The Sizing of Pipework in Hydraulic Systems

Dr.-Ing. Norbert Achten

1 Introduction

The obvious task of the pipework in hydraulic systems is to carry the hydraulic fluid to and from the various components. In the process, it is subjected to mechanical, thermal and corrosive stresses either individually or all at once. It is these stresses that are the governing factor for the sizing of the pipework.

Mechanical stresses are mostly as a result of the pressure varying with respect to time. The task of the designer is to produce an economical, safe and reliable design appropriate for these circumstances. The procedure for attaining this target is shown diagrammatically in Fig. 156. There are company specifications and standards to be followed as well as all the general rules and recommendations that are applicable.

The procedure for the design and sizing of pipework is based on the original circuit diagram and the principal data such as the medium to be used, the flow per unit time, the pressure and the temperature. As can be seen from *Table 40* there are also a number of other factors of influence affecting the principal parameters which must also be included in the calculations, i.e.

- pipe inside diameter
- wall thickness and
- material.

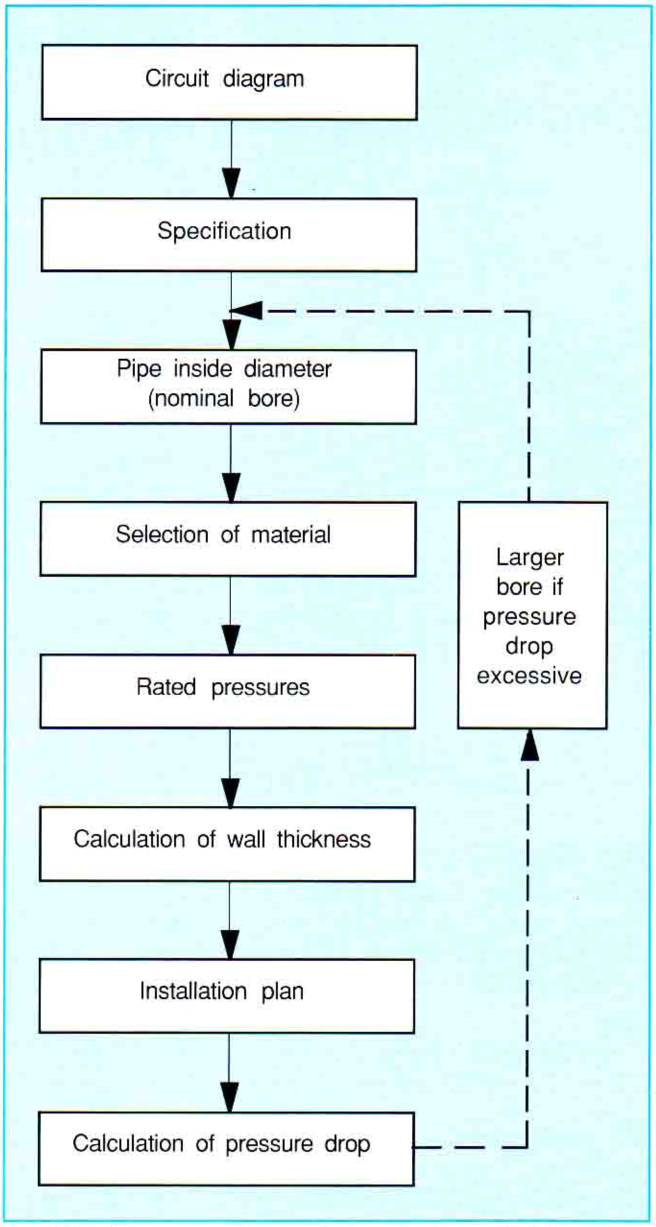


Fig. 156: *Sequence diagram for the design and sizing of hydraulic system pipework*

Parameter	Factors of influence
Pipe inside diameter	Volumetric flow Flow velocity Fluid viscosity Pressure losses
Pipe wall thickness	Operating pressure (and any extra stresses) Safety factors required or specified Reduced wall thickness due to manufacturing Internal and external corrosion Strength of material Operating and ambient temperatures Standard dimensions
Pipe material	Strength parameters Preconditions for use (surface finish, weldability) Effects of corrosion Permitted temperature range

Table 40: *Factors of influence for the sizing of pipework*

2 Determining the inside diameter or bore

Together with the flow and physical properties of the hydraulic fluid, the inside diameter or bore of the pipes also affects the flow resistance. In order to determine the required pump power it is necessary to calculate the total flow losses in the system. If the calculated pressure losses are too high compared with the projected values, the pipework will have to be re-sized choosing a larger bore.

The flow $\dot{V}$ given in the principal data is used for determining the pipe bore d_i. According to Equation (1) it is:

$$d_i = \sqrt{\frac{4 \cdot \dot{V}}{w\,\pi}}\,. \qquad (1)$$

Substituting the flow in L/min and the average velocity w in m/s in Equation (1) gives the pipe bore in mm thus:

$$d_i = 4{,}607 \sqrt{\frac{\dot{V}}{w}}\,. \qquad (2)$$

The average velocity in Equations (1) and (2) must be determined according to economic and technical factors. The economic aspect includes capital costs and operating costs. On the technical side there are also limits related to the flow, which, if exceeded, lead to noise emission, excessive vibration of the pipework and erosion at points of change in direction. Starting points for the selection of an average velocity [1] can be taken from *Table 41* which shows recommended figures from both German and American sources.

Determining the bore of the pipe also fixes the nominal size (abbreviation DN) of the pipe to DIN 2402 [2] *(see Table 42)*. This has the advantage that all other pipe components used will be of the appropriate size for connection.

3 Selecting the material

The choice of material for the pipework depends mainly on the strength needed, although there are other significant factors such as the method of manufacture - seamless or welded, any subsequent fabrication needed and the suitability of pipe connectors. In view of possible internal or external corrosion the resistance of the material to such attack must also be examined.

In the field of hydraulics, the most widely used material up to DN 32 is precision steel tube to DIN 2391-C [3] made of St 35 supplied normalized (DIN 2391, Part 2). Its popularity is due to its excellent suitability for fabrication (welding, bending and flaring), high resistance to repeated stress and excellent matching of its outside diameter to pipe connectors. For the extra strength required for high-pressure applications St 52 can be used instead of St 35. Seamless steel tube to DIN 2448 [4] and 2445 [5] in St 37.4 or St 52.4 to DIN 1630 [6] is used for sizes over DN 40.

Suction line		Pressure line		Return line
Kinematic viscosity ν in mm²/s	*w* in m/s	pressure *p* in bar	*w* in m/s	*w* in m/s
150	0,6	25	2,5 to 3	1,7 to 4,5
100	0,75	50	3,5 to 4	
50	1,2	100	4,5 to 5	
30	1,3	200	5 to 6	
		> 200	6	
		When ν= 30 to 150 mm²/s		

Table 41: *Recommended values of flow velocity in hydraulic system pipework*

Table 42: *Nominal sizes (DN) of pipework to DIN 2402 (extract)*

	10	100
	12	125
	15	150
	20	200
	25	250
3	32	300 350
4	40	400 450
5	50	500
6	65	600 700
8	80	800 900

Federal Republic of Germany			United Kingdom		USA		France	
Material designation	Material No.	Standard	Material designation	Standard	Material designation	Standard	Material designation	Standard
St 37.4	1.0255	DIN 1630	CDS 23	BS 3602	A	ASTM A53	—	—
St 52.4	1.0581	DIN 1630	HFS 23	BS 1775	3	ASTM A252	—	—
St 35	1.0308	DIN 2391	CDS 3	BS 980	1010	ASTM A519	Tu 37-b	PRA 49-310
St 37.0	1.0254	DIN 1626	ERW 360	BS 3601	A	ASTM A53	Tu 37-b	A 49.112
X6CrNiMoTi 17122	1.4571	DIN 17 458	320 S17	BS 970 P.4	316Ti	AISI	Z8CNDT 17-12	A 35-572
X6CrNiTi 1810	1.4541	DIN 17 458	321 S12	BS 970 P.4	321	AISI	Z6CNDT 18-11	A 35-572

Table 43: *Preferred pipe materials in German and foreign standards*

Due to the high pressures involved, the only types of welded tube used should be those complying with special quality standards (Group 2) and having a ratio of weld strength to parent metal strength of unity. Welded tube cannot be used with cutting ring fittings or flared joints. Table 43 shows a comparison of the preferred pipe materials for hydraulic systems according to German and foreign standards. It also lists stainless steels for precision tube to DIN 2463 [7]. The foreign materials listed in the table are equivalent to the German ones and must be used accordingly.

It is usually necessary for tube exposed to high pressures to be certified in accordance with DIN 50049-3.1B [8]. So-called "commercial quality" tube should not be used because its pressure range is limited and larger safety factors would have to be allowed.

4 Nominal pressures

The nominal pressure of pipe and pipe components is the name given to the pressure grading of components of identical construction and identical connection dimensions. The standard pressure grades are listed in DIN 2401, Part 1 [9] (Table 44). A plain figure is stated for nominal pressure (abbreviation PN); there are no units such as "bar". The numerical value of nominal pressure is the maximum pressure of use at a reference temperature of 20°C.

1	10	100	1000
1,6	16	160	1600
2,5	25	250	2500
4	40	400	4000
6	63	630	6300

Table 44: *Pressure grading (PN) of pipe to DIN 2401, Part 1*

5 Calculating the wall thickness

Calculation of the required wall thickness of a pipe can generally be performed for a specific load to DIN 2413 [10] or, as part of a pressure vessel subject to certification, according to AD-Merkblatt B1 [11]. These calculation references are applicable to piping systems which are either operated in Germany or are recognized by the competent certification authority when installed in other countries. The overview (Table 45) lists the calculation formulae for determining the theoretical wall thickness according to these regulations. The safety factors S in Formulae (3) to (6) and the weld efficiencies v can be taken from *Tables 46 and 47. Table 46* also lists the strength coefficients K to be used in the individual formulae.

The formulae to DIN 2413 are based on the requirement that the operating pressure must cause no plastic flow of the material at the most highly stressed inner fibre of the pipe.

There are three load cases to take into account:

- Case I

  Primarily steady-state stress up to a maximum temperature of 120°C

- Case II

  Primarily steady-state stress over 120°C (also applicable to temperatures below 120°C under certain circumstances)

- Case III

Repeated stress.

Cases I and II are based on primarily steady-state stress whereby certain maximum numbers of stress cycles must not be exceeded. "Stress cycles" means alternating pressures of large amplitude such as when starting up and shutting down a hydraulic system. *Tables 48 and 49* list the maximum numbers of stress cycles in relation to the tensile strength R_m and the permitted stress *K/S* for two different types of steel tube. When numbers of stress cycles above the specified limits are anticipated, the theoretical wall thickness for predominantly steady-state stress is calculated first.

Reference	Application limits	Type of stress	Formulae for theoretical wall thickness
DIN 2413	$d_a/d_i \leq 1{,}7$ Temperature ≤ 120 °C	I, primarily steady-state	$s_v = \dfrac{d_i \cdot p}{20\,\dfrac{K}{S} \cdot v - 2p}$ (3)
DIN 2413	a) $d_a/d_i \leq 1{,}7$ Temperature > 120 °C b) $d_a/d_i \geq 1{,}1$ and $\leq 1{,}7$ Temperature < 120 °C	II, primarily steady-state	$s_v = \dfrac{d_i \cdot p}{(20\,\dfrac{K}{S} - p) \cdot v}$ (4)
DIN 2413	$d_a/d_i \leq 1{,}7$	III, repeated	a) s_v according to formulae (3) b) $s_v = \dfrac{d_i \cdot (\hat{p} - \check{p})}{20\,\dfrac{K}{S} - 3 \cdot (\hat{p} - \check{p})}$ (5) Use $s_{v\,max}$ from a) and b)
AD-Merkblatt B1	$d_a/d_i \leq 1{,}2$ or $d_a \leq 200$ mm and $d_a/d_i \leq 1{,}7$	primarily steady-state	$s_v = \dfrac{d_i \cdot p}{20\,\dfrac{K}{S} \cdot v - p}$ (6) $s_{v\,min} = 2$ mm

Table 45: *Basis of calculation to DIN 2413 and AD-Merkblatt B1*

Reference	Strength coefficient *K*	Elongation at fracture A_5	Safety factor for pipes with acceptance test certificate to DIN 50 049 *S*
DIN 2413 Case I	$R_{p\,0,2}$ at 20 °C	≥ 25 % 20 % 15 %	1,5 1,6 1,7
DIN 2413 Case II	a) Minimum value from $R_{p\,0,2}$ *) and $R_{m/2 \cdot 10^5}$ at calculation temperature		1,5
	b) $R_{p\,0,2}$ at 20 °C	≥ 25 % 20 % 15 %	1,6 1,7 1,8
DIN 2413 Case III	σ_{Sch}		1,5
AD-Merkblatt B1	$R_{p\,0,2}$ or $R_{m/10^5}$ at calculation temperature to AD-Merkblatt W4		1,5
**) Rp1 at calculation temperature can be used for pipes of 1.4571 or 1.4541*			

Table 46: *Safety factors*

Pipes	Material complying with	Tests	Weld efficiency *v*
For general use (commercial quality) DIN 1626	DIN 17 100 Quality group 1	without factory certification with factory certification	0,5 0,7
With quality specification DIN 1626	DIN 17 100 Quality group 2	without user's inspection with user's inspection	0,8 0,9
With special quality specification*	At least DIN 17 100 Quality group 2	Special tests, primarily 100% weld seam test	1,0
**As longitudinally seam-welded tube, this is to be preferred for hydraulic applications because of the pressures involved*			

Table 47: *Weld efficiency of longitudinally-welded tube to DIN 2413*

The calculation for Case III must also be performed, whereby only stress cycles of the same pressure fluctuation amplitude between maximum pressure $\hat{p}$ and minimum pressure $\check{p}$ are taken into account. The larger wall thickness of the two calculations is then used. In the case of pipes which are exposed to a changing pressure fluctuation amplitude at irregular intervals, calculation of the wall thickness by means of the given formulae is impossible. Special studies are necessary in such cases concerning primarily the checking of damage anticipated during normal operation.

Unlike steady-state stress, dynamic stress also requires the appropriate strength coefficients to be brought in. The simplest way of doing this for a repeated internal pressure stress is with a stress-number diagram (SN diagram). *Diagram 55* shows how the calculation of the pipe wall thickness under dynamic stress can be performed for either the fatigue limit range or fatigue strength range. It should be noted that the fatigue life is related to the appropriate number of stress cycles, i.e. the calculation of pipe wall thickness is only valid for this number of stress cycles.

Permitted stress K/S in N/mm²	Tensile strength R_m in N/mm²				
	≤ 450	500	550	600	650
160	100 000	> 100 000	> 100 000	> 100 000	> 100 000
180	50 000	90 000	> 100 000	> 100 000	> 100 000
200	30 000	50 000	80 000	> 100 000	> 100 000
250	10 000	17 000	26 000	40 000	56 000
300				16 000	22 000
350					10 000

Table 48: *Maximum number of stress cycles to DIN 2413 (Cases I and II) for seamless and HF-welded steel tube ($v = 1$) with a stress cycle safety factor $S_L = 10$*

Permitted stress K/S in N/mm²	tensile strength R_m in N/mm²				
	≤ 500	550	600	650	700
120	32 000	50 000	80 000	>100 000	> 100 000
140	18 000	26 000	40 000	56 000	80 000
160	10 000	15 000	22 000	30 000	42 000
180	6 000	10 000	13 000	19 000	25 000
200	4 000	6 000	8 000	11 000	16 000
250			3 000	5 000	6 000
300				2 000	3 000

Table 49: *Maximum number of stress cycles to DIN 2413 (Cases I and II) for submerged-arc welded steel tube ($v = 1$) with a stress cycle safety factor $S_L = 10$*

In contrast, there is no limiting number of stress cycles for fatigue strength. *Diagrams 56 and 57* show the SN diagrams for seamless, HF-welded and submerged-arc welded steel tube to DIN 2413 subjected to pulsating stress; the strength values can be taken directly from the diagrams.

In the case of pipes that form part of a pressure vessel, the calculation of the tube wall thickness is performed in accordance with AD-Merkblatt B1 *(see Formula 6)*. In this case the governing strength coefficients are those given in Material Sheet AD-W1.

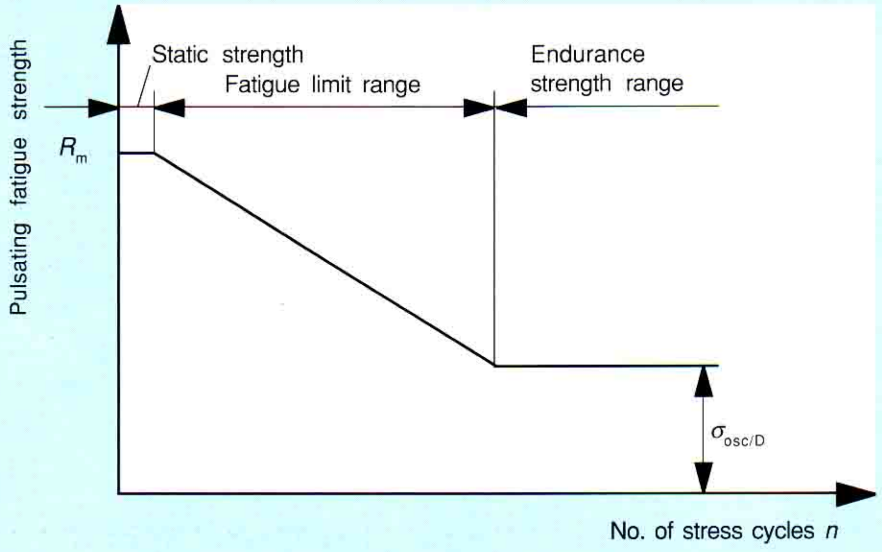


Diagram 55: *SN diagram*

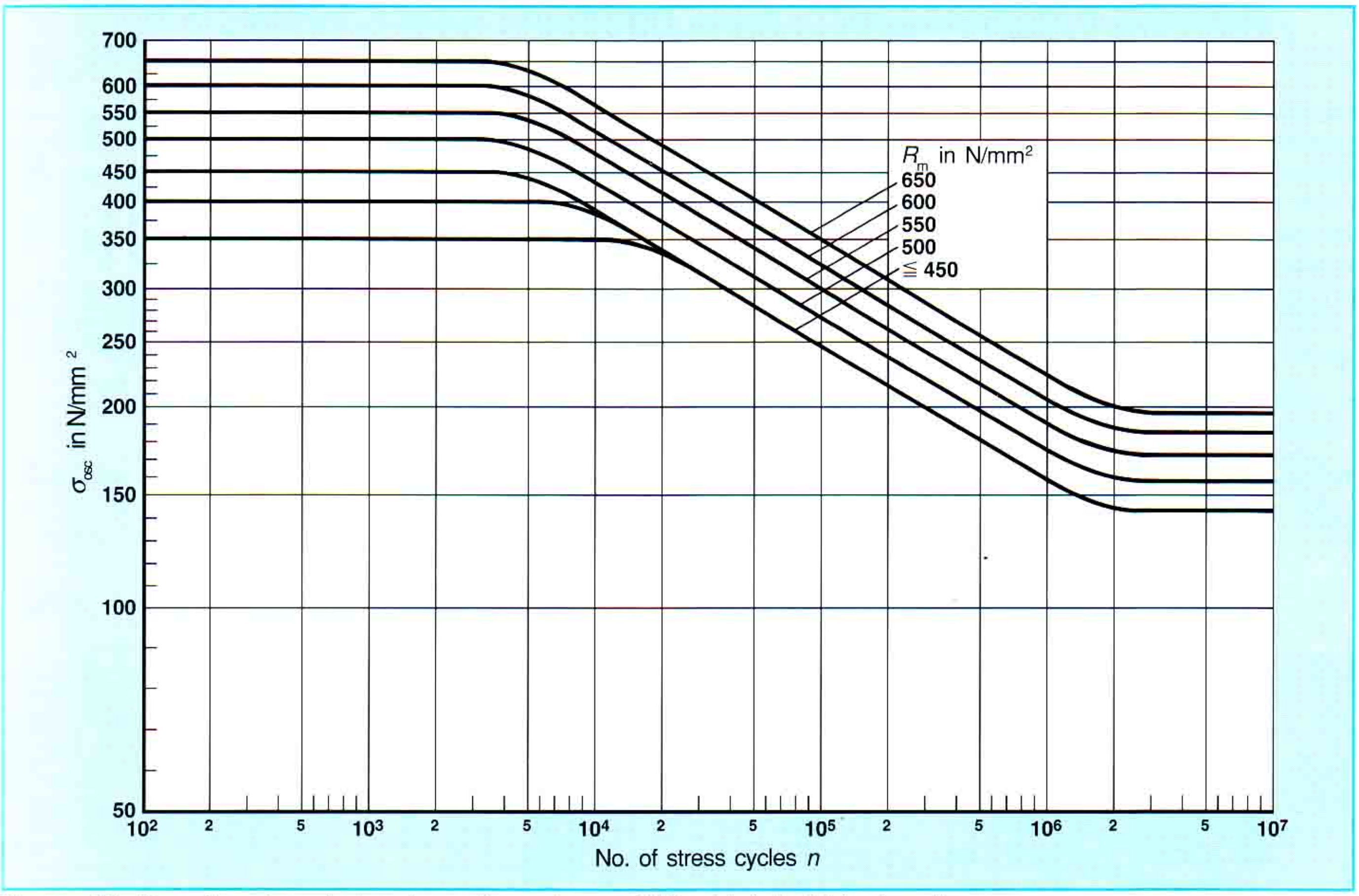


Diagram 56: *Strength under pulsating stress of seamless and HF-welded steel tube ($v = 1$)*

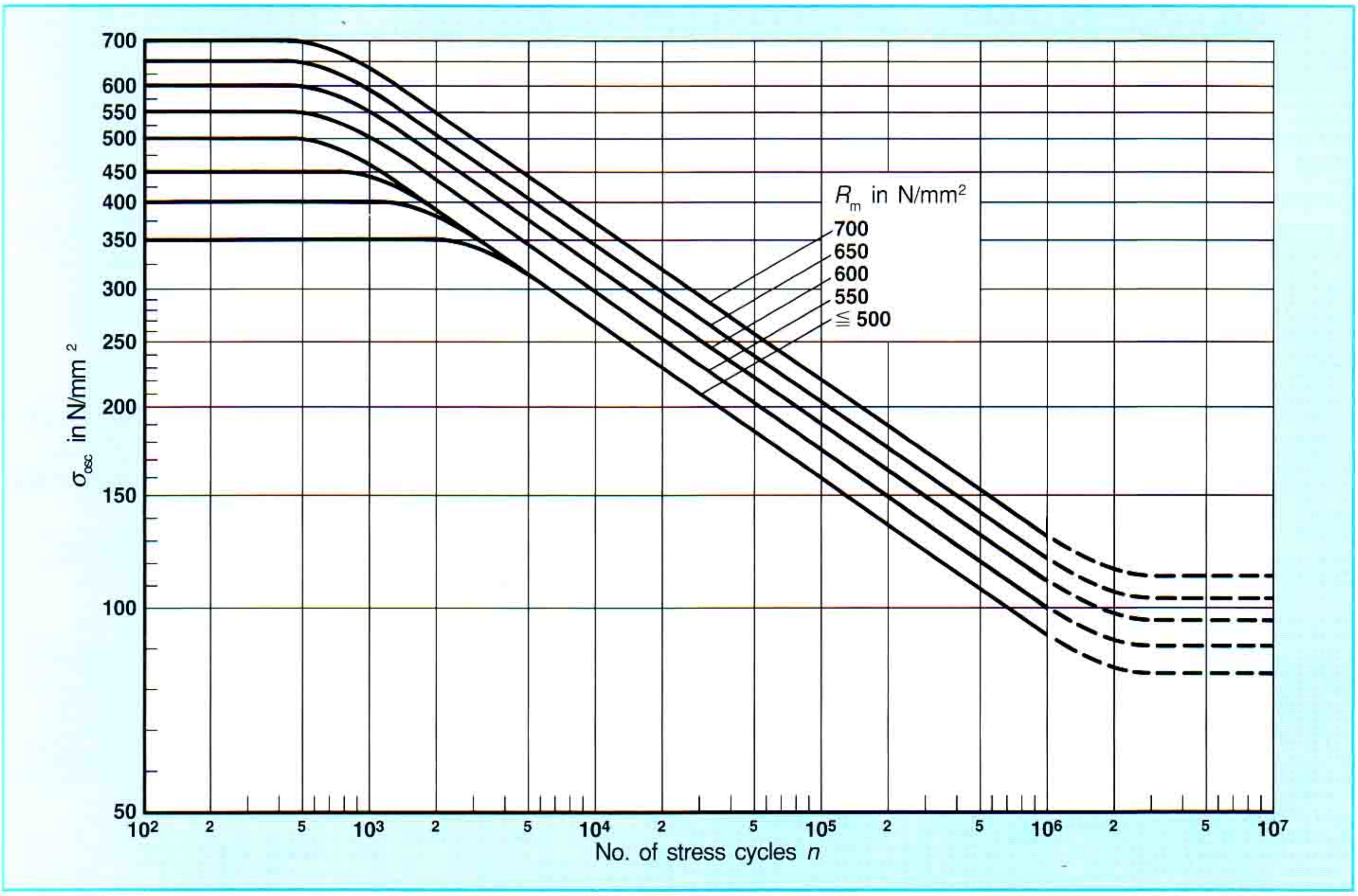


Diagram 57: *Strength under pulsating stress of submerged-arc welded steel tube ($v = 1$)*

5.1 Calculation of wall thickness to non-German standards

Special calculation formulae taken from the relevant guide-lines of the foreign acceptance authorities must be employed for installations built to non-German regulations. It must be established before the pipework is designed what regulations are to be employed for the calculation. The following formulae are representative of the principal foreign regulations; there is no claim that the list is complete:

- **Wall thickness calculation to British Standard BS 778, Appendix A**

In the United Kingdom the calculation formula for pipe wall thickness is laid down in BS 778, Appendix A [12]. The formula is:

$$s_V = \frac{d_i \cdot p}{(20\,\frac{K}{S} - p)} + x. \qquad (7)$$

Formula (7) is identical to DIN 2413/II and AD-B1 except for the wall thickness allowance x. The allowance is generally 12.5% and takes care of any weakness caused by bending. The minimum value of tensile strength is taken as the strength coefficient. The safety factor specified here is 4 for non-corrosive media and 4.5 for water. The minimum bending radii must be three times the outside diameter of the pipe and the eccentricity must not exceed 5% of the outside diameter.

- **Pipe calculations to French Standard NF A 49-300**

Unlike their German and British counterparts, the French standard for pipe calculations [13] does not specify a direct calculation of the wall thickness but gives basic guide-lines for the calculation of the test pressure and bursting pressure of actual tubes. The information allows the following calculation formulae for determining the pipe wall thickness to be derived:

$$s_V = \frac{d_i \cdot p'}{20\,K - 1{,}2\,p'}, \qquad (8)$$

$$s_V = \frac{d_i \cdot p}{\frac{20\,K}{S} - 1{,}2\,p}. \qquad (9)$$

The theoretical wall thickness for the test pressure p' is ascertained with Formula (8), with 90% of the $R_{p0.2}$ yield point being used as the strength coefficient. In contrast, the operating pressure and the minimum tensile strength are used in Formula (9). The French standard does not state any required safety factor S. It simply refers to the existing regulations for different fields of application.

- **Pipe calculations to the Barlow formula (USA)**

Most American regulations for pipe calculations make use of the Barlow formula [14]

$$s_V = \frac{d_i \cdot p}{20\,\frac{K}{S} - 2\,p} \qquad (10)$$

Basically, Formula (10) is broadly identical to the calculation formula of DIN 2413, Case I except that the minimum tensile strength of the pipe material is used as the strength coefficient. The following safety factors are applicable to the different applications:

$S = 4$ - normal operating conditions

$S = 6$ - high hydraulic and mechanical stress peaks

$S = 8$ - harsh operating conditions, dangerous applications.

5.2 Influencing variables

The calculation formulae of German regulations contain no influencing variables related to the effects of corrosion, vibration due to non-steady-state flow, e.g. pressure pulsation, or others. However, such factors must not be underestimated because, under some circumstances, they can establish different preconditions for the design data or exceed them by a multiple. In the case of pressure pulsations that can occur as a result of fast-closing valves, the magnitude of the pulsations must be calculated and added to the operating pressure. The relevant formulae for this are given in DIN 2413.

The final determination of the pipe wall thickness s must take into account two other influencing variables:

- pipe wall thickness undersize c_1
- wear due to corrosion c_2.

The pipe wall thickness undersize (minimum tolerance level) arises from manufacturing tolerances and is specified in the conditions of supply and delivery for seamless and welded tube *(see Table 50).*

The allowance for corrosion is normally 1 mm for ferritic steels. This allowance can be dispensed with if media or environmental conditions are involved which cause no corrosive attack at all. It can also be dispensed with for austenitic (i.e. stainless) pipe materials. The actual pipe wall thickness required is then:

$$s = s_V + c_1 + c_2 \qquad (11)$$

If the wall thickness undersize is given in %, s can be calculated from Formula (12)

$$s = (s_V + c_2) \cdot \frac{100}{100 - c_1} \qquad (12)$$

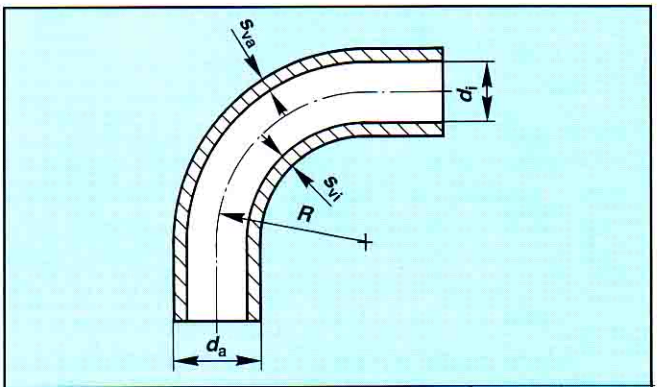
5.3 Calculation of pipe bends

The calculations for the wall thickness of pipe bends are mostly based on the calculations for straight lengths of pipe. However, as a result of bending, greater values of wall thickness undersize and different stressing of the outside and inside of the bend must be anticipated. In order to prevent an adverse effect on the endurance limit at repeated stress, primarily during dynamic stressing of the pipe, there must be no major wall thickness undersize or flattening as a result of bending. Therefore, the bending radii should not be made too small. DIN 5508 [15] recommends suitable bending radii in relation to the outside diameter *(see Table 51)*. The ratio of bending radius to outside diameter of the pipe is usually 2.5 to 3 and is given as a minimum dimension for thin-walled tube.

	Outside diameter d_a in mm	Wall thickness s	Wall thickness undersize c_1
Seamless precision steel tube nato ch DIN 2391, Part 1	< 5 $6 \le d_a \le 8$ > 8		20 % 15 % 10 %
Seamless precision steel tube to DIN 1629 (extract)	≤ 130	$< 4\ s_n$ * $> 4\ s_n$	10 % 9 %
Welded steel tube to DIN 1628		$s \le 3$ mm 3 mm $< s \le 10$ mm $s > 10$ mm	0,25 mm 0,35 mm 0,50 mm

* s_n Normal wall thickness to DIN 2448

Table 50: *Permitted wall thickness undersize of seamless and welded steel tube*



d_a in mm	6	8	10	12	14 15 16	18
R in mm	16	20	25	32,5	40	45
d_a in mm	20	22 25	28 30	35 38	42	60
R in mm	55	65	80	100	110	160

Table 51: *Recommended bending radii to DIN 5508 (extract)*

The required wall thickness on the inside and outside of the bend (sv_i and sv_o) is calculated according to DIN 2413 from:

$$s_{vi} = s_v \cdot B_i \text{ and} \tag{13}$$

$$s_{vo} = s_v \cdot B_o. \tag{14}$$

In Formulae (13) and (14) B_i and B_o are coefficients that can be taken from Diagram 58 with reference to the bend radius R/d_i and the parameter s_v/d_i. For thin-walled tubes ($s_v/d_i < 0.02$) approximate values of the coefficients can also be calculated with the following formulae

$$B_i = \frac{2R - \frac{d_o}{2}}{2R - d_o}, \tag{15}$$

$$B_o = \frac{2R + \frac{d_o}{2}}{2R + d_o}. \tag{16}$$

6 Calculating the pressure losses

The pressure drop Δp_i due to friction between the hydraulic fluid and the inner wall of the tube can be calculated from:

$$\Delta p_\lambda = \lambda \frac{L}{d_i} \cdot \rho \cdot \frac{\overline{w}^2}{2}. \tag{17}$$

Where λ is the coefficient of friction, L the length of the pipe and ρ the density of the fluid. The coefficient of friction depends on the surface finish k of the tube and on the Reynolds number

$$Re = \frac{\overline{w} \cdot d_i}{\nu}. \tag{18}$$

The coefficient of friction for the pipe can be taken from *Diagram 59* using the values of surface finish for steel tube given in Table 52 and the Reynolds number.

The total pressure losses throughout a whole hydraulic system comprise not only the length-related resistances of individual lengths of pipe but also the pressure drops across individual points of resistance as represented by valves, fittings and other similar components. Therefore, it is useful to calculate the total pressure drop Δp_v from the resistance coefficient of all individual resistances. This gives the total pressure drop thus:

$$\Delta p_v = \Delta p_\lambda + \Delta p_\xi \tag{19}$$

and

$$\Delta p_\xi = \Sigma \xi \cdot \rho \frac{\overline{w}^2}{2}. \tag{20}$$

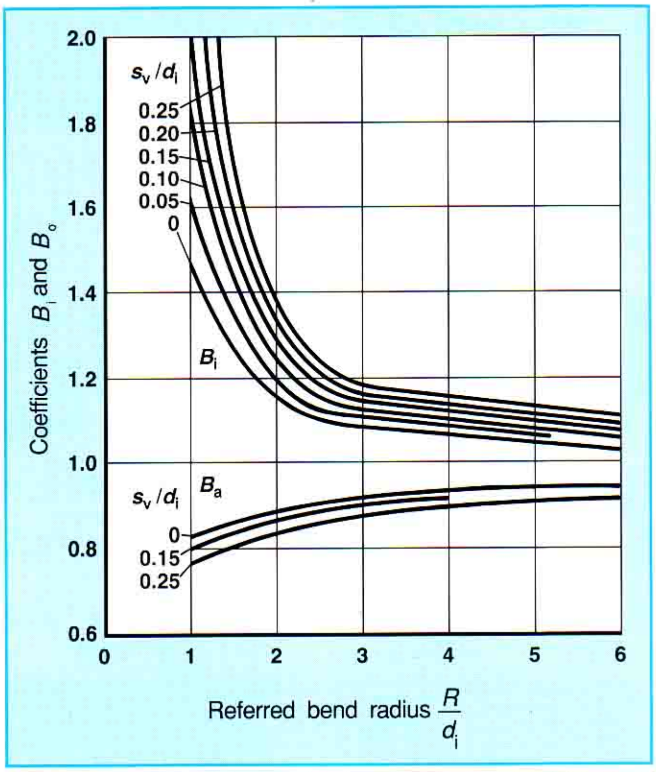


Diagram 58: *Coefficients for calculating the wall thickness of tube bends*

Substituting Formulae (17) and (20) in Formulae (19) gives:

$$\Delta p_v = \left(\frac{\lambda L}{d_i} + \Sigma \xi\right) \cdot \rho \cdot \frac{\overline{w}^2}{2}. \tag{21}$$

The resistance values of the proposed valves and fittings can be taken from the manufacturer's catalogues. In most cases manufacturer's documentation also gives the pressure drop directly in the form of a curve versus flow. This allows the pressure drops of the individual fittings for the particular value of flow to be summated and substituted directly in Formula (19).

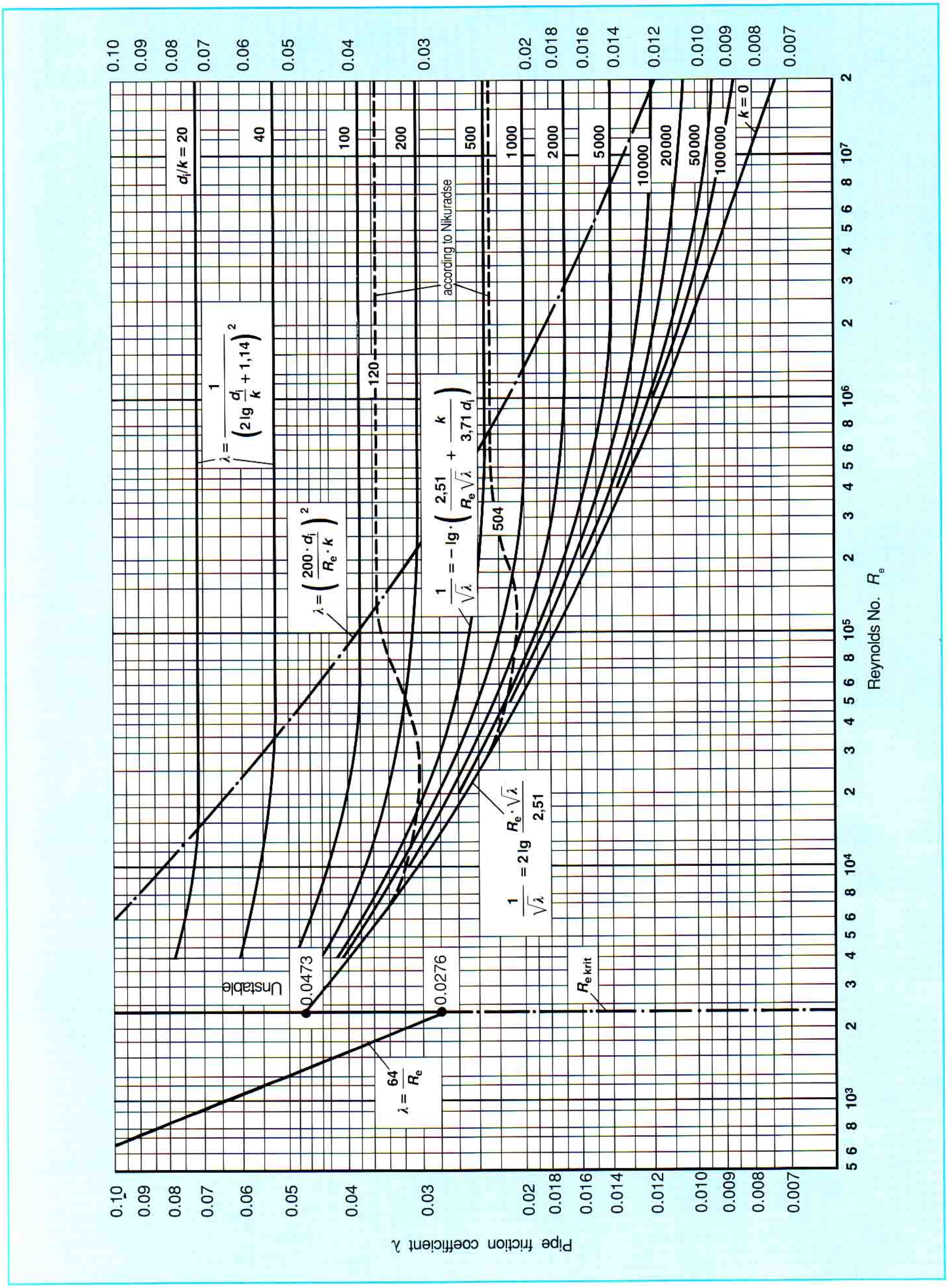


Diagram 59: *Pipe coefficient of friction l versus Reynolds number Re (see [16] (for example))*

Material	Pipes		Absolute roughness k in mm
	Type	Condition	
Steel	Seamless (commercial quality)	new • as-rolled • pickled • galvanized	 0.02 to 0.06 0.03 bis 0.04 0.07 bis 0.10
	Longitudinally seam-welded	new • as-rolled • bitumenized • galvanized	 0.04 to 0.10 0.01 to 0.05 0.008
	Seamless and longitudinally seam-welded	used • medium rusting or slight incrustation	0.1 to 0.2

Table 52: *Internal surface finish of steel tube (see [16](for example))*

7 Examples

Example 1

Calculate the size of a pressure line subjected to predominantly steady-state stress by a maximum operating pressure of 210 bar and a temperature of 50°C. The material is to be precision steel tube St 35 to DIN 2391-C. The pump delivery is 160 L/min.

Solution

1. Calculating the pipe inside diameter using Formula 2

$$d_i = 4{,}607 \sqrt{\frac{\dot{V}}{w}} \;.$$

Assuming that the mineral-oil fluid has a kinematic viscosity of 30 mm^2/s and a density of 0.3 g/cm^3 at operating temperature, the average value of flow velocity given by *Table 41* is 6 m/s.

This gives:

$$d_i = 4.607 \sqrt{\frac{160}{6}} = 23.79 \text{ mm},$$

selected from Table 55:

$d_o = 35$ mm, $s = 3$ mm, $d_i = 29$ mm

2. Calculating the required wall thickness to DIN 2413, Case I (see Formula 3)

$$s_V = \frac{d_i \cdot p}{20 \cdot \frac{K}{S} \cdot v - 2p}$$

The following *Table 53* lists the mechanical parameters for various tube materials. From $K = 235$ N/mm^2, $S = 1.5$ *(see Table 46)* and $v = 1$ for seamless tube it is possible to calculate the wall thickness from

$$s_V = \frac{29 \cdot 210}{20 \cdot \frac{235}{1{,}5} - 2 \cdot 210} = 2.25 \text{ mm}.$$

Checking the diameter ratio

$$\frac{d_o}{d_i} = \frac{35}{29} = 1.21 < 1.7$$

3. Calculating the actual wall thickness required

As the wall thickness undersize is given in % for the selected type of precision seamless steel tube the actual wall thickness required is calculated from Formula (12).

$$s = (s_V + c_2) \cdot \frac{100}{100 - c_1}$$

Table 50 shows the appropriate wall thickness undersize to be 10%. The wear allowance can be neglected because there is no corrosion from the fluid or the environment.

$$s = 2.25 \cdot \frac{100}{100 - 10} = 2.5 \text{ mm} < 3 \text{ mm}$$

Therefore, the selected tube DIN 2391-C-35x3-St 35 NBK is adequately sized.

4. Calculating pipe bends

Table 51 shows the bending radius *R* for the type of tube being used to be 100 mm. Formulae 13 and 14 give the required wall thickness for the inside and outside of the bend as:

$$s_{vi} = s_v \cdot B_i$$

$$s_{vo} = s_v \cdot B_o$$

Coefficients B_i and B_o can be taken from *Diagram 58.*

$$\frac{R}{d_i} = \frac{100}{29} = 3.45 \quad \text{and}$$

$$\frac{s_V}{d_i} = \frac{2.25}{29} = 0.078$$

gives $B_i = 1.15$ and $B_o = 0.92$

$$s_{vi} = 2.25 \cdot 1.15 = 2.59 \text{ mm}$$
$$s_{va} = 2.25 \cdot 0.92 = 2.07 \text{ mm}$$

The pipe must be bent so that there is no undersize of these two values of wall thickness on the inside and outside of the bend.

5. Calculating the pressure losses

The pressure drop per unit length due to pipe friction can be calculated with Formula 17:

$$\frac{\Delta p_\lambda}{L} = \lambda \cdot \frac{1}{d_i} \cdot \rho \cdot \frac{\overline{w}^2}{2}$$

Determining the pipe coefficient of friction

First calculate the Reynolds number with Formula 18:

$$Re = \frac{\overline{w} \cdot d_i}{\nu}$$

The velocity for the type of tube selected is given by:

$$\overline{w} = \frac{\dot{V}}{d_i^2 \cdot \frac{\pi}{4}} = \frac{160 \cdot 10^3}{29^2 \cdot \frac{\pi}{4} \cdot 60} = 4.04 \text{ m/s}.$$

which gives:

$$Re = \frac{4.04 \cdot 29 \cdot 10^3}{30} = 3905.3$$

Table 52 shows the average value of internal roughness of a seamless steel tube with a rolled finish to be 0.04 mm.

Using the ratio: $\frac{d_i}{k} = \frac{29}{0{,}04} = 725$

it is possible to read off the value of 0.04 from *Diagram 59* for the coefficient of friction. The pressure drop per unit length can now be calculated thus:

$$\frac{\Delta p_\lambda}{L} = 0.04 \cdot \frac{1}{29} \cdot 0.9 \cdot \frac{4.04^2}{2} \cdot 10 = 0.101 \, \frac{\text{bar}}{\text{m}}.$$

Example 2

For the type of tube used in *Example 1* now determine what maximum value of pulsating pressure can be tolerated continuously.

Solution

The calculation is performed according to Case III in DIN 2413. The lower value of operating pressure is taken as zero, which gives the maximum pressure from Formula 5 as follows:

$$\hat{p} = \frac{20 \cdot \frac{K}{S} \cdot s_V}{d_i + 3\,s_V}.$$

In this case the endurance limit at repeated stress must be used for the strength coefficient *K* in *Table 46*; for this tube material it is 226 N/mm² *(see Table 53)*. The theoretical value of wall thickness to be used for the existing tube is calculated with Formula 12 thus:

$$s_V = s \cdot \frac{100 - c_1}{100} - c_2 = 3\,\frac{100 - 10}{100} = 2.7 \text{ mm}$$

Which gives:

$$\hat{p} = \frac{20 \cdot \frac{226}{1.5} \cdot 2.7}{29 + 3 \cdot 2.7} = 219.3 \text{ bar}.$$

According to Case I the maximum tolerable pressure is:

$$p = \frac{20 \cdot \frac{K}{S}\, v \cdot s_V}{d_i + 2\,s_V}$$

$$= \frac{20 \cdot \frac{235}{1.5} \cdot 1 \cdot 2.7}{29 + 2 \cdot 27} = 245.9 \text{ bar}.$$

Therefore: min $(\hat{p}, p) = 219.3$ bar

Which means that the pipe can permanently withstand a pulsating pressure of 219 bar without suffering damage. This assumes, however, that there are no other stresses act on the pipe.

8 Mechanical properties of tube materials and tube selection tables

Designation	St 37.4	St 52.4	St 37.4	St 37.0	St 35 NBK	X6CrNiMoTi17 122	X6CrNiTi1810
Material No. DIN	1.0255 1630	1.0581 1630	1.0255 1628	1.0254 1626	1.0308 2391	1.4571 17458	1.4541 17458
Tensile strength R_m in N/mm² (min)	340	490	340	340	340	500	500
0,2% yield strength $R_{p\,0,2}$ in N/mm² (min) or upper yield point R_{eH} in N/mm² (min)	235 *	350 *	235 *	235	235	20 °C: 210 50 °C: 202 100 °C: 185	200 190 176
1% yield strength R_{p1} in N/mm² (min)	—	—	—	—	—	20 °C: 245 50 °C: 234 100 °C: 218	235 222 208
Elongation at fracture (min) A_5 in % ($L_o = 5 \cdot d_o$)	25	21	25	25	25	> 30	> 30
Strength coefficient K in N/mm² to AD-Merkblatt W 4 at 20 °C at 100 (120) °C	235 186	355 255	235 186	235 186	235 186	—	—
Endurance limit at repeated stress $\sigma_{osc\,/\,D}$ in N/mm² to DIN 2445 supplement to DIN 2413 see sheet 3.1/3.2	226	—	—	—	—	(190) **	(190) **

* For calculations to DIN 2413 the given values can be used up to 120°C

** Not given in DIN 2445 (see [1])

Table 53: *Mechanical properties of different tube materials*

Material St 52.4 to DIN 1630, certification e.g. to DIN 50 049-3.1 B												
	PN 100			PN 160			PN 320			PN 400		
DN	d_o	s	d_i	d_o	s	d_i	d_o	s	d_i	d_o	s	d_i
40	48,3	3,6	41,1	48,3	4	40,3	48,3	8	32,3	70	14,2	41,6
50	60,3	4,5	51,3	60,3	5	50,3	60,3	10	40,3	88,9	17,5	53,9
65	76,1	4,5	67,1	76,1	6,3	63,5	76,1	12,5	51,1	101,6	20	61,6
80	88,9	6,3	76,7	101,6	8,8	84	101,6	16	69,6	139,7	28	83,7
100	114,3	8,8	96,7	114,3	10	94,3	114,3	17,5	79,3	168,3	32	104
125	139,7	10	119,7	152,4	12,5	127	193,7	30	134	219,1	45	129
150	168,3	12,5	143,3	177,8	16	146	219,1	36	147	244,5	50	144
200	219,1	16	187,1	244,5	20	204	298,5	45	208	323,9	65	194
250	273	20	233	298,5	25	248	355,6	55	246	406,4	75	256
300	355,6	25	305,6	355,6	30	296	—	—	—	—	—	—

Designation of steel tube to DIN 2448 of 76.1 mm outside diameter and 12.5 mm wall thickness made of St 52.4 steel and user's inspection to DIN 1630

Tube DIN 2448-76.1 x 12.5 DIN 1630-St 52.4

Table 54: *Selection table for seamless steel tube for pulsating pressure to DIN 2445, Sheet 1*

Material St 35; as-supplied to DIN 2391, Part 2 July 81; certification e.g. to DIN 50 049-2.2							
Tube 4 to 16 mm				Tube 18 to 42 mm			
d_o	s	d_i	PN	d_o	s	d_i	PN
4	1,0	2	400	18	1,5	15	160
6	1,0	4	320	20	3,0	14	320
6	1,5	3	400	22	2,0	18	160
8	1,5	5	320	25	3,0	19	250
10	1,5	7	320	25	4,0	17	320
10	2,0	6	400	28	3,0	22	160
12	1,5	9	160	30	4,0	22	250
12	2,0	8	320	35	3,0	29	160
12	3,0	6	400	38	4,0	30	160
15	1,5	12	160	38	5,0	28	250
16	2,5	11	320	42	3,0	36	160

Designation of precision steel tube of 30 mm outside diameter and 4 mm wall thickness in St 35, as-supplied to DIN 2391, Part 2, July 81, normalized NBK
Tube DIN 2391-C- 30 x 4-St 35 NBK

Table 55: *Selection table for precision seamless steel tube to DIN 2391*

	PN 16			PN 160			PN 320		
	Material St 37.0 to DIN 1629, Oct. 84 certification e.g. to DIN 50 049-2.2			Material St 37.0 to DIN 1629, Oct. 84 certification e.g. to DIN 50 049-3.1 B			Material St 37.4 N to DIN 1630, Oct. 84 certification e.g. to DIN 50 049-3.1 B		
DN	d_o	s	d_i	d_o	s	d_i	d_o	s	d_i
							48,3	8,0	32,3
40	48,3	3,2	41,9	48,3	4,5	39,3	60,3	10,0	40,3
50	60,3	3,6	53,1	60,3	5,6	49,1	76,1	12,5	51,1
63	76,1	3,6	68,9	76,1	7,1	61,9	88,9	14,2	60,5
80	88,9	3,6	81,7	101,6	8,8	84,0	114,3	20,0	74,3
100	114,3	3,6	107,1	114,3	10,0	94,3	152,4	25,0	102,4
125	139,7	4,0	131,7	139,7	12,5	114,7	177,8	30,0	117,8
150	168,3	4,5	159,3	193,7	25,0	143,7	219,1	38,0	143,1
200	219,1	5,9	207,3						

Designation of seamless steel tube to DIN 2448 of 88.9 mm outside diameter and 14.2 mm wall thickness in steel St 37.4 DIN 1630 (Material No. 1.0255), normalized (N)
Tube DIN 2448 - 88.9 x 14.2 DIN 1630-St 37.4 N

Table 56: *Selection table for seamless steel tube to DIN 2448*

Note

Tables 54, 55 and 56 use the notation according to DIN 1629 and DIN 1630

9 Symbols and subscripts

Symbols

Symbols	Units	Quantity
A_5	%	Elongation at fracture ($L_0 = 5 \cdot d$)
c_1	mm, %	Allowance for waal thickness undersize
c_2	mm	Corrosion and wear allowance
d	mm	Diameter
K	N/mm²	Strength coefficient
k	mm	Internal roughness of tube
L	mm	Length
p	bar	Design pressure, i.e. maximum permitted peritted internal pressure allowing for all imaginable operating states including pressure shock
p'	bar	Test pressure
Δp	bar	Pressure drop
R	mm	Bending radius
R_{eH}	N/mm²	Upper yield point
R_m	N/mm²	Tensile strength
$R_{m/10^5}$	N/mm²	Fatigue strength for 100,000 hours
$R_{m/2 \cdot 10^5}$	N/mm²	Fatigue strength for 200,000 hours
$R_{p\,0,2}$	N/mm²	0,2% yield strength
$R_{p\,1}$	N/mm²	1% yield strength
s	mm	Actual wall thickness
s_v	mm	Theoretical wall thickness (without allowances)
$\dot{V}$	L/min	Volumetric flow
$\overline{w}$	m/s	Mean flow velocity
x	%	Wall thickness allowance to British Standards
ν	mm²/s	Kinematic viscosity
ρ	g/cm³	Density
σ_{osc}	N/mm²	Fatigue strength under pulsating stress
$\sigma_{osc/D}$	N/mm²	Endurance limit at repeated stress

Dimensionless symbols

Symbols	Quantity
B_o, B_i	Coefficients allowing for reduced stress at outside and inside of pipe bends
n	No. of stress cycles
Re	Reynolds No.
S	Safety factor
S_L	Load cycles safety factor
v	Weld efficiency
λ	Pipe friction coefficient
ξ	Resistance coefficient

Indizes

Symbols	Quantity
o	outside
i	inside
max	maximum
min	minimum
v	loss
λ	referred to pipe friction
ξ	referred to individual resistances

Headers

Symbols	Quantity
^	Maximum value
v	Minimum value

10 References

[1] Fiala O., Köhnlechner R., Ordelheide G.: Berechnung und Dimensionierung von Rohrleitungen in der Hydraulik. Ölhydraulik und Pneumatik 27 (1983) 5, S. 335 - 341

[2] DIN 2402: Nennweiten. Beuth Verlag, Berlin, Febr. 1975

[3] DIN 2391, Teil 1 und 2: Nahtlose Präzisionsstahlrohre mit besonderer Maßgenauigkeit. Juli 1981

[4] DIN 2448: Nahtlose Stahlrohre. Febr. 1981

[5] DIN 2445: Nahtlose Stahlrohre für schwellende Beanspruchung. Nov. 1974

[6] DIN 1630: Nahtlose kreisförmige Rohre aus unlegierten Stählen für besonders hohe Anforderungen. Okt. 1984

[7] DIN 2463: Geschweißte Rohre aus austenitischen nichtrostenden Stählen. März 1981

[8] DIN 50049: Bescheinigung über Materialprüfungen. Juli 1982

[9] DIN 2401, Teil 1: Druck- und Temperaturangaben. Mai 1977

[10] DIN 2413: Stahlrohre. Juni 1972

[11] AD-Merkblatt B1: Zylinder- und Kugelschalen unter innerem Überdruck. Juni 1986

[12] BS 778: Specification for Steel PIPES And JOINTS FOR HYDRAULIC PURPOSES. British Standards Institution, 1966

[13] NF A 49-330: TUBES SANS SOUDURE ETIRES A FROID POUR CIRCUITS HYDRAULIQUES ET PNEUMATIQUES. NORME FRANCAISE ENREGISTREE, 1976

[14] SAE Handbook Supplement HS 150, 1982 Edition

[15] DIN 5508: Biegeradien für Rohre. Nov. 1979

[16] Wagner W.: Rohrleitungstechnik. Vogel Verlag, Würzburg, 2. Auflage 1983 S. 130-131