Water hammer

Speed pressure waves in the pipe:

$$a = \frac{c}{\sqrt{1 + \frac{D}{e} * \frac{K}{E}}}$$

a	speed pressure waves in the pipe	[m/s]
c	sound speed in liquid	[m/s]
D	internal pipe diameter	[mm]
e	thickness of the pipe wall	[mm]
K	volume elastic modulus	[Pa]
E	Young's modulus for pipe	[Pa]

Sound speed in liquid:

$$c = \sqrt{\frac{K}{\rho}}$$

c	sound speed in liquid	[m/s]
K	volume elastic modulus	[Pa]
ρ	destiny	[Kg/m^3]

Volume elastic modulus:

$$K = \frac{1}{\beta}$$

K	volume elastic modulus	[Pa]
β	medium compressibility factor	[Pa^{-1}]

Young's modulus for pipe:

Pipe material	[Pa]
Steel	$2*10^{11}$
Copper	$1,17*10^{11}$
Cast iron	$0,7*10^{11}$
Glass	$0,8*10^{11}$
Polyvinyl chloride (PVC)	$3*10^{9}$
Rubber	$4,2*10^{6}$
Reinforced concrete	$0,21*10^{11}$
Polypropylene (PP)	$7*10^{8}$

Medium compressibility factor:

Medium compressibility factor $\beta*10^{-12}$ [Pa^{-1}] water depending on pressure and temperature

Pressure [MPa]	Temperature [°C]												
	0°	5°	10°	15°	20°	30°	40°	50°	60°	70°	80°	90°	100°
0,1-10	520,9	502,6	492,4	482,2	477,1	468,9	457,7	457,7	463,8	471	478,1	487,3	-
10-20	501,5	484,2	469,9	459,7	450,6	444,4	437,3	433,2	435,3	447,5	459,7	477,1	822,6
20-30	489,3	471	461,8	451,6	442,4	430,2	422	421	423	433,2	444,4	467,9	783,9
30-40	475	457,7	449,5	441,4	432,2	421	414,9	409,8	413,9	419	430,2	454,6	745,2
40-50	463,8	452,6	438,3	430,2	423	413,9	411,8	406,7	401,6	405,7	415,9	442,2	695,2
50-60	446,5	438,3	426,1	419	411,8	399,6	397,6	397,6	395,5	398,6	406,7	424,1	671,8
60-70	437,3	416,9	412,8	405,7	401,6	394,5	389,4	384,3	390,4	387,4	394,5	414,9	639,1

Density:

Density ρ [Kg/m^3] water depending on temperature and pressure

Temperature [°C]	Pressure [MPa]					
	0,1	0,25	0,5	1	1,5	2
0°	999,8	999,9	1000	1000,3	1000,6	1000,8
10°	999,7	999,8	999,9	1000,1	1000,4	1000,6
20°	998,2	998,3	998,4	998,6	998,8	999,1
30°	995,6	995,7	995,8	996	996,3	996,5
40°	992,2	992,3	992,4	992,7	992,9	993
50°	988,1	988,1	988,2	988,4	988,6	988,8
60°	983,2	983,3	983,4	983,6	983,9	984,1
70°	977,8	977,8	978	978,2	978,4	978,6
80°	971,8	971,9	972	972,2	972,4	972,7
90°	965,3	965,3	965,5	965,7	966	966,2
100°	-	958,4	958,5	958,8	959	959,2

Density ρ [Kg/m^3] water depending on temperature and pressure

Temperature [°C]	Pressure [MPa]					
	2,5	3	3,5	4	4,5	5
0°	1001,1	1001,3	1001,6	1001,8	1002,1	1002,3
10°	1000,8	1001	1001,3	1001,6	1001,8	1002
20°	999,3	999,5	999,8	1000	1000,2	1000,4
30°	996,7	996,9	997,2	997,4	997,6	997,8
40°	993,3	993,4	993,7	993,9	994,1	994,3
50°	989,1	989,2	989,5	989,7	989,9	990,2
60°	984,3	984,5	984,6	984,9	985,1	985,3
70°	978,9	979,1	979,2	979,5	979,7	979,9
80°	972,9	973,1	973,3	973,5	973,8	974
90°	966,4	966,6	966,8	967,1	967,3	967,6
100°	959,5	959,7	960	960,2	960,4	960,6

Density ρ [Kg/m^3] water depending on temperature and pressure

Temperature [°C]	Pressure [MPa]					
	6	7	8	9	10	12,5
0°	1002,8	1003,3	1003,8	1004,3	1004,8	1006
10°	1002,5	1003	1003,4	1003,9	1004,4	1005,5
20°	1000,9	1001,3	1001,8	1002,2	1002,7	1003,8
30°	998,3	998,7	999,1	999,6	1000	1001,1
40°	994,8	995,2	995,6	996,1	996,5	997,6
50°	990,6	991	991,5	991,9	992,3	993,3
60°	985,8	989,2	986,6	987,1	987,5	988,5
70°	980,4	980,8	981,3	981,6	982,1	983,2
80°	974,5	974,9	975,3	975,7	976,2	977,2
90°	968	968,4	968,9	969,4	969,7	970,9
100°	961,1	961,5	962	962,5	962,9	964

Density ρ [Kg/m^3] water depending on temperature and pressure

Temperature [°C]	Pressure [MPa]					
	15	17,5	20	25	30	35
0°	1007,3	1008,5	1009,7	1012,1	1014,5	1016,9
10°	1006,7	1007,9	1009	1011,3	1013,6	1015,7
20°	1004,9	1006	1007,2	1009,3	1011,4	1013,6
30°	1002,2	1003,2	1004,3	1006,5	1008,6	1010,6
40°	998,6	999,7	1000,8	1002,8	1004,9	1007
50°	994,4	995,5	996,5	998,6	1000,7	1002,7
60°	989,6	990,7	991,7	993,7	995,8	997,9
70°	984,3	985,3	986,4	988,4	990,5	992,6
80°	978,4	979,4	980,5	982,6	984,7	986,8
90°	972	973,1	974,2	976,4	978,5	980,6
100°	965,2	966,3	967,4	969,7	971,8	974

Density ρ [Kg/m^3] water depending on temperature and pressure

Temperature [°C]	Pressure [MPa]					
	40	45	50	60	70	80
0°	1019,3	1021,6	1023,9	1028,3	1032,7	1037
10°	1018	1020,2	1022,3	1026,6	1030,7	1034,9
20°	1015,7	1017,8	1019,9	1024,1	1028,1	1032
30°	1012,8	1014,7	1016,8	1020,8	1024,7	1028,5
40°	1009	1011	1013	1017	1020,8	1024,6
50°	1004,7	1006,8	1008,7	1012,6	1016,4	1020,2
60°	999,9	1001,9	1003,8	1007,8	1011,5	1015,3
70°	994,6	996,6	998,6	1002,5	1006,3	1010,1
80°	988,8	990,9	992,9	996,8	1000,7	1004,4
90°	982,7	984,7	986,8	990,8	994,6	998,5
100°	976,1	978,2	980,3	984,3	988,3	992,3

Water hammer (for linear closure):

For slow and linear closing of the valve.

$$t \geq \frac{2L}{a}$$

t	valve closing time	[s]
L	pipe length	[m]
a	speed pressure waves in the pipe	[m/s]

$$P = \frac{\rho * L * v}{t}$$

P	water hammer	[Pa]
ρ	density	[Kg/m^3]
L	pipe length	[m]
v	pipeline speed	[m/s]
t	valve closing time	[s]

Water hammer (for nonlinear closure):

For slow closing of the valve.

$$t = t_r * c_{ef}$$

t	valve closed time water hammer calculation	[s]
t_r	closing time	[s]
c_{ef}	Effective closing time factor	[]

$$t \geq \frac{2L}{a}$$

t	valve closed time water hammer calculation	[s]
L	pipe length	[m]
a	speed pressure waves in the pipe	[m/s]

$$P = \frac{\rho * L * v}{t}$$

P	water hammer	[Pa]
ρ	density	[Kg/m^3]
L	pipe length	[m]
v	pipeline speed	[m/s]
t	valve closed time water hammer calculation	[s]

Pipeline speed:

$$v = \frac{Q}{\frac{\pi * D^2}{4}}$$

v	pipeline speed	[m/s]
Q	flow	[m^3/s]
D	internal pipe diameter	[mm]

Effective closing time factor:

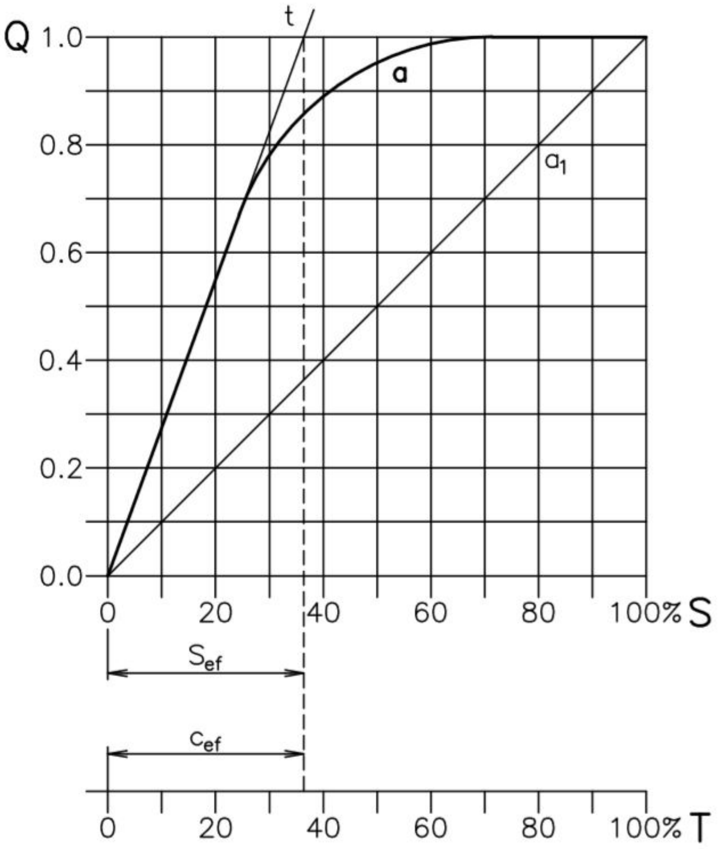

Fig.1

The water hammer formula is valid assuming linear flow characteristics (at even closure - the linear relationship between the flow and the position of the closure valve). This assumption is difficult to accomplish with most valves without pre-treatment (modification of structural characteristics).

If we calculate the proportional flow rate by a valve for several valve positions, we can graphically represent the relationship between the proportional flow and the stroke (or turn) of the closure valve. This dependence is shown in Figure 1 by line “**a”**. The line “$\mathbf{a_1}$“ shows the linear relationship between the flow and the valve of the closure. It can be seen from the figure that only a partial part of the total stroke influences the substantial flow limitation.

To the decreasing line “**a”** we can build a tangent line “**t”**, which on the horizontal line “**Q”** determine the effective stroke $\mathbf{S_{ef}}$. We assume that only the effective stroke has an effect on the flow limitation and, moreover, that in its range the relationship between flow and stroke linear.

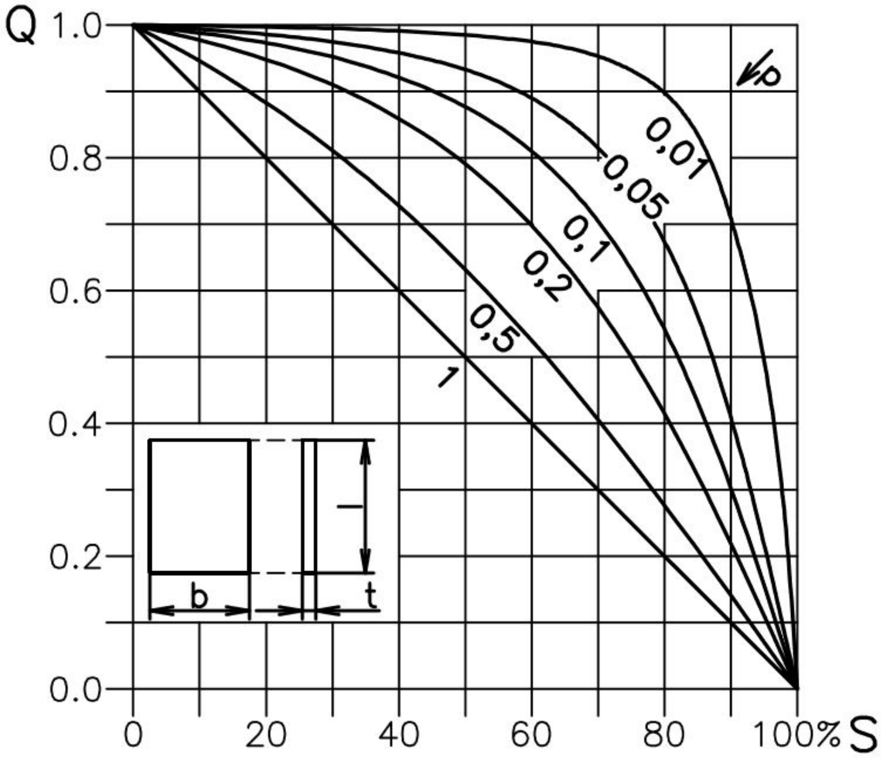

Fig.2 Proportional flow characteristic of the knife valve - ξ=0,01

The value of the effective closing time factor c_{ef} [] from of the proportional flow characteristics of the knife valve Fig.2

p	1	0,5	0,2	0,1	0,05	0,01
c_{ef}	1	0,73	0,46	0,33	0,24	0,141

Pressure parameter:

$$p = \frac{\Delta h}{h_0}$$

p	pressure parameter	[]
Δh	theoretical pressure in the closure at full opening	[m]
h_0	rated net head	[m]

Theoretical pressure in the closure at full opening:

$$\Delta h = \frac{v_0^2}{2g} * (\xi + 1)$$

Δh	theoretical pressure in the closure at full opening	[m]
v_0	valve speed	[m/s]
g	gravitational acceleration	[m/s^2]
ζ	local loss factor for open valve	[]

valve speed:

$$v_0 = \frac{Q}{\frac{\pi * D_0^2}{4}}$$

v_0	valve speed	[m/s]
Q	flow	[m^3/s]
D_0	valve diameter	[mm]

Example:
We have to determine the water hammer size for the linear and nonlinear shut-off of the DN300 knife valve with the following parameters:
L = 12000m; steel pipe D = 600mm; thickness of the pipe wall e = 10mm; h_0 = 33m;
Q = 0,314 m^3/s; density water ρ = 998,3Kg/m^3;
medium compressibility factor β = 477,1*10^{-12}; closing time 200s

Water hammer (for linear closure):

- volume elastic modulus

$$K = \frac{1}{\beta} = \frac{1}{477{,}1 * 10^{-12}} = 2{,}096 * 10^9 [Pa]$$

- sound speed in liquid

$$c = \sqrt{\frac{K}{\rho}} = \sqrt{\frac{2{,}096 * 10^9}{998{,}3}} = 1448{,}989 [m/s]$$

- speed pressure waves in the pipe

$$a = \frac{c}{\sqrt{1 + \frac{D}{e} * \frac{K}{E}}} = \frac{1448{,}989}{\sqrt{1 + \frac{600}{10} * \frac{2{,}096 * 10^9}{2 * 10^{11}}}} = 1135{,}3 [m/s]$$

$$t \geq \frac{2L}{a} \rightarrow \frac{2 * 12000}{1135{,}2} = 21{,}14 [s] \leq 200 [s] \rightarrow OK$$

- pipeline speed

$$v = \frac{Q}{\frac{\pi * D^2}{4}} = \frac{0{,}314}{\frac{\pi * 0{,}6^2}{4}} = 1{,}11 [m/s]$$

- water hammer

$$P = \frac{\rho * L * v}{t} = \frac{998{,}3 * 12000 * 1{,}11}{200} = 66486{,}78 [Pa]$$

Water hammer (for nonlinear closure):

- valve speed

$$v_0 = \frac{Q}{\frac{\pi * D_0^2}{4}} = \frac{0{,}314}{\frac{\pi * 0{,}3^2}{4}} = 4{,}44[m/s]$$

- theoretical pressure in the closure at full opening

$$\Delta h = \frac{v_0^2}{2g} * (\xi + 1) = \frac{4{,}44^2}{2 * 9{,}81} * (0{,}01 + 1) = 1{,}015[m]$$

- pressure parameter

$p = \frac{\Delta h}{h_0} = \frac{1{,}015}{33} = 0{,}03[\,] \rightarrow c_{ef} = 0{,}2[\,]$ this value is determined from the table using interpolation.

- valve closed time water hammer calculation

$$t = t_r * c_{ef} = 200 * 0{,}2 = 40[s]$$

- volume elastic modulus

$$K = \frac{1}{\beta} = \frac{1}{477{,}1 * 10^{-12}} = 2{,}096 * 10^9[Pa]$$

- sound speed in liquid

$$c = \sqrt{\frac{K}{\rho}} = \sqrt{\frac{2{,}096 * 10^9}{998{,}3}} = 1448{,}989[m/s]$$

- speed pressure waves in the pipe

$$a = \frac{c}{\sqrt{1 + \frac{D}{e} * \frac{K}{E}}} = \frac{1448{,}989}{\sqrt{1 + \frac{600}{10} * \frac{2{,}096 * 10^9}{2 * 10^{11}}}} = 1135{,}3[m/s]$$

$$t \geq \frac{2L}{a} \rightarrow \frac{2 * 12000}{1135{,}2} = 21{,}14[s] \leq 40[s] \rightarrow OK$$

- pipeline speed

$$v = \frac{Q}{\frac{\pi * D^2}{4}} = \frac{0{,}314}{\frac{\pi * 0{,}6^2}{4}} = 1{,}11[m/s]$$

- water hammer

$$P = \frac{\rho * L * v}{t} = \frac{998{,}3 * 12000 * 1{,}11}{40} = 332433{,}9[Pa]$$

Water hammer for nonlinear closure is **5x** bigger, than for linear closure.

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