Hydraulic Design Of Polyethylene Pipes

Waters & Farr polyethylene pipes offer a hydraulically smooth bore that provides excellent flow characteristics. Other advantages of Waters & Farr polyethylene pipes, like inert, corrosion free pipe material, excellent toughness and abrasion resistance, ensure that the pipes maintain this smooth bore throughout their service life.

The rate of flow of fluids through a pipe is determined by the inside diameter, ***D***, whereas Series 1 (to AS/NZS 4130) pipes are designated by nominal outside diameter, **DN**. Limits for ***D*** of the pipes are given in AS/NZS 4130 (see also Waters & Farr guidelines). As an approximate value for flow calculations only, ***D*** of Series 1 pipes may be calculated as follows:

$$D = \text{DN} - 2.12 \times \left(\frac{\text{DN}}{\text{SDR}} \right) \qquad \text{(HD-1)}$$

Flow of fluids in a pipe is a subject to resistance due to viscous shear stresses within the fluid and friction against the pipe wall, resulting in a pressure loss. A number of formulas, both theoretical and empirical, are used for flow calculations, and there are a number of flow charts based on these formulas.

The **Darcy-Weisbach formula** is:

$$H = f \frac{L \times V^2}{D \times 2g} \qquad \text{(HD-2)}$$

Where H – head loss, m,

f – friction factor, dimensionless, dependent upon surface roughness and Reynolds number,

L – pipe length, m,

V – average flow velocity, m/s; V may be estimated as follows:

$$V = \frac{4 \times 10^{-3} \times Q}{\pi \times D^2} \qquad \text{(HD-3)}$$

Q – flow, l/s,

D – mean internal diameter of pipe, m,

g – gravitational acceleration; $g = 9.807$ m/s² may be assumed.

For laminar flow (Reynolds number, ***Re***, below 2000), the friction factor is calculated using formula (HD-4), and dimensionless Reynolds number, ***Re***, is calculated by formula (HD-5):

$$f = \frac{64}{\text{Re}} \qquad \text{(HD-4)}$$

$$\text{Re} = \frac{V \times D}{\nu} \qquad \text{(HD-5)}$$

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Within transition zone between laminar and full turbulent flow, as is the likely case for most pipe applications, the **Colebrook formula** applies:

$$\frac{1}{\sqrt{f}} = -2 \times \log\left\{\frac{k}{3.7D} + \frac{2.51\nu}{\mathrm{Re} \times \sqrt{f}}\right\} \qquad \text{(HD-6)}$$

Where *k* – linear measure of roughness, mm; for polyethylene pipes, k = 0.007 mm is usually assumed (if to allow for some deposition with age, k = 0.01 mm),

v – kinematic viscosity, m²/s; a value of 1.141×10^{-6} m²/s may be assumed for water at 15°C.

The **Colebrook-White formula** for the velocity of water in a smooth bore pipe under laminar conditions takes the form:

$$V = -2 \times \sqrt{2gDJ} \times \log\left\{\frac{k}{3.7D} + \frac{2.51\nu}{D \times \sqrt{2gDJ}}\right\} \qquad \text{(HD-7)}$$

Where *J* – hydraulic gradient (slope), m/m.

Design flow charts for polyethylene pipes based on the above formula and on value of k = 0.01 mm are given in Figures 1 to 6.

The **Hazen-Williams formula** for smooth bore pipe full of water may be written in form:

$$Q = 278 \times C \times D^{2.63} \times J^{0.54} \qquad \text{(HD-8)}$$

Where *Q* – flow, l/s,

D – mean internal diameter of pipe, m,

J – hydraulic gradient, m/m,

C – Hazen-Williams roughness coefficient, dimensionless; for polyethylene pipes, the range of C is between 150 and 160, values of 150 or 155 may be assumed.

ISO/TR 10501:1993 provides the following formulas for calculation of head drop (***J***).

For water at 20°C, the head drop $\boldsymbol{J_o}$, m/m:

If $4 \times 10^3 \le Re < 1.5 \times 10^5$, $J_o = 5.37 \times 10^{-4} \times (D^{-1.24} \times V^{1.76})$. (HD-9)

If $1.5 \times 10^5 \le Re \le 1 \times 10^6$, $J_o = 5.79 \times 10^{-4} \times (D^{-1.20} \times V^{1.80})$. (HD-10)

Where *Re* – Reynolds number, dimensionless.

For water at a temperature different from 20°C, the head drop $\boldsymbol{J_t}$, m/m:

$$J_t = K_t \times J_o . \qquad \text{(HD-11)}$$

Where J_t – coefficient dependent upon temperature and Reynolds number as shown in the table to the left.

Temp., °C	K_t	
	$4 \times 10^3 \le Re < 1.5 \times 10^5$	$1.5 \times 10^5 \le Re \le 1 \times 10^6$
0	1.148	1.122
5	1.105	1.087
10	1.067	1.055
15	1.033	1.027
20	1.000	1.000
25	0.972	0.977
30	0.947	0.956
35	0.925	0.937
40	0.904	0.919
45	0.885	0.903

For a liquid other than water at 20°C, the head drop $\boldsymbol{J_x}$, m/m:

$$J_x = J_0 \left(\frac{\nu_x}{\nu_w} \right)^b \qquad \text{(HD-12)}$$

Where ν_x – kinematic viscosity of the liquid, m²/s,
ν_w – kinematic viscosity of water at 20°C,
b – coefficient dependent upon Reynolds number:

if $4 \times 10^3 \lesseqgtr Re < 1.5 \times 10^5$, $b = 0.24$,
if $1.5 \times 10^5 \lesseqgtr Re \leq 1 \times 10^6$, $b = 0.20$.

Head loss ***H***, m, for a pipe of a length ***L***, m, may be calculated as follows:

$$H = J \times L. \qquad \text{(HD-13)}$$

For practical use, charts based on empirical formulas are commonly developed in form of nomograms (e.g., charts based on Hazen-Williams formula are given in AS 2200). As a reference, on Figure 7 is reproduced a chart based on Lamont S3 formula for small and medium sized smooth pipes carrying water at 12.8°C (courtesy of Innovene):

- for metric units, $V_m = 0.551 \times D^{0.6935} \times J^{0.5645}$, $Q_m = 433 \times 10^{-6} \times D^{2.6935} \times J^{0.5645}$,
- for imperial units, $V = 95.5 \times D^{0.6935} \times J^{0.5645}$, $Q = 34.6 \times D^{2.6935} \times J^{0.5645}$.

Changes in elevation provide for losses or gains in line pressure and have to be taken into account in hydraulic calculations. For liquids, the pressure loss (or gain) for a given elevation change may be calculated as follows:

$$H_E = h_1 - h_2 , \qquad \text{(HD-14)}$$

Where H_E – elevation head loss, m,
h_1 – pipeline elevation at point 1, m,
h_2 – pipeline elevation at point 2, m.

The elevation points may be taken at the ends of the pipeline in case of uniform elevation change, or at the ends of each section of the pipeline that is a subject to uniform elevation change in case of several elevation changes (overall elevation head loss is then calculated by summing the sectional head losses).

If a pipeline has a high point significantly elevated regarding both ends, accumulation of air or vacuum at the high point will affect the flow in the line (or lead to vacuum collapse of the pipe). Where such events are possible, appropriate vents should be incorporated in the pipeline design to prevent their occurrence.

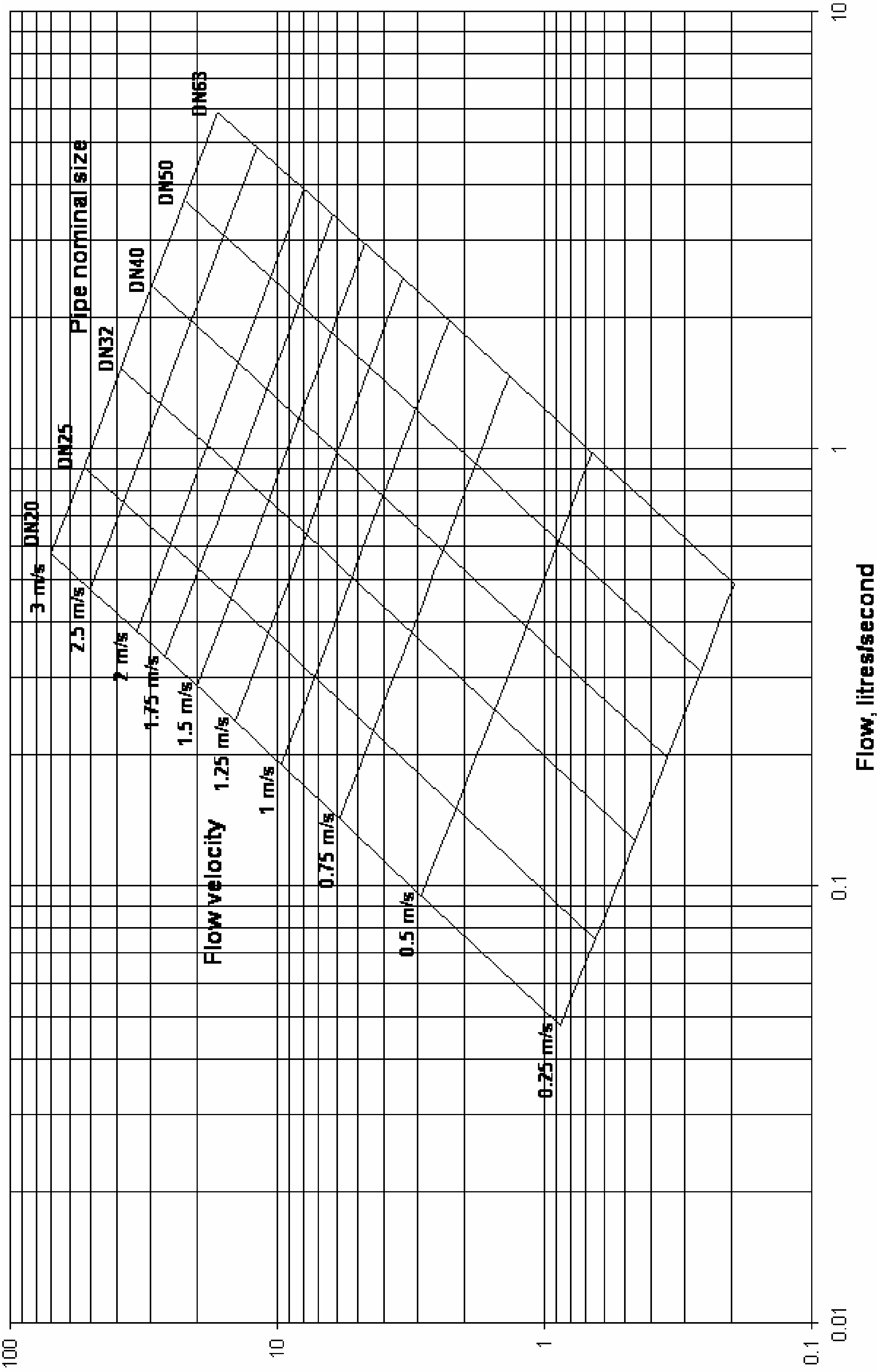


Fig. 1. Colebrook-White friction loss chart for DN20 – DN63 SDR 11 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

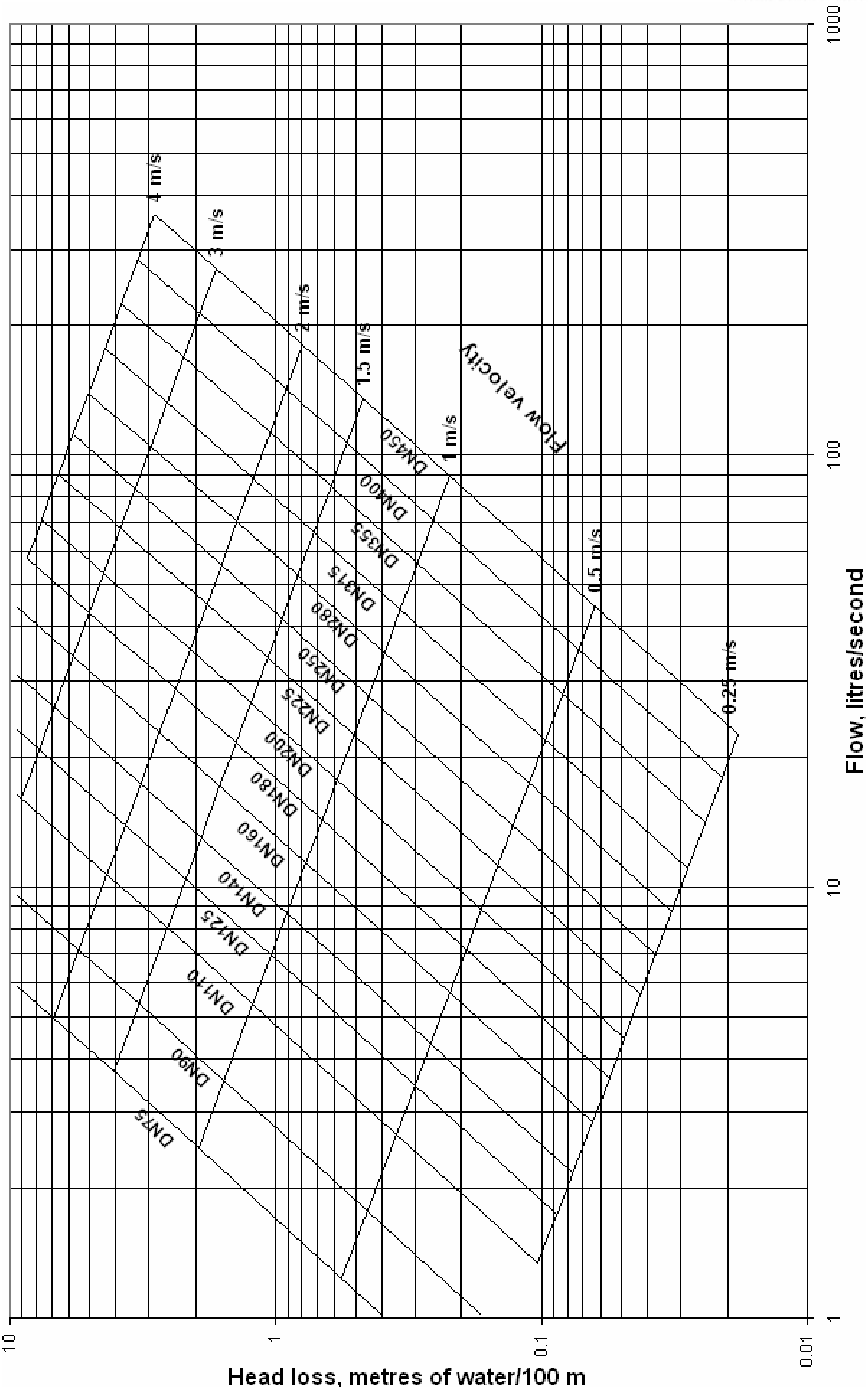


Fig. 2. Colebrook-White friction loss chart for DN75 – DN450 SDR 9 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

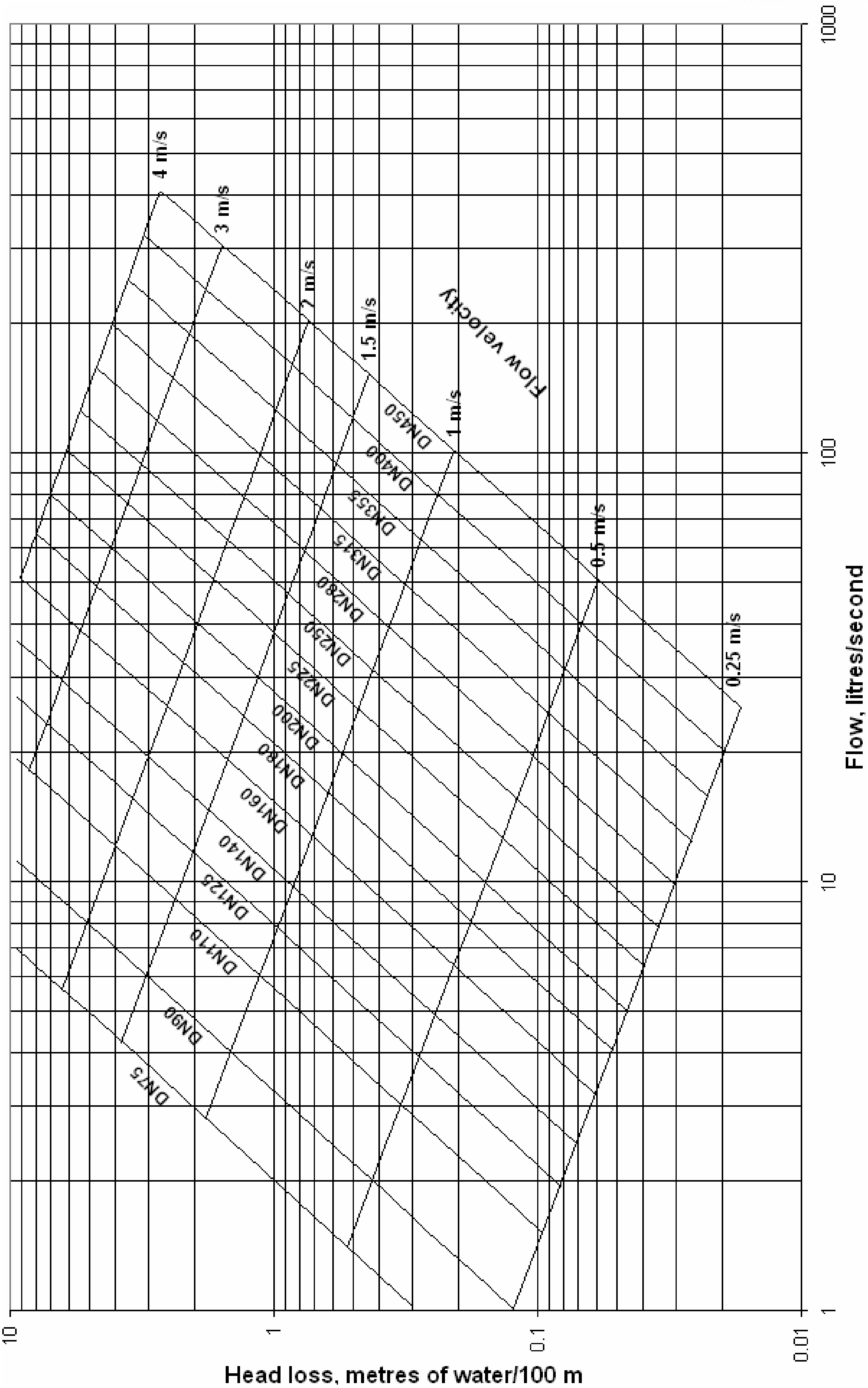


Fig. 3. Colebrook-White friction loss chart for DN75 – DN450 SDR 11 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

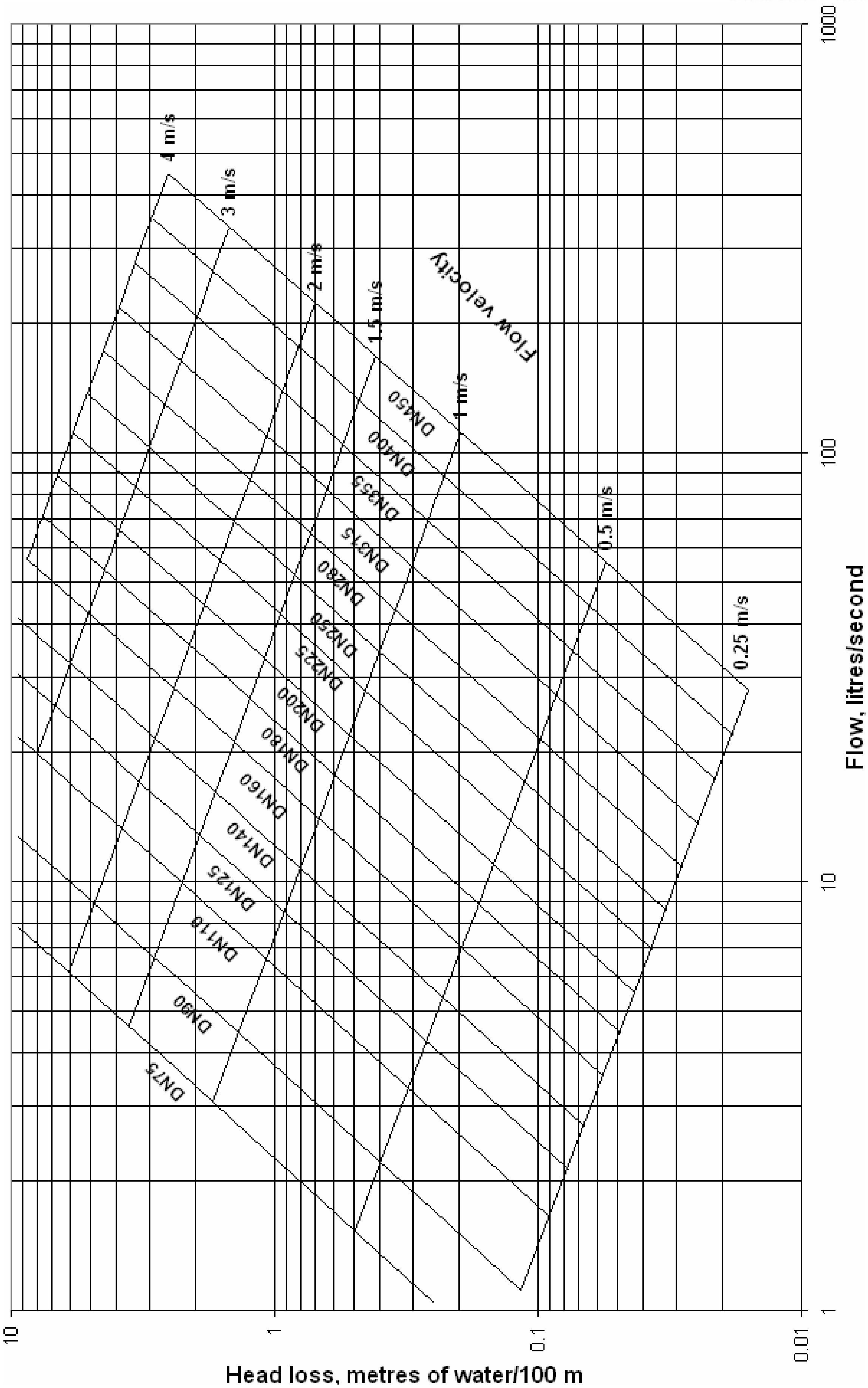


Fig. 4. Colebrook-White friction loss chart for DN75 – DN450 SDR 13.6 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

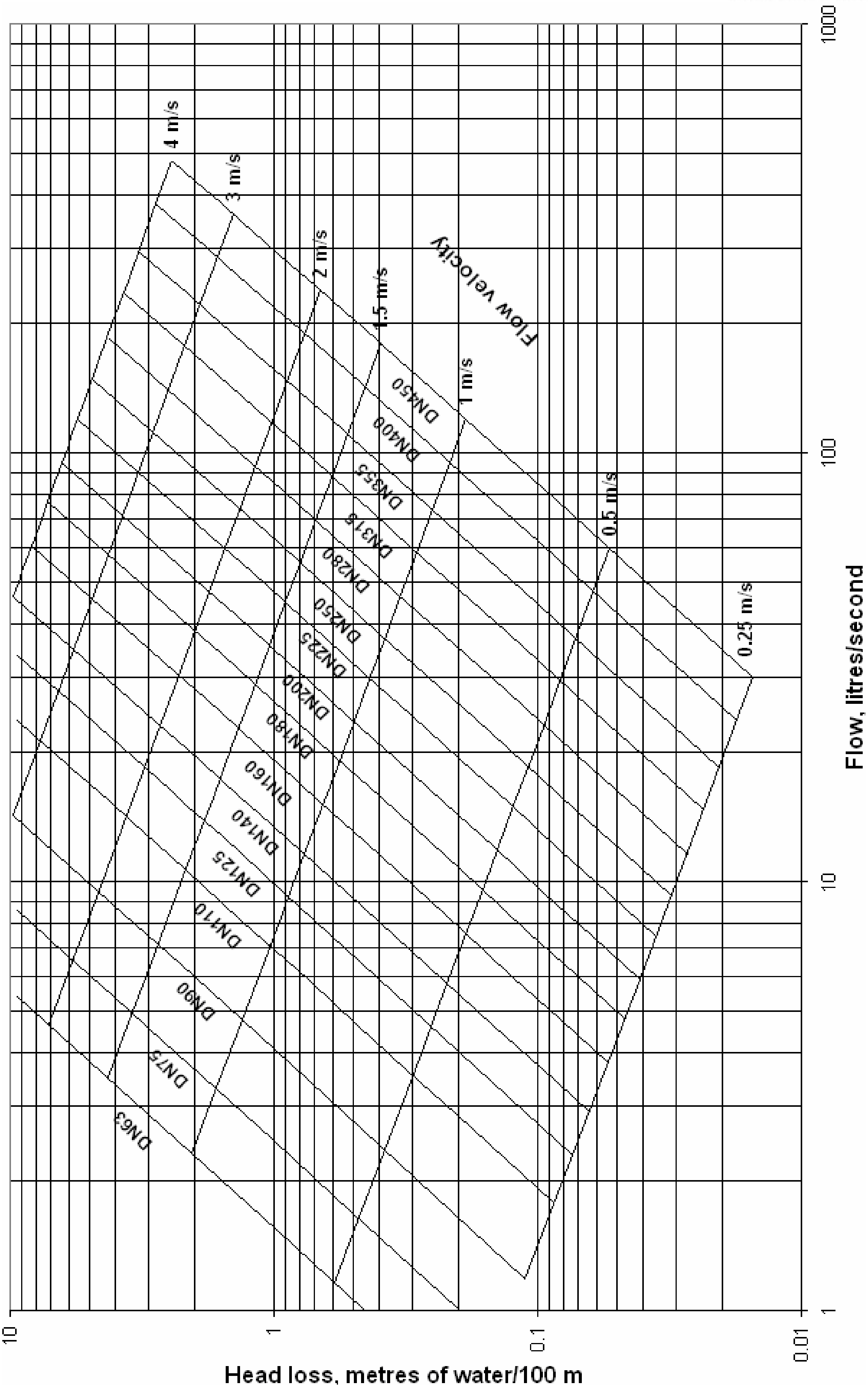


Fig. 5. Colebrook-White friction loss chart for DN63 – DN450 SDR 17 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

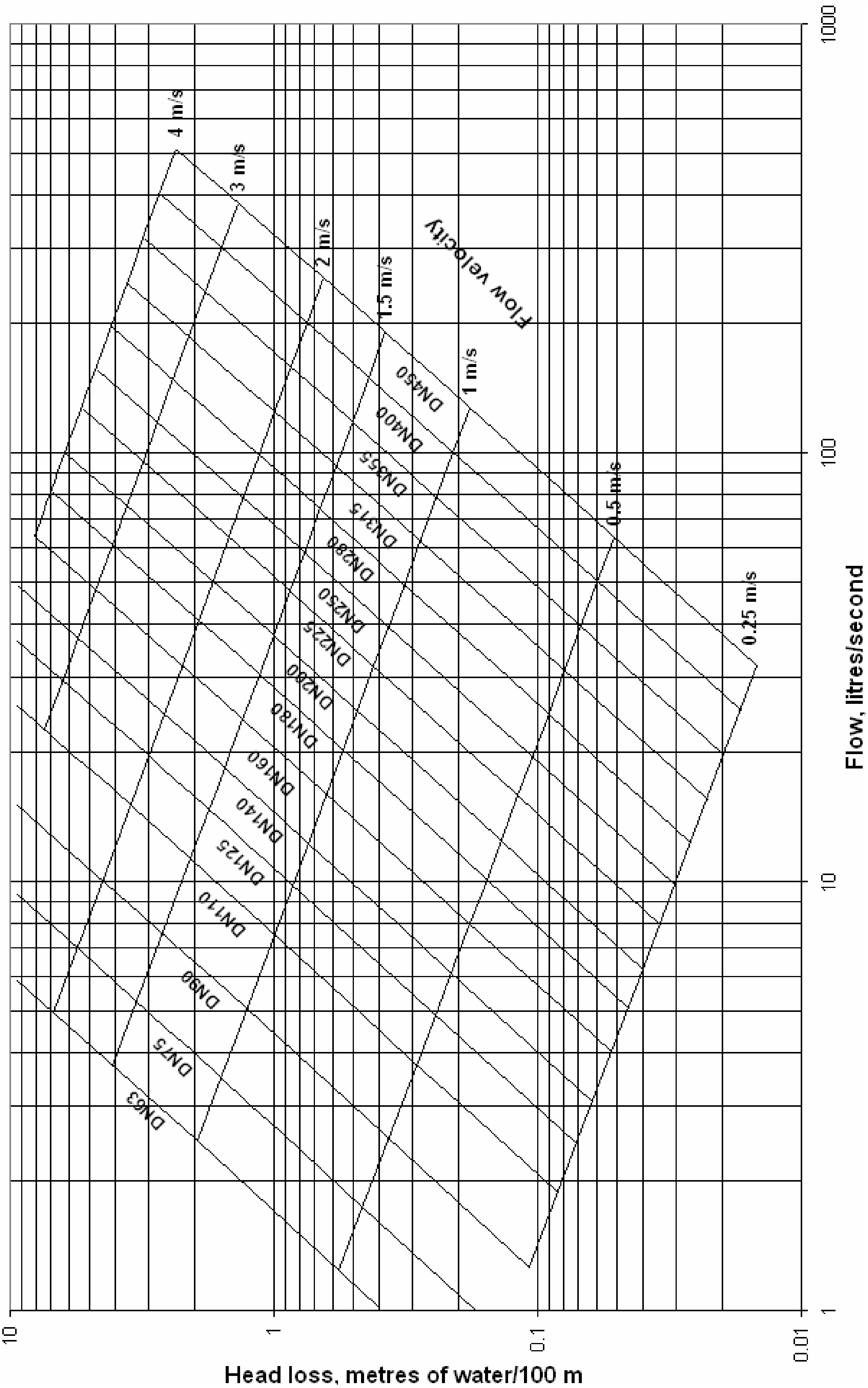


Fig. 6. Colebrook-White friction loss chart for DN63 – DN450 SDR 21 polyethylene pipes, running full of water at 15°C (*k* = 0.01 mm)

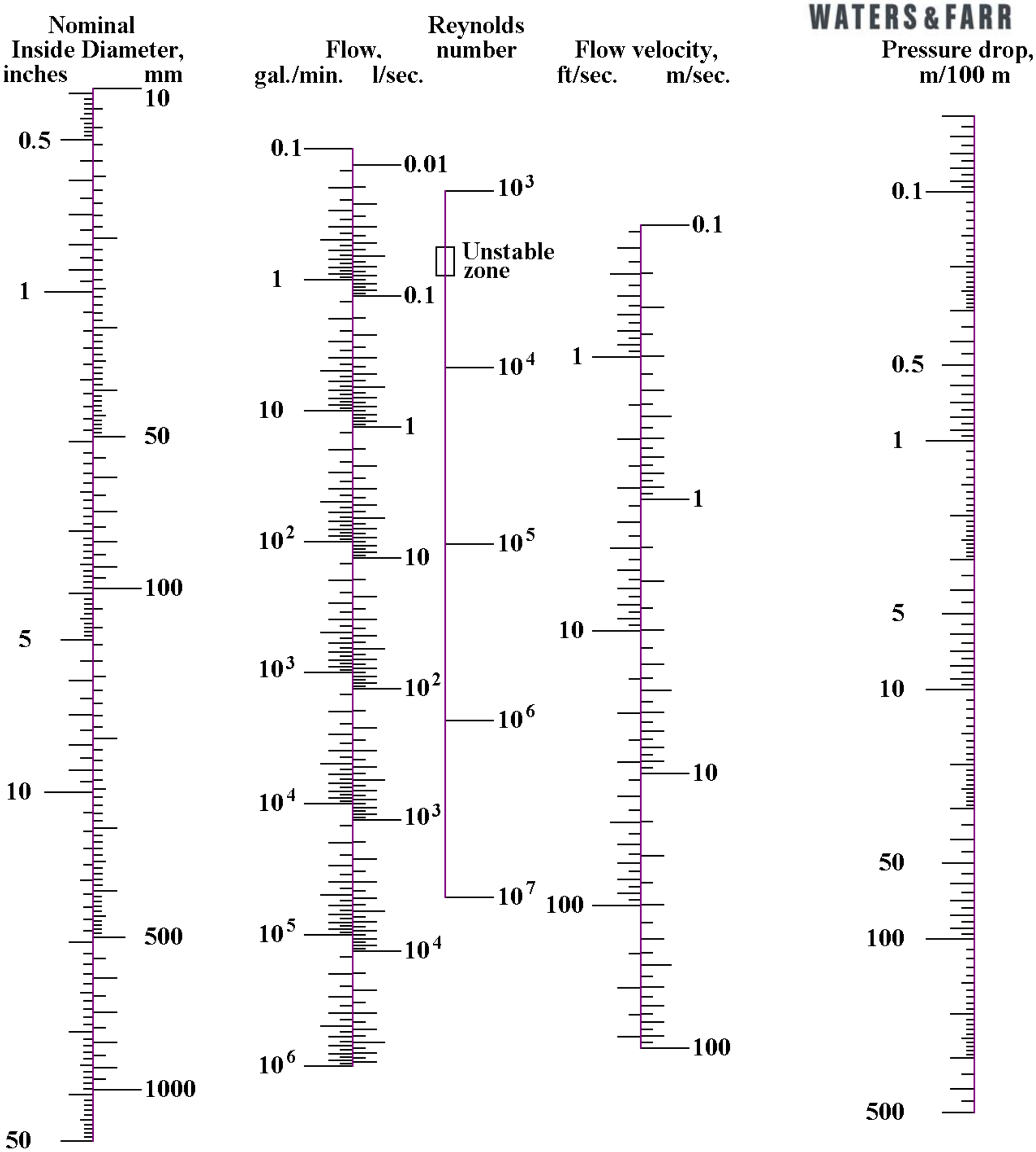


Fig. 7. Nomogram for flow characteristics of water in smooth pipelines

Courtesy of Innovene

To use the nomogram:

- mark the given flow on the flow scale of the nomogram;
- mark inside diameter on the pipe inside diameter scale of the nomogram, or head pressure on the pressure drop scale of the nomogram, whichever is given;
- draw a straight line connecting these to marks and extend it to other scales of the nomogram;
- the pipe inside diameter, or the pressure drop, and/or the flow velocity and Reynolds number can be determined from the intersection of the straight line drawn with the corresponding scale of the nomogram.

Valves and fittings are causing additional friction losses to the flow of fluids in a pipeline. The Darcy-Weisbach equation modified for head losses in fittings becomes:

$$H = K\frac{V^2}{2g} \qquad \text{(HD-15)}$$

Fitting type	***K***
Elbow 90°	1.0
Elbow 45°	0.4
Elbow 22.5°	0.2
Bend 90°	0.2
Bend 45°	0.1
Bend 22.5°	0.05
Tee 90° - flow in line	0.35
Tee 90° - flow into branch	1.20
Gate valve: open ¼ closed ½ closed ¾ closed	0.12 1.0 6.0 24.0
Butterfly valve: open	0.3

Where *H* – head loss, m,
K – friction coefficient, dimensionless, dependent on type of fitting: commonly used values for ***K*** are given in the table to the left (source: Polyethylene Pipe Systems, WRC, UK),
V – average flow velocity, m/s,
g – gravitational acceleration, m/s².

Comparing the formula (HD-15) with the formula (HD-2) for straight length of pipe, the frictional resistance of valves, fittings, obstructions, etc., may be expressed in terms of equivalent length of straight pipe:

$$L = K\frac{D}{f} \qquad \text{(HD-16)}$$

Where *L* – pipe length, m,
D – mean internal diameter of pipe, m,
f – friction factor, dimensionless.

An example of the corresponding chart is given on Fig. 8.

The effect of the frictional resistance created by the **internal beads** in butt welded joints may be neglected in normal circumstances, but may also be taken into consideration for smaller pipe sizes or where the joints are frequent.

Pipes filled with liquid may be subjected to a **pressure wave** caused by a sudden significant change in flow velocity. Such events, known as **water hammer**, are usually caused by starting and stopping of pumps, opening and closing of valves, failures of pipeline components, etc. This results in a short-term pressure surge above usual working pressure.

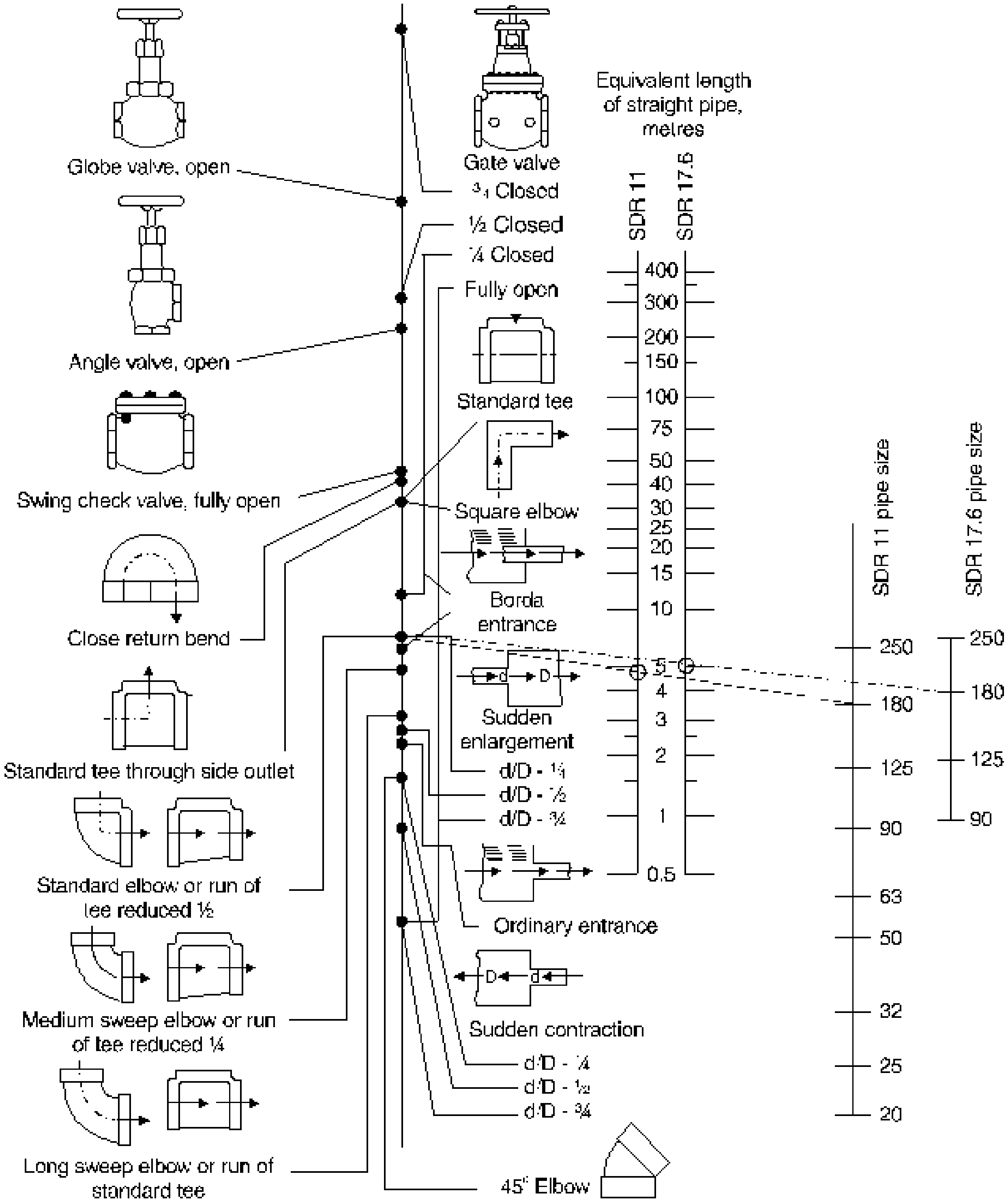
Due to its viscoelastic properties, Waters & Farr polyethylene pipes provide excellent surge tolerance compared to pipes of different materials. For the same liquid and velocity change, surge pressures in polyethylene pipe are about 80% less than in ductile iron pipe and about 50% less than in PVC pipe.

The pressure change, **Δ*P***, and the wave velocity, ***C***, are approximately correlated by the following:

$$\Delta P = \frac{\rho}{g} \times C \times \Delta V \qquad \text{(HD-17)}$$

Where ΔP – pressure change, N/m² (1 N/m² = 1 × 10^{-6} MPa),
ρ – fluid density, kg/m³; for water, □ = 1000 kg/m³ may be assumed,
g – gravitational acceleration; *g* = 9.807 m/s² may be assumed,
C – wave velocity (usually referred to as celerity), m/s,
ΔV – fluid flow velocity change, m/s.

RESISTANCE OF VALVES AND FITTINGS TO FLOW OF FLUIDS



EXAMPLE: The dashed line shows the resistance of a 180 mm standard elbow in equivalent lengths of 180 mm SDR 11 pipe (≙ 4.7 metres of pipe).

The chain dotted line shows the resistance of a 180 mm standard elbow in equivalent lengths of 180 mm SDR 17.6 pipe (≙5.0 metres of pipe).

NOTE: For sudden enlargements or sudden contractions use the smaller diameter, d on the pipe-size scale. Head loss through check valves varies with types manufactured. Consult with manufacturer for correct values.

Source: Polyethylene Pipe Systems, WRC, UK (online)

Fig. 8.

Celerity may be calculated by the following formula:

$$C = \left[\frac{\rho}{g} \times \left(\frac{1}{E_w} + \frac{\text{SDR}}{E_b} \right) \right]^{-1/2} \times 10^3 \qquad \text{(HD-18)}$$

Where SDR – Standard Dimension Ratio, dimensionless,

E_w – fluid bulk modulus, MPa; for water, E_w = 2150 MPa may be assumed,

E_b – pipe material modulus of elasticity, short-term, MPa;
at 20°C: for PE 80B, E_b = 700 MPa; for PE 100, E_b = 950 MPa.

The pressure change is superimposed on the pipe system, and may be either positive or negative. Conservative estimates show that in general, PE 80B and PE 100 pipes will withstand occasional surge pressures at least equal to their nominal pressure rating (in addition to the nominal working pressure), or at least equal to half of the nominal pressure rating in case of recurrent surges (like frequent repetitive pump start-stop operations), without de-rating of the nominal pressure rating of the pipe. Very high wave velocity, or very high frequency of surge events (causing fatigue in the pipe material), may cause necessity to de-rate the nominal pressure rating of the pipe.

Polyethylene pipes can resist quite low transient negative pressures that may occur during a surge event, without collapse. Where a full (or near full) vacuum generation is possible, buckling resistance of the pipe may be estimated (and consequently, use of pipes of lower SDR may be advisable). Refer to buckling calculations given, for instance, in AS/NZS 2566.1. External dynamic (cyclic) loading imposed on pipe buried under a road is usually not taken into consideration, but may become more significant for very shallow burial or bad quality of the road.

Effect of surges on pipe systems is dependent not only on surge pressure magnitude, pressurisation rate and surge frequency, but also on the system design (including arrangement of restraints and connections, types of fittings used, in-line equipment characteristics, etc.). High resistance of pipes themselves to surge events does not mean that other components of the pipeline are not affected by dynamic loading caused by surges. Surge wave analysis is complex, and if required, should be undertaken by experts with extensive knowledge and experience. In simplified version, the analysis may be carried out using available computer programs.

Water hammer effects may be controlled by reducing the suddenness of a velocity change. Where possible, repetitive operations causing surge waves should be properly controlled, e.g. the flow must not be shut off any faster than it takes the surge wave initiated at the beginning of valve closure to travel the length of the pipeline and return (note, that effective closure time for a valve is usually taken as one half of the actual closing time). This wave travel time may be calculated as follows:

$$t = \frac{2L}{C} \qquad \text{(HD-19)}$$

Where t – time, s,

L – length of the pipeline, m,

C – wave velocity, m/s.

Reduction or even elimination of water hammer effects can be achieved by installation of appropriate equipment, like pressure/vacuum relief valves, speed controls for valve closure and opening, surge arrestors, surge tanks, as well as by careful design of the pipe system, by proper procedure of initial filling of the pipeline, etc.

Calculations described above refer to a situation where the pipes are fully filled. For open channel flow under conditions of constant slope, and uniform channel cross-section (as often is the case where the pipes are only **partially filled**), the **Manning equation** may be used (for water):

$$V = \frac{1}{n} R^{2/3} J^{1/2} \qquad \text{(HD-20)}$$

Where V – average flow velocity, m/s,

n – Manning roughness coefficient, dimensionless; a value of 0.009 may be taken for polyethylene pipe,

R – hydraulic radius, m; R may be calculated as follows:

$$R = \frac{A}{P} \qquad \text{(HD-21)}$$

J – hydraulic gradient (slope), m/m,

A – flow cross-sectional area, m²,

P – wetted perimeter, m.

Manning equation for gravity flow in pipelines running full of clean water may be presented as follows:

$$Q = \frac{4000}{n} \pi \left(\frac{D}{4}\right)^{8/3} J^{1/2} \qquad \text{(HD-22)}$$

Where Q – flow, l/s,

D – mean internal diameter of pipe, m.

Design charts for hydraulic design of pipes using Manning formula (and examples) are given in AS 2200 and other literature.

Flow of water in partially filled pipes may also be calculated using Colebrook-White formula (HD-6), where mean internal diameter, ***D***, is replaced by a value (**4*R***), where R – hydraulic radius:

$$V = -2 \times \sqrt{2g \times 4R \times J} \times \log\left\{\frac{k}{3.7D} + \frac{2.51\nu}{D \times \sqrt{2g \times 4R \times J}}\right\} \qquad \text{(HD-23)}$$

For partially filled pipes (Fig. 9), the diagram on Fig. 10 showing the relationship between partial and full average velocity V/V_f (based on Manning equation), flow Q/Q_f, hydraulic radius R/R_f and utilised area A/A_f at various filling levels, may be used.

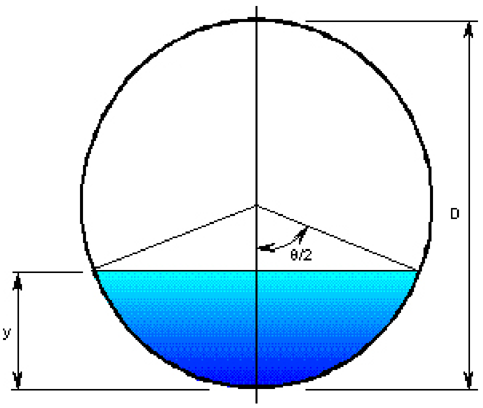


Fig. 9. Partially filled pipe

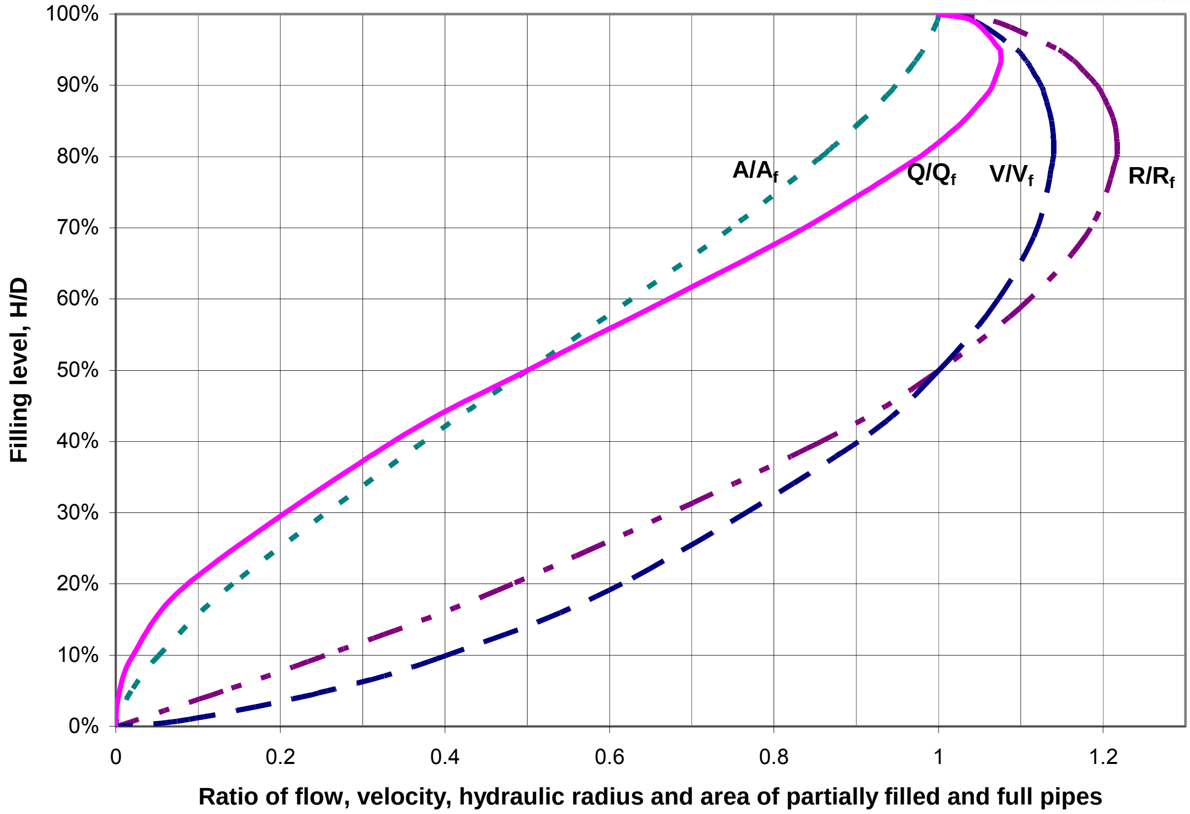


Fig. 10. Proportional flow in partially filled pipes.