

Hydraulics and units of measurement

A HYDRAULICS

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1 Preliminary definitions

1.1 Magnitudes

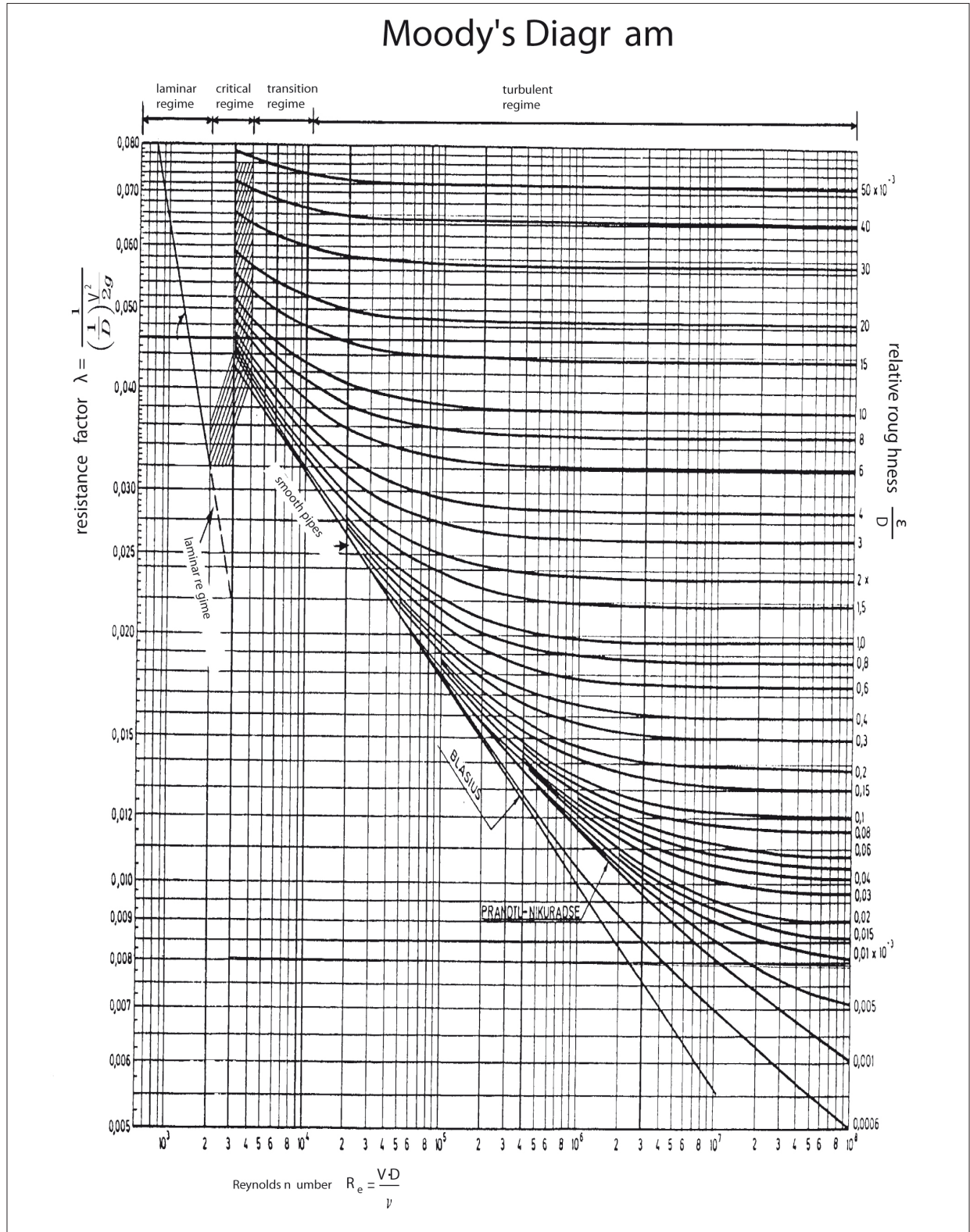
Parameter	Units I.S.	Symbol/Formula	Comments									
Density	kg.s²/m⁴	ρ	For water at normal temperatures it is possible to use the value: ρ = 101.9 kg.s² / m⁴									
Absolute or dynamic viscosity	kg.s / m²	μ	For water at atmospheric pressure and at 20°C, the value is: μ = 1.025 x 10⁻⁴ kg.s / m²									
Kinematic viscosity	m² / s	$\nu = \frac{\mu}{\rho}$	The value changes with temperature: <table><tr><th>ν (m²/s)</th></tr><tr><td>5 1.52 x 10⁻⁶</td></tr><tr><td>10 1 x 10⁻⁶</td></tr><tr><td>15 4 x 10⁻⁶</td></tr><tr><td>20 1 x 10⁻⁶</td></tr><tr><td>25 0 x 10⁻⁶</td></tr><tr><td>30 0 x 10⁻⁶</td></tr><tr><td>35 3 x 10⁻⁶</td></tr><tr><td>40 6 x 10⁻⁶</td></tr></table> (Normally the value at 20° C is used)	ν (m²/s)	5 1.52 x 10⁻⁶	10 1 x 10⁻⁶	15 4 x 10⁻⁶	20 1 x 10⁻⁶	25 0 x 10⁻⁶	30 0 x 10⁻⁶	35 3 x 10⁻⁶	40 6 x 10⁻⁶
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Reynolds number	Non-dimensional	$R_e = \frac{DV}{\nu}$ formulas where: D = inside diameter V = velocity	It is important because it determines the range of application for empiric									

Parameter	Units I.S.	Symbol/Formula	Comments
Absolute equivalent roughness	m	ε	Experimental parameter characteristic for each type of pipe
Relative roughness	Non-dimensional	$\frac{\varepsilon}{D}$	
Friction speed	m/s	$V^* = V \sqrt{\frac{f}{8}}$	
Roughness Reynolds number	Non-dimensional	$(R_e)_r$ or R_r $(R_e)_r = \frac{kV^*}{\nu}$	Used to establish the type of flow regime (see Section 1.2)

1.2 Regimes in forced flow

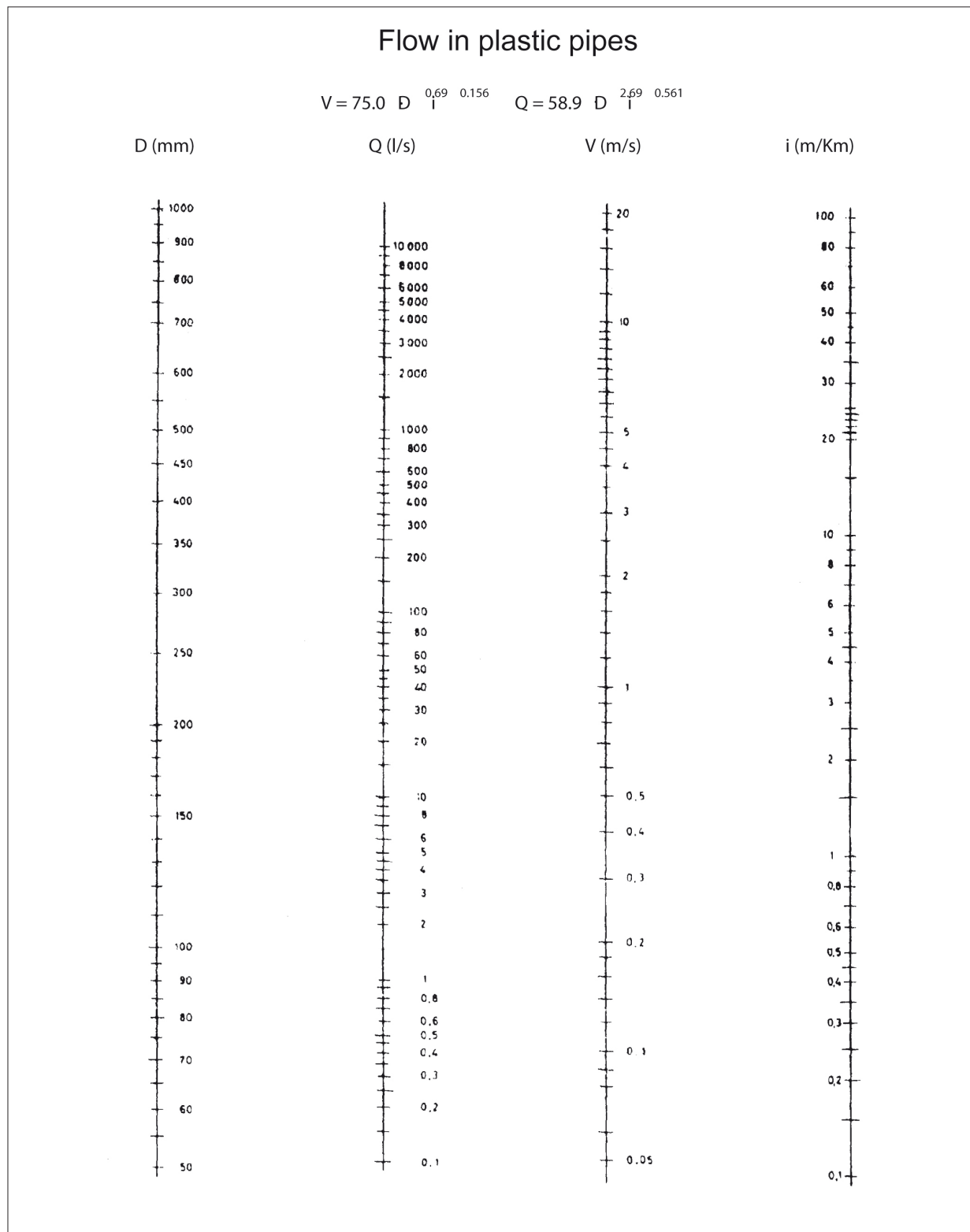
Regime	Re	$(R_e)_r$	What happens
Laminar	$\leq 2\,000$		Viscous forces prevail
Critical	2 000 – 4 000		Not known, not usual
Turbulent			
Smooth	$> 4\,000$	$(R_e)_r \leq 3.5 - 5$	Viscous forces prevail
Intermediate or transition		$5 < (R_e)_r \leq 70$	
Rough		$(R_e)_r > 70$	Inertial forces prevail

2 Moody's diagram



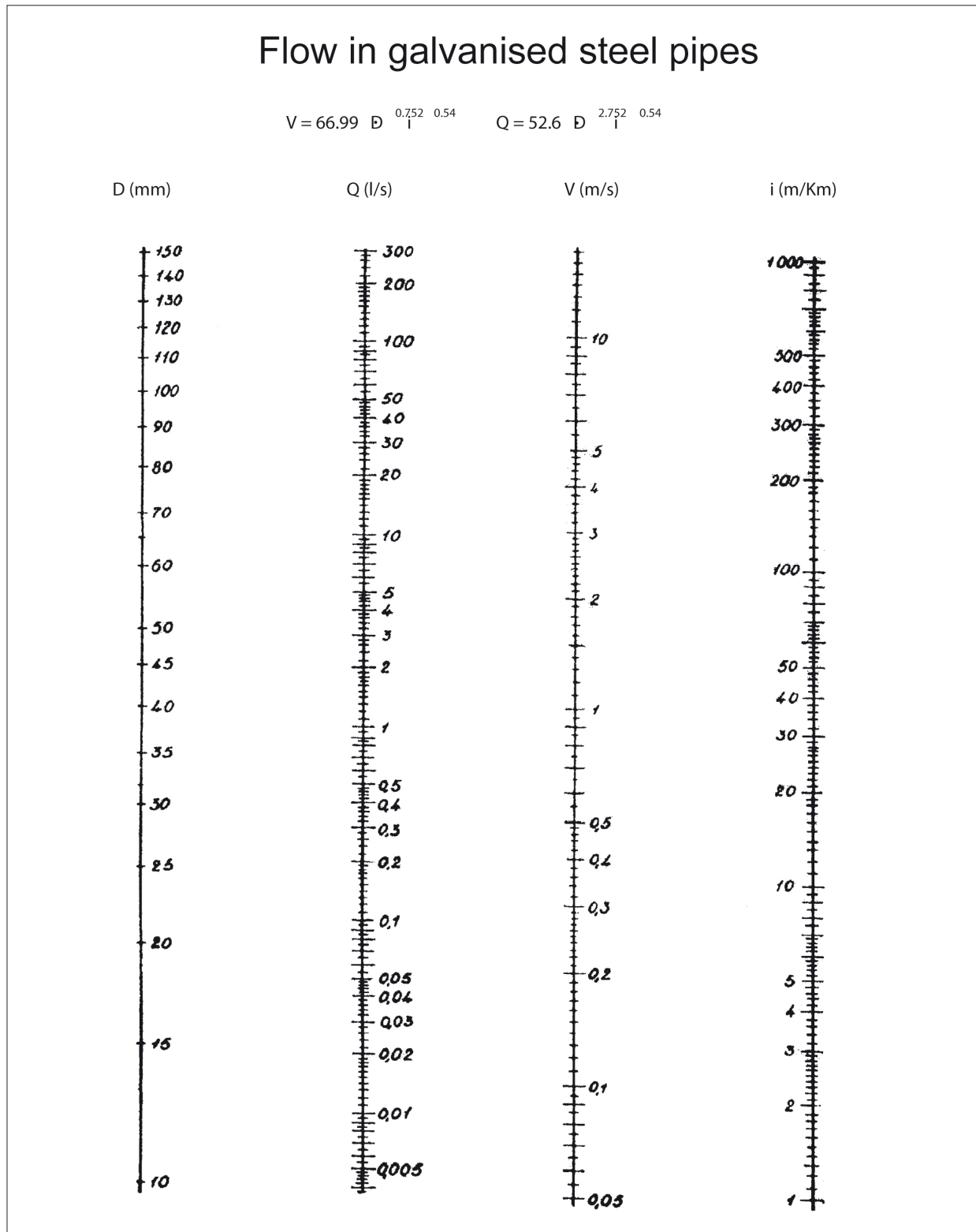
3 Nomogram for linear head losses in plastic pipes

FLOW IN PLASTIC PIPES



4 Nomogram for linear head losses in steel pipes

FLOW IN GALVANISED STEEL PIPES



5 Head losses

5.1 Linear head losses

5.1.1 GENERAL EXPRESSIONS

The general equation for head losses is written:

$$\Delta H = \lambda \frac{L}{D} \frac{V^2}{2g}$$

where H is head losses (or energy loss) (m), λ head-loss coefficient (non-dimensional), D pipe internal diameter (m), and L pipe length (m).

In a pipe, head losses per unit length, are:

$$\Delta H = \lambda \frac{V^2}{2g D}$$

To calculate linear head losses numerically, the only unknown factor is λ , the head-loss coefficient, which is given by various formulae (Lencastre 1995):

– in laminar regimes:

$$\lambda = \frac{64}{R_e}$$

– in turbulent regimes, for smooth pipes, there are different formulae. One that has been considered valid for a long time is the Blasius equation:

$$\lambda = \frac{0.3164}{R_e^{0.25}}$$

– in turbulent regimes, for rough pipes, the most widely used is the Colebrook-White formula:

$$\frac{1}{\sqrt{\lambda}} = -2 \log_{10} \left[\frac{\varepsilon}{3.7D} + \frac{2.51}{R_e \sqrt{\lambda}} \right]$$

where ε is the absolute roughness of the pipe. Therefore, the only difficulty in the calculation of head losses with this formula resides in the choice of a roughness coefficient ε . The values presented in Table I are proposed by Degrémont (1989).

5.1.2 MOODY'S DIAGRAM

Moody established an nomogram where λ is given in terms of R_e and ε/D (the relative roughness), basing his work on a large number of tests, and on the various formulas proposed for the calculation of head losses. This nomogram is important because it can be applied to any fluid, and to any type of flow (laminar, transient or turbulent).

In practice, this is the universal nomogram recommended here. The procedure is as follows:

- calculate R_e , fixing the flow velocity at 1 m/s;
- calculate the relative viscosity ε/D ;
- transfer these two values to Moody's diagram, so that coefficient λ can be worked out;
- calculate head losses using the general formula $\Delta H = \lambda (L/D) (V^2/2g)$;
- for verification, λ is calculated using the Colebrook-White formula. In practice, this formula proves to be valid almost always, and therefore is the best for this kind of calculation. Table II gives λ/D based on the Colebrook-White formula.

Table I: Values of absolute roughness for different materials (Degrémont 1989).

Materials	ε in mm
New steel	0.1
New cast iron	0.1 to 1
Plastic	0.03 to 0.1
Concrete - smooth moulds	0.2 to 0.5
Concrete - coarse moulds	1 to 2

Table II: Coefficient of head losses in pipes.

Pipe diameter (m)	Coefficient λ/D depending on the value of ε (absolute roughness)			
	$\varepsilon = 0.1$ mm	$\varepsilon = 0.5$ mm	$\varepsilon = 1$ mm	$\varepsilon = 2$ mm
0.025	1.26	2	2.84	
0.03	1.02	1.54	2.00	2.71
0.04	0.70	1.04	1.34	1.80
0.05	0.528	0.78	0.985	1.3
0.065	0.35	0.50	0.615	0.80
0.08	0.29	0.413	0.512	0.66
0.1	0.222	0.31	0.38	0.49
0.125	0.168	0.232	0.284	0.36
0.150	0.133	0.182	0.223	0.28
0.200	0.0935	0.128	0.153	0.19
0.250	0.071	0.096	0.114	0.141
0.300	0.0573	0.076	0.09	0.11
0.350	0.0475	0.0625	0.0735	0.09
0.400	0.04	0.0530	0.0625	0.0758
0.450	0.0351	0.0460	0.0538	0.065
0.500	0.0308	0.04	0.047	0.0566
0.600	0.0245	0.0322	0.0371	0.0477
0.700	0.0206	0.0266	0.0307	0.0368
0.800	0.0175	0.0225	0.0260	0.0310
0.900	0.0151	0.0194	0.0225	0.0267
1.000	0.0134	0.0170	0.0197	0.0234
1.100	0.01163	0.015	0.01754	0.0209
1.200	0.0104	0.01358	0.01583	0.01875
1.250	0.0102	0.013	0.015	0.0177
1.300	0.00946	0.0123	0.0142	0.01676
1.400	0.00878	0.01128	0.01307	0.01535
1.500	0.00827	0.0104	0.012	0.014
1.600	0.00737	0.00956	0.01106	0.0131
1.700	0.00694	0.00882	0.0103	0.01235
1.800	0.00655	0.00833	0.00966	0.0111
1.900	0.00605	0.00773	0.00894	0.0104
2.000	0.00586	0.00735	0.0084	0.0098

5.1.3 EMPIRICAL FORMULAE

To determine linear head losses, there are many nomograms based on empirical formulae. Those found in Lencastre (1995), which contains a great variety of nomograms, allow the calculation of head losses in galvanized steel pipes:

$$V = 66.99 D^{0.752} i^{0.54} \quad \text{and} \quad Q = 52.6 D^{2.752} i^{0.54}$$

and in plastic pipes:

$$V = 75 D^{0.69} i^{0.156} \quad \text{and} \quad Q = 58.9 D^{2.69} i^{0.561}$$

where V is the water velocity (m/s), D the internal pipe diameter (mm), and i the head-loss coefficient (m/km).

5.2 Secondary head losses

According to Lencastre (1995), the expression for secondary head losses can be written as follows:

$$\Delta H = K \frac{V^2}{2g}$$

where K is a parameter depending on R_e and on ε , but essentially on the geometry of the feature (bend, fitting etc.).

These head losses can be disregarded when the length of the pipe between two features is more than 100 times its diameter.

The main coefficients of secondary head losses are for an abrupt narrowing, such as at a tank outlet (Figure 1), an elbow, (Figure 2), and a tee (Figure 3).

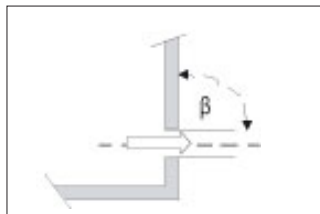


Figure 1: Head-loss coefficient as a function of angle β between the pipe and the wall at outlet from a tank.

β	20°	30°	45°	60°	70°	80°	90°
K	0.96	0.91	0.81	0.70	0.63	0.56	0.50

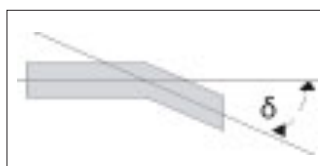


Figure 2: Head-loss coefficient as a function of angle δ of a bend.

δ	22.5°	30°	45°	60°	75°	90°
K	0.17	0.20	0.45	0.70	1	1.50

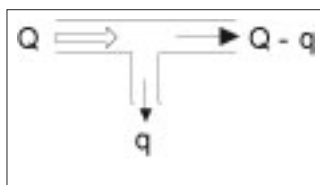


Figure 3: Head-loss coefficient as a function of the division of flow in a tee.

A: flow out Q . B: flow in Q .

A											
q/Q	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
K_q		1	1.01	1.03	1.05	1.09	1.15	1.22	1.32	1.38	1.40
K_{Q-q}	0	0.004	0.02	0.04	0.06	0.10	0.15	0.20	0.26	0.32	
B											
$Q/(Q+q)$	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
K_q		-0.37	-0.18	-0.07	0.26	0.46	0.62	0.78	0.94	1.08	1.20
K_{Q+q}	0	0.16	0.27	0.38	0.46	0.53	0.57	0.59	0.60	0.59	0.50

B UNITS OF MEASUREMENT

1	Main units	729
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1 Main units

SI units are given in bold.

Magnitude	Unit	Standard symbol	Expression in base units	Expression in other units
SPACE				
Length	metre	m		
	micron	μm	10^{-6} m	
	inch	in or "	$2.54 \times 10^{-2} \text{ m}$	
Area	square metre	m^2		
	are	a	100 m^2	
	hectare	ha	$10\,000 \text{ m}^2$	
Volume	acre	ac	$4\,047 \text{ m}^2$	
	cubic metre	m^3		
	litre	l		10^{-3} m^3 – 1 dm^3
Plane angle	radian	rad		
	degree	$^\circ$		$(\pi/180) \text{ rad}$
	minute	'		$(1/60)^\circ$
	second	"		$(1/60)'$
	grade	gr		$(\pi/200) \text{ rad}$
TIME				
Time	second	s		
	minute	min	60 s	
	hour	h	3 600 s	
	day	d	86 400 s	
	year	y	$3.16 \times 10^7 \text{ s}$	
Frequency	hertz	Hz	s^{-1}	
MASS				
Mass	kilogram	kg		
Density	kilogram per cubic metre	kg.m^{-3}		
Specific volume	cubic metre per kilogram	$\text{m}^3.\text{kg}^{-1}$		
SPEED				
Velocity	metre per second	m.s^{-1}		
Angular velocity	radian per second	rd.s^{-1}		
MECHANICS				
Acceleration	metre per second squared	m.s^{-2}		
Force, weight	newton	N	m.kg.s^{-2}	
	dyne	dyn		10^{-5} N
	kilogram-force	kgf		9.81 N
Moment of a force	newton per metre	N.m	$\text{kg.m}^2.\text{s}^{-2}$	

Magnitude	Unit	Standard symbol	Expression in base units	Expression in other units
MECHANICS				
Energy, work, heat	joule	J	$\text{m}^2.\text{kg}.\text{s}^{-2}$	
	kilogram metre	kgm		9.81 J
	calorie (small)	cal ₁₅		4.1855 J
	calorie (large)	cal		4.1868 J
	kilocalorie	kcal		4 186.8 J
	watt-hour	Wh		3 600 J
	electron volt	eV	$\text{m}^2.\text{kg}.\text{s}^{-3}$	$1.60219 \times 10^{-19} \text{ J}$
Mass flow	kilogram metre per second	$\text{kg}.\text{m}.\text{s}^{-1}$		
Power	watt	W		$\text{N}.\text{m}.\text{s}^{-1} - \text{J}.\text{s}^{-1}$
	metric horsepower	HP		735.499 W
Thermal flux	watt per square metre	$\text{W}.\text{m}^{-2}$		
Pressure, stress	pascal	Pa	$\text{m}^{-1}.\text{kg}.\text{s}^{-2}$	$\text{N}.\text{m}^{-2}$
	bar	bar		105 Pa
	normal atmosphere	atm		101 325 Pa
	millimetre of water	mmH ₂ O		9.81 Pa
	millimetre of mercury	mmHg		133.322 Pa
	pascal second	Pa.s		
Dynamic viscosity	poise	P		10^{-1} Pa.s
	poiseuille	PI		1 Pa.s
	square metres per second	$\text{m}^2.\text{s}^{-1}$		
Kinematic viscosity	stokes	St	$10^{-4} \text{ m}^2.\text{s}^{-1}$	
Thermodynamic temperature	kelvin	K		
HEAT				
Temperature, Celsius	degree celsius	°	+ 273.15	$T (^{\circ}\text{C}) = T (\text{K})$
Thermal capacity	joule per kelvin	$\text{J}.\text{K}^{-1}$		
Thermal conductivity	watt per metre kelvin	$\text{W}.\text{m}^{-1}.\text{K}^{-1}$		
OPTICS				
Luminous intensity	candela	cd		
Luminous flux	lumen	lm		cd.sr
Illuminance	lux	lx		$\text{lm}.\text{m}^{-2}$
Luminance	candela per square metre	$\text{cd}.\text{m}^{-2}$		
	lambert	L		$3.183 \times 10^3 \text{ cd}.\text{m}^{-2}$
MAGNETISM–ELECTRICITY				
Electric current intensity	ampere	A		
Electric charge	coulomb	C	A.s	
	faraday			$9.64870 \times 10^4 \text{ C}$
Voltage, potential	volt	V	$\text{m}^2.\text{kg}.\text{s}^{-3}.\text{A}^{-1}$	$\text{W}.\text{A}^{-1}$
Electric field	volt per metre	$\text{V}.\text{m}^{-1}$		
Electric capacitance	farad	F	$\text{m}^{-2}.\text{kg}^{-1}.\text{s}^4.\text{A}^2$	$\text{C}.\text{V}^{-1}$
Electric energy	kilowatt-hour	kWh		$3.6 \times 10^6 \text{ J}$
Magnetic field	ampere per metre	$\text{A}.\text{m}^{-1}$		
Magnetic induction	tesla	T	$\text{kg}.\text{s}^{-2}.\text{A}^{-1}$	$\text{Wb}.\text{m}^{-2}$
	gauss	G		10^{-4} T
	weber	Wb	$\text{m}^2.\text{kg}.\text{s}^{-2}.\text{A}^{-1}$	V.s
Magnetic induction flux	maxwell	Mx		10^{-8} Wbs
	henry	H	$\text{m}^2.\text{kg}.\text{s}^{-2}.\text{A}^{-2}$	$\text{Wb}.\text{A}^{-1}$
Resistance, impedance	ohm	Ω	$\text{m}^2.\text{kg}.\text{s}^{-3}.\text{A}^{-2}$	$\text{V}.\text{A}^{-1}$
Conductance	siemens	S	$\text{m}^{-2}.\text{kg}^{-1}.\text{s}^3.\text{A}^{-2}$	$\text{A}.\text{V}^{-1} - \Omega^{-1}$
Resistivity	mho	mho		S^{-1}
	ohm metre	$\Omega.\text{m}$	$\text{m}^3.\text{kg}.\text{s}^{-3}.\text{A}^{-2}$	
Conductivity	siemens per metre	$\text{S}.\text{m}^{-1}$	$\text{m}^{-3}.\text{kg}^{-1}.\text{s}^3.\text{A}^{-2}$	

Magnitude	Unit	Standard symbol	Expression in base units	Expression in other units
CHEMISTRY- PHYSICS				
Amount of substance	mole	mol	6.023 x 10 ²³ atoms	
Molar mass	kilogram per mole	kg.mol ⁻¹		
Molar volume	cubic metre per mole	m ³ .mol ⁻¹		
Density	kilogram per cubic metre	kg.m ⁻³	(number of mole x molar mass) / volume of the solution	
	part per million	ppm	(number of mole x molar mass) / mass of the solution	
	milli-equivalent per litre	meq.l ⁻¹	(number of mole x ionic charges) / volume of the solution	
Molar concentration, molarity	mole per cubic metre	mol.m ⁻³	number of mole / volume of the solution	
Molality	mole per kilogram	mol.kg ⁻¹	number of mole / mass of the solution	

2 Prefixes for multiples and sub-multiples of units

Factor multiplier	Prefix	Symbol
10 ¹²	tera	T
10 ⁹	giga	G
10 ⁶	mega	M
10 ³	kilo	k
10 ²	hecto	h
10	deca	da
10 ⁻¹	deci	d
10 ⁻²	centi	c
10 ⁻³	milli	m
10 ⁻⁶	micro	μ
10 ⁻⁹	nano	n
10 ⁻¹²	pico	p
10 ⁻¹⁵	femto	f
10 ⁻¹⁸	atto	a

3 Imperial and US customary units and conversions

Unit	Symbol	Remarks	Conversion
LENGTH			
inch	in or "		1 in = 0.0254 m
foot	ft or '	1 ft = 12 in	1 ft = 0.3048 m
mile	mi	1 mi = 1 760 yds	1 mi = 1 609.35 m
yard	yd	1 yd = 3 ft	1 yd = 0.9144 m
AREA			
square inch	sq in		1 sq in = $6.452 \cdot 10^{-4}$ m ²
square foot	sq ft	1 sq ft = 144 sq in	1 sq ft = 0.0929 m ²
acre	ac	1 ac = 4 840 yd ²	1 ac = 4 047 m ²
VOLUME			
imperial pint	UK pt		1 UK pt = 0.5683 l
imperial gallon	UK gal	1 UK gal = 8 UK pts	1 UK gal = 4.546 l
US liquid pint	US pt		1 US pt = 0.473 l
US gallon	US gal	1 US gal = 8 US pt	1 US gal = 3.785 l
cubic foot	cu ft		1 cu ft = 2.832×10^{-2} m ³
FLOW			
imperial gallons per second	UK gps		1 imp gps = 4.546×10^{-3} m ³ .s ⁻¹
US gallons per second	US gps		1 US gps = 3.785×10^{-3} m ³ .s ⁻¹
cubic feet per second	ft ³ .s ⁻¹		1 ft ³ .s ⁻¹ = 2.832×10 m ³ .s ⁻¹
MASS			
ounce	oz		1 oz = 28.350 g
pound	lb	1 lb = 16 oz	1 lb = 453.592 g
long ton (UK)	UK ton	1 UK ton = 2 240 lb	1 UK ton = 1 016 kg
short ton (US)	US ton	1 US ton = 2 000 lb	1 US ton = 907 kg
FORCE			
pound force	lbf		1 lbf = 0.0448 N
poundal	pdl		1 pdl = 0.138 N
PRESSURE			
pound force per square inch	psi		1 psi = 6 894.76 Pa
ENERGY			
British thermal unit	BTU		1 BTU = 1 055.06 J