		2,0			
9					1		0			
10					1		0			

Heating Systems – Pipe Design

Example 4:

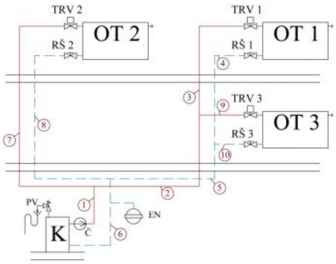
60/50 °C



To OT1 is a way:
1+2+3+4+5+6

Heating Systems – Pressure Loss

Example 4:



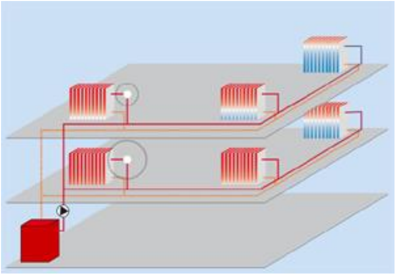
Next step is to set TRV (thermostatic valve) and RV (regulation valve) on each radiator in such way to achieve the same total pressure loss as in circuit OT 2 (i.e. increase pressure loss of circuits OT 1 and OT 3).

More in E161566 – Heating!

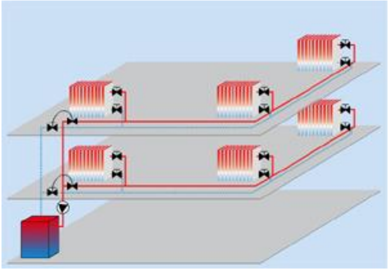
Heating Systems – Pressure Loss

Example 4:

Without hydronic balancing



With hydronic balancing

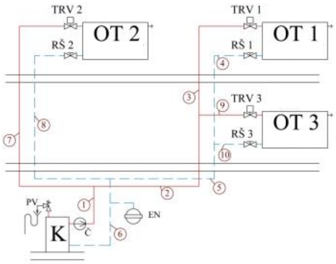


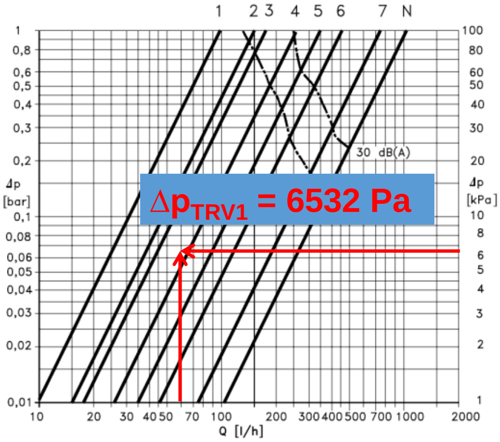
Disadvantages:
High energy consumption
Overheated or under-cooled rooms
Flow noises at the valves

Advantages:
Energy saving effect
Optimum room temperatures
No flow noises
Good regulation behaviour of the system

Heating Systems – Pressure Loss

Example 4:

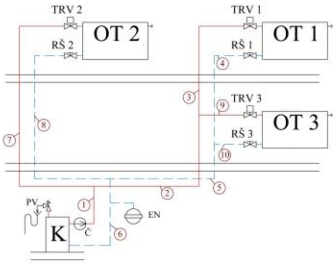




Δp_{TRV1} = 6532 Pa

Heating Systems – Pressure Loss

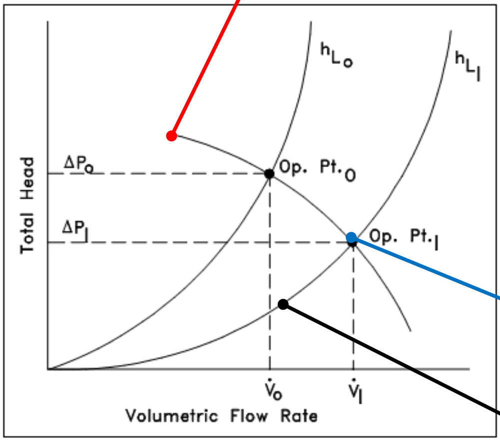
Example 4:

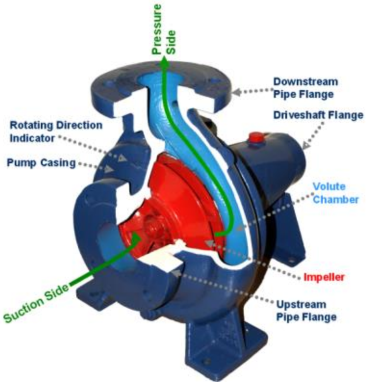


Finally – in all parts of heating system is the same pressure loss 15 331 Pa and 438 kg/h.

Heating Systems – Pump

Pump characteristic:



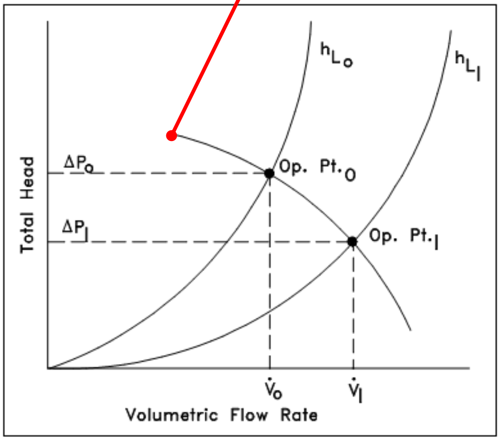


Operating point

System characteristic

Heating Systems – Pump

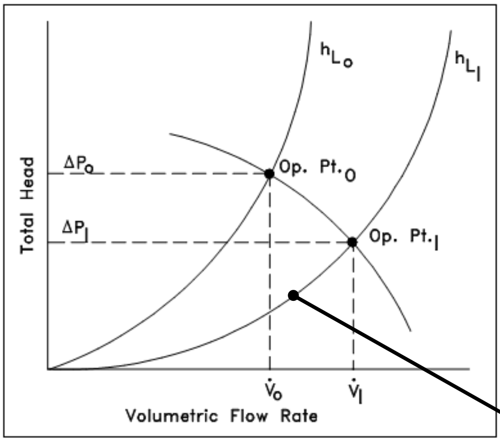
Pump characteristic:



The **pump characteristic** curve describes the delivery pump pressure (or head) (Δp or H) as a function of the delivery volume of water, i.e. $\Delta p = f(V)$ or $H = f(V)$.

Heating Systems – Pump

Pump characteristic:

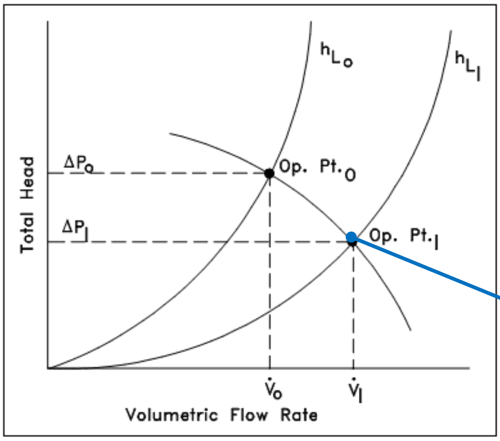


The **system characteristic** curve expresses the total pressure loss Δp_t (or total head loss H_t) required by the system as a function of the water flow rate *V*.

System characteristic

Heating Systems – Pump

Pump characteristic:

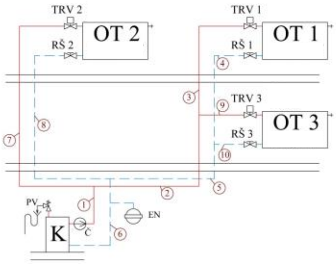


The **intersection point** of the system characteristic and the characteristic curve of a pump is called **operating point.** The point of operation determines current operating pressure (head) and the operating volume flow rate in the system.

Operating point

Heating Systems – Pressure Loss

Example 4:



Finally – in all parts of heating system is the same pressure loss 15 331 Pa and 438 kg/h.

https://product-selection.grundfos.com/

Heating Systems – Expansion Vessel

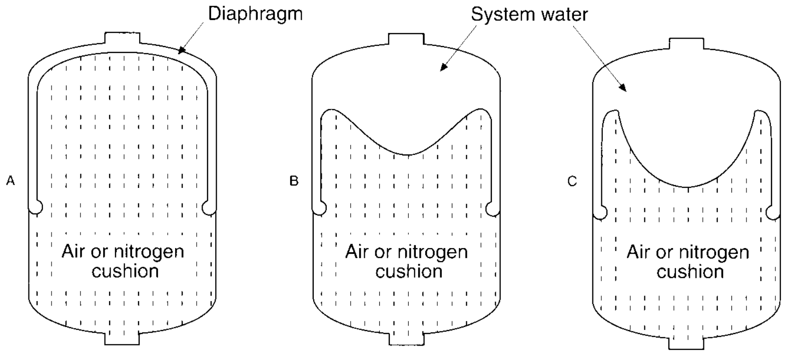
Mostly it is the expansion vessel (tank) - a “cushion” for the expansion of hot water caused by heating. The size of this vessel depends on the overall water content in the heating system.

Different types:

- closed (pressure) expansion vessel
  - with half membrane (for small plants)
  - with full membrane

- automatic expansion device

Heating Systems – Expansion Vessel



A. When system is filled, no water enters tank when cushion and water pressure are in equilibrium

B. As temperature increases, diaphragm moves to accept expanded water

C. When water rises to maximum, full acceptance of expansion is achieved

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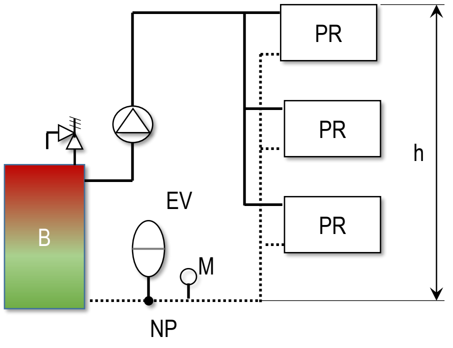
Heating Systems – Expansion Vessel



PR – Panel radiator
B – Boiler
EV – Expansion vessel
NP – Neutral point
M – Manometer
h – Hydrostatic height

$$V_{EV} = 1{,}3 \cdot V_o \cdot n \cdot \frac{1}{\eta}$$

V_{EV} - volume of closed exp. vessel [litres]
1,3 - safety coefficient [-]
V_o - volume of water in the heating system [litres]
n - expansion coefficient [-]
η - degree of utilization of closed expansion vessel [-]

Heating Systems – Expansion Vessel

Example 5:

V_o is in our case 320 litres (the sum of water volume in pipes, heating radiators, boiler, etc.)

$n = f(\Delta t_{max} = t_{max} - t_{min})$

t_{max} is e.g. **60 °C** (according to maximum design temperature in our heating system)

t_{min} is usually **10 °C** (supposed as minimum temperature of cold water in heating systems - when filling system)

$$V_{EV} = 1{,}3 \cdot V_o \cdot n \cdot \frac{1}{\eta}$$

Δt_{max} [K]	20	30	40	45	50	55	60	65	70
n [-]	0,00401	0,00749	0,01169	0,01413	0,01672	0,01949	0,02243	0,02551	0,02863
Δt_{max} [K]	75	80	85	90	95	100	105	110	115
n [-]	0,03198	0,03553	0,03916	0,04313	0,04704	0,05112	0,05529	0,05991	0,06435

Heating Systems – Expansion Vessel

Example 5:

V_o is in our case 320 litres (the sum of water volume in pipes, heating radiators, boiler, etc.)

$$V_{EV} = 1{,}3 \cdot V_o \cdot n \cdot \frac{1}{\eta}$$

η is calculated according to following formula:

$$\eta = \frac{p_{h,dov,A} - p_{d,dov,A}}{p_{h,dov,A}}$$

Where pressures are the same as described previously, but they have to be expressed like absolute pressures by adding up barometric pressure p_B = *100 kPa* (e.g. $p_{h,dov,A} = p_{h,dov}$ +100 kPa)!

Highest allowed pressure is equal to opening pressure of safety valve an it is p_{ot} = 350 kPa.

$$p_{d,dov,A} = 1{,}1 \cdot \rho \cdot g \cdot h \cdot 10^{-3} + p_B$$

Height *h* of our system is 4,5 m, density of water is 1000 kg.m^{-3}

Heading Systems – Expansion Vessel

Example 5:

V_o is in our case 320 litres (the sum of water volume in pipes, heating radiators, boiler, etc.)

Δt_{max} = 60 -10 = 50 K

n = 0,01672 (from the table)

$p_{h,dov,A} = p_{ot,A}$ = 350 + 100 = 450 kPa

$$p_{d,dov,A} = 1{,}1 \cdot \rho \cdot g \cdot h \cdot 10^{-3} + p_B = 1{,}1 \cdot 1000 \cdot 9{,}81 \cdot 4{,}5 \cdot 10^{-3} + 100 = \ldots$$

$$\eta = \frac{p_{h,dov,A} - p_{d,dov,A}}{p_{h,dov,A}} = \frac{450 - \ldots}{450} = \ldots$$

$$V_{EV} = 1{,}3 \cdot V_o \cdot n \cdot \frac{1}{\eta} = 1{,}3 \cdot 320 \cdot \ldots \cdot \frac{1}{\ldots} = \ldots$$

Then you have to select vessel with the closest higher volume from the available sizes of the production line (2,4,6,10,15,30,60,… litres)

FACULTY
OF MECHANICAL
ENGINEERING
CTU IN PRAGUE

THANK YOU FOR YOUR ATTENTION

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