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Pipeline Vibrations
Fluid transients in non-rigid, unbranched planar piping systems

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PIPELINE VIBRATIONS
FLUID TRANSIENTS IN NON-RIGID, UNBRANCHED PLANAR PIPING SYSTEMS

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PIPELINE VIBRATIONS
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1. NOTATION AND UNITS

Any consistent system of units may be used in the equations of this Item.

		SI	*British*
A	cross-sectional flow area of pipe	m^2	ft^2
a	speed of propagation of pressure waves in liquid (wave speed)	m/s	ft/s
C_d	instantaneous non-dimensional discharge coefficient of valve	–	–
$C_d A_v$	product of discharge coefficient and cross-sectional flow area of valve (*i.e.* effective flow area)	m^2	ft^2
$(C_d A_v)_0$	product of discharge coefficient and cross-sectional flow area of valve (*i.e.* effective flow area) at steady-state conditions	m^2	ft^2
$(C_d A_v)_p$	product of discharge coefficient and cross-sectional flow area of valve (*i.e.* effective flow area) at point p on valve characteristic (see Section 3.4.3)	m^2	ft^2
D	internal diameter of circular pipe or equivalent internal diameter of non-circular pipe, defined as $D = 4A/P_E$	m	ft
E	Young's modulus of elasticity of pipe wall material	N/m^2	$^*lbf/ft^2$
E_{ref}	reference value of Young's modulus of elasticity (see Section 3.3.2)	N/m^2	$^*lbf/ft^2$
f	Fanning friction factor for straight length of pipe [see Equation (3.1)]	–	–
f_w	contribution to friction factor, f, of pipe wall roughness [see Equation (3.2)]	–	–
H_P	available head at pump	m	ft
H_R	pump rated head	m	ft
I_P	inertia of rotating components of pump	$kg\ m^2$	$^\dagger slug\ ft^2$
K	bulk modulus of liquid (see Section 3.3.2)	N/m^2	$^*lbf/ft^2$
Σk_l	sum of local non-dimensional loss factors in a length of pipe (see Section 3.3.1)	–	–
L	pipe length	m	ft
N_P	instantaneous value of pump rotational speed	rev/min	rev/min
N_R	pump rated rotational speed	rev/min	rev/min
N_{SS}	steady-state value of pump rotational speed	rev/min	rev/min
P_E	internal perimeter of pipe	m	ft

For footnotes see end of Notation section.

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P_P	instantaneous pump shaft power	W	‡ft lbf/s
P_R	rated pump shaft power	W	‡ft lbf/s
Δp_d	pressure drop across open or partially-open valve	N/m^2	*lbf/ft^2
Δp_f	pressure drop along straight length of pipe due to pipe wall friction and local losses	N/m^2	*lbf/ft^2
Q	volume flow rate	m^3/s	ft^3/s
Q_P	instantaneous volume flow rate of pump	m^3/s	ft^3/s
Q_R	rated volume flow rate of pump	m^3/s	ft^3/s
q	non-dimensional flow rate delivered by pump ($= Q_P / Q_R$)	–	–
Re	Reynolds number, $Re = \rho V_0 D_E / \mu 0$, see Equation (3.3)	–	–
t	time, or pipe wall thickness	s m	s ft
t_c	valve closure time	s	s
t_p	value of time on valve characteristic curve (see Section 3.4)	s	s
V	liquid flow velocity	m/s	ft/s
V_R	maximum permitted reverse flow velocity through one-way valve at pump outlet (see Section 3.4.2)	m/s	ft/s
V_0	steady-state flow velocity in a uniform, straight length of pipe	m/s	ft/s
ε	effective surface roughness of pipe wall (see Section 3.3.1)	m	ft
ζ_j	modal damping ratio for j^{th} mode of vibration, typically in range 0.02 to 0.10 (see Section 3.2)	–	–
η_R	pump rated efficiency (see Section 3.4.2)	–	–
μ	liquid dynamic viscosity (see Section 3.3.1)	kg/m s	†slug/ft s
ρ	density of liquid	kg/m^3	†$slug/ft^3$

* 1 lbf/ft^2 = 1/144 lbf/in^2.

† 1 slug = 32.174 lb (pound mass).

‡ 1 ft lbf/s = 0.001818 hp (horsepower).

Subscript

The following additional subscript is not defined in the above notation.

ref	refers to reference value

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2. INTRODUCTION

2.1 Background

This Item is the second of a group of Data Items concerning the vibration of liquid-filled pipelines. A computer method is provided that will predict the fluctuating values of the liquid pressure and flow and the structural motion along the length of a planar pipeline following a disturbance in the flow. These flow disturbances are, for the purposes of the computer program, caused by changing the operating conditions of either a downstream valve or an upstream pump.

This Item is used in conjunction with the first* of the group of Data Items concerning pipeline vibrations. The first Item provides a means of calculating the undamped natural vibration parameters of non-rigid planar pipelines with elastic or rigid supports and attached components. The pipeline can be either empty or running full. These natural vibration parameters are required as input data to the computer program provided in this Item.

The third Item† in this group allows similar estimates to be made of the transient pressure and flow and structural motion in more complex systems that are not necessarily planar. A method of analysis is used that does not require the separate calculation of the natural vibration parameters.

2.1.1 Pipeline vibrations

Pipeline vibrations can occur following changes in the flow rate, due to valve closure or pump trip for example, or when the pipeline is subjected to some form of dynamic external loading, such as that due to earthquake excitation. The transient pressure changes, or fluid transients, which propagate through a contained fluid following a disturbance in the flow lead to pressure differences across lengths of pipework and across bends and other components. These pressure differences exert fluctuating forces on the pipework that can cause significant structural motion and in turn affect the pressure and flow in the fluid. The effects of fluid/structure interaction in a simple piping system are illustrated in Sketch 2.1.

* ESDU 88022 “Pipeline vibrations. Undamped natural vibrations of pipelines” (Reference 27).

† ESDU 93031 “Pipeline vibrations. Computer program for the prediction of fluid transients in flexible, unbranched three- dimensional piping systems” (Reference 30)

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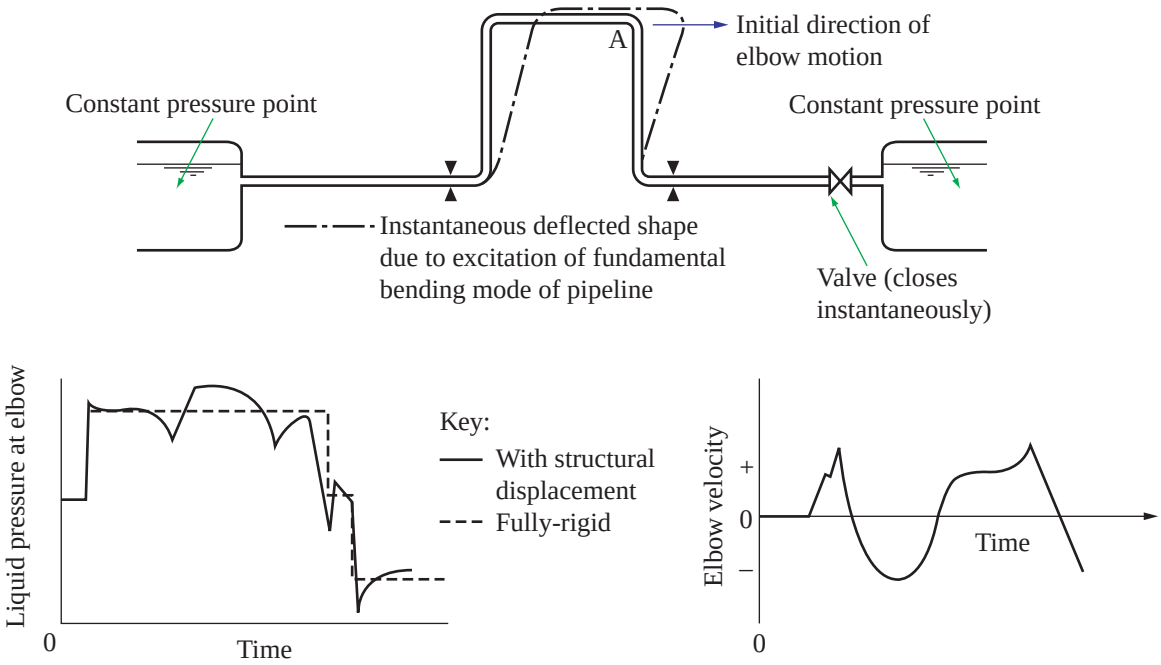

Sketch 2.1 Fluid/structure interaction in a simple piping system

In this sketch, following rapid closure of the downstream valve the fluctuating pressure in the liquid and the structural velocity at point A in the pipe loop are shown for two cases, where

(i) the pipework is rigid, and

(ii) structural motion is allowed in the plane of the pipework.

In most cases, as for this particular example, the peak pressure is greater for the case where structural displacement is allowed.

In more simplified procedures for the calculation of the transient pressure and structural motion in liquid-filled piping systems, it is common to neglect the mutual coupling between the fluid and structural motion. In such uncoupled analyses, time-dependent piping forces are first estimated, based on records of fluctuating pressure calculated throughout the piping system assuming that there is no structural motion. These data are then used as the input to a structural model of the piping system in which the rigidity restraints are removed. This approach often leads to misleading estimates of pressure and stress in liquid-filled flexible piping systems. For example, very small deflections at a pipe elbow that is assumed to be rigid may lead to instantaneous values of structural velocity at the elbow that are of the same order of magnitude as the flow velocity. The transient pressure changes caused by elbow motion, over and above those generated by the flow disturbance, may lead to peak pressures that are significantly greater than those expected for a rigid system. Further guidance on coupled fluid/structure interaction in liquid-filled pipelines is given in Derivation 2 and References 9, 10, 19, 21, 22, 25, 26, 28 and 29.

Systems for which the effects of fluid/structure interaction should be investigated include high pressure lines in processing plant (commonly suspended from the roof of the plant) or systems that have a degree of flexibility to allow for thermal expansion over the likely range of operating temperatures. Other applications include nuclear, petrochemical and power plants, and aircraft and rocket fuel systems. Data

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are not applicable to continuously supported and damped piping systems such as buried water supply lines or large oil pipelines. In systems filled with compressible fluids such as low-density steam, the fluid/structure interaction coupling is usually very weak, and uncoupled analyses may be suitable.

Piping vibration due to external excitation and resonant vibrations in pulsating flow are not considered in this Item.

2.1.2 Coupled fluid/structure response calculations

In order to obtain reliable estimates of the liquid and structural parameters in non-rigid piping systems following a flow disturbance, it is necessary to use a model in which the liquid and structural parameters are coupled.

The data provided in this Item allow estimates to be made of the fluctuating pressure and flow and structural displacement, velocity, acceleration and piping forces along liquid-filled, unbranched planar piping systems following valve operation and/or pump trip. The pipeline consists of a number of straight lengths of pipe that are not necessarily of the same specification. Steady-state conditions of pressure, flow velocity, structural displacement and piping forces are calculated prior to the transients analysis. Fluid/structure coupling is assumed to occur at junctions such as pipe bends. Additional pressure changes due to axial stress waves in the pipe walls are neglected. The effects on the liquid pressure of axial strain in the walls of vibrating pipelines are discussed in Section 3.6.1.

In order to use the computer program in this Item, the natural vibration parameters for the modes of vibration of interest must be known. These data are the undamped natural frequencies and the corresponding mode shapes and generalised masses of the system. The computer program introduced in ESDU 88022 can be used to provide these data. Alternatively, field measurements may be used. It is important to note that the natural vibration parameters of a particular system are strongly dependent upon the piping layout and the nature and locations of the supports. It is unlikely that systems with similar fluid performance characteristics have identical dynamic characteristics. The effects on the fluid and structural parameters of changing the location and specification of piping supports is often overlooked, but may be readily investigated using this Item in conjunction with ESDU 88022.

2.1.3 Fluid transient calculations without fluid/structure coupling

A series of Data Items* is available that allows estimates to be made of the transient pressure and flow changes in piping systems in which fluid-structure interaction effects are not included. Transient pressure changes are generated by changes in operating conditions of components such as pumps and valves. The effects on the flow changes of various surge suppression devices can be investigated. Data are provided for unbranched and network systems.

* The following constitute the 'Fluid Transients' group of Data Items, and are part of the Fluid Mechanics, Internal Flow Series (note that these Data Items are referenced fully in Section 4):
ESDU 83046 'Speed of propagation of pressure waves' (Reference 14),
ESDU 84013 'Reduction and control of pressure surges in liquids.' (Reference 15),
ESDU 84038 'Pressure surge following pump trip in rising mains and other similar discharge lines. Suppression using air vessels.' (Reference 17),
ESDU 85009 'Use of air inlet/outlet valves as surge suppression devices' (Reference 18),
ESDU 85044 'Pressure surge following booster pump trip' (Reference 20.),
ESDU 86015 'Estimation of maximum pressures and forces in steam lines' (Reference 23),
ESDU 87027 'Computer program for the prediction of fluid transients in liquid-filled systems' (Derivation 3).

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Time histories of fluctuating pressure and flow throughout piping systems can be calculated using the computer programs of ESDU 84013, 85009, 85044, 86015 and 87027. These data can be used to estimate the time histories of fluctuating forces at pipe bends and other components. These dynamic forces can then be used as input data to a suitable structural dynamics computer program for the estimation of the uncoupled structural response of the piping system.

The option to uncouple the fluid and structural parameters is provided in the computer program of this Item. This facility may be used to estimate the importance (or otherwise) of fluid/structure coupling in a particular system.

2.2 Content of this Item

A computer program is introduced in Appendix A for the estimation of the fluctuating values of pressure, flow velocity, structural displacement, velocity and acceleration and piping forces in unbranched, non-rigid planar piping systems following disturbances in the flow. These flow disturbances are caused by valve operation and/or pump trip. Prior to performing the transient analysis, the program calculates the steady-state conditions of pressure, flow velocity, structural displacement and piping forces throughout the system. The procedure for calculating the steady-state and transient values of the flow and structural parameters is described in detail in Appendix B.

The idealisations described in Section 3.1 are imposed on the model of the piping system. Two data files are required in order to run the program. The first data file, referred to as the Structural Data File, can be created using the computer program introduced in ESDU 88022, and contains both physical data for the piping system and natural vibration data, formatted in the manner demanded by the program of this Item. The second data file, referred to as the Liquid and Components Data File, contains the remaining data necessary for the fluid/structure interaction analysis, formatted as described in Section A.4.

Throughout this Item it is assumed that the pipeline lies entirely in one plane and all structural deformations occur in that plane. The vibration characteristics in a different plane are unlikely to be identical to those in the plane of the pipeline. When performing a natural vibration analysis using ESDU 88022, separate portions of a piping system between rigid boundaries may be considered in isolation to reduce the computational effort. However, the data file generated by the program in such a case will not contain all the piping data required for the computer program of this Item: some alterations to the data file will be necessary prior to the fluid/structure interaction analysis. Further guidance on this matter is given in Section A.4.

3. PIPEWORK MODEL

The way in which planar piping systems are idealised for the purposes of the computer model of both this Item and ESDU 88022 is described in Section 3.1. The method of solution for the model is outlined in Section 3.5 and described fully in Appendix B. Limitations of the analysis are discussed in Section 3.6.

3.1 Scope of Pipework Model

A typical non-rigid piping system of the type considered in this Item is shown in Sketch 3.1. The system is modelled as a series of continuous straight lengths of pipe. Each individual length of pipe exhibits uniformity of section, material properties and pipe roughness over its length. The following idealisations are made for the computer model.

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(i) The steady flow velocity is assumed to be very small compared to the wave speed in the liquid.

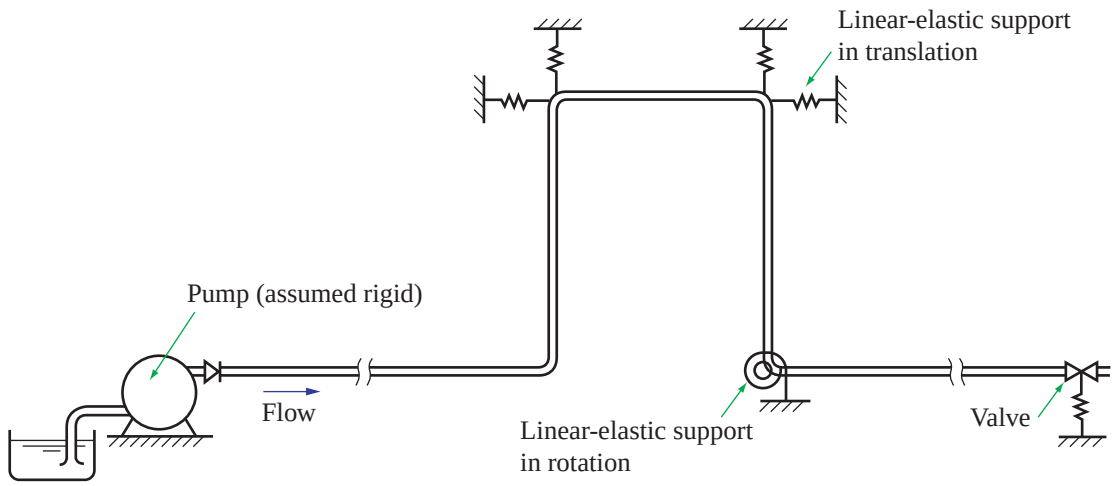
(ii) The pipework is considered to vibrate in the plane of the piping system only.

(iii) Cavitation and column separation do not occur (although the onset of these phenomena is indicated by the program).

(iv) All structural displacements are small, allowing a linear elastic analysis.

(v) The effect of the fluid on the structural mode shapes is to increase the mass of the system, with no effect on the stiffness.

The structural, liquid and component parameters are discussed in Sections 3.2, 3.3 and 3.4 respectively.



Sketch 3.1 Single-line, planar piping system

3.2 Structural Parameters

In order to calculate the natural vibration parameters of a non-rigid piping system, the mass, stiffness and geometrical parameters must first be defined. The pipework is modelled as described in Section 3.1. The effects on the analysis of flexible bends and elbows, elastic or rigid pipe restraints and large components that increase the inertia of the system are accounted for when calculating the natural vibration parameters. Guidance on these effects is given in ESDU 88022. Changes in the location or stiffness of piping supports may be readily accommodated in the computer model of that Item.

The only structural parameter that remains to be defined is the damping for each mode of vibration. For a vibrating system, damping is a measure of the energy dissipation over each cycle of vibration. The mechanisms that cause this dissipation of vibrational energy are given below.

(i) Internal dissipation of energy between the elements and connections of the piping system, leading to structural damping,

(ii) storage of vibrational energy in the pipes, leading to material damping, and

(iii) energy losses in the liquid, leading to fluid damping.

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In the case of elastic materials, material damping is small compared with structural damping. The amount of damping in each mode of vibration is accounted for by the modal damping ratio, ζ_j, expressed as a fraction of critical damping. The same level of damping is assumed throughout the piping system which, given the complex nature of the problem and the absence of damping data for individual components, is an adequate representation. Some damping values for piping systems are given in References 11, 12, 16 and 25. Values of the modal damping ratio are likely to be within the range 2 to 10 per cent of critical (*i.e.* $\zeta_j = 0.02$ to 0.10) for most piping systems, depending predominantly on the nature of the supports. Measured damping values should be treated with caution; poor measurement techniques and failure to account for amplitude-dependency are common. In a fluid/structure interaction analysis, in common with all dynamic analyses, it is prudent to consider a range of values, in order to check that any critical case is treated.

The program provides the option of either specifying a single value of modal damping ratio or individual values for each considered mode of vibration.

3.3 Liquid Parameters

It is envisaged that the computer program of this Item will be used in conjunction with the program of ESDU 88022. Data files generated by that program (or assembled from field measurements or an alternative method of analysis) define fully the structural parameters and geometry of the system for the purposes of the analysis (see Section A.4). Additional data are required to define the properties of the enclosed liquid, the roughness of the pipe walls (leading to the estimation of pipe wall friction factor) and the wave speed in the liquid. These data are discussed below. The types of the components at the upstream and downstream ends of the pipes and their operating conditions are discussed in Section 3.4.

3.3.1 Pipe wall friction representation

Losses in the pipes, due to pipe wall friction and local losses at components and bends, are included in the analysis by specifying either

(i) a friction factor for each length of pipe, or

(ii) the effective pipe wall surface roughness values and the summation of all loss factors for each length of pipe.

These options are discussed below. The program allows single values or pairs of values to be specified as appropriate for all straight lengths of pipe.

The numerical values of friction factors may be estimated using data presented in ESDU 66027 and 79014, based upon the pressure losses due to friction over uniform straight pipe lengths. The friction factor, f, over a uniform straight length of pipe is given by the expression

$$f = \frac{1}{2}\frac{\Delta p_f}{\rho V_0^2}\frac{D}{L}, \tag{3.1}$$

where Δp_f is the steady flow pressure loss over the length of pipe, ρ is the liquid density, L the internal diameter, L the length of the pipe and V_0 the steady-state flow velocity in the pipe. In many practical situations, the sum of the pressure losses at components and bends may be a significant proportion of the

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overall pressure loss in the pipe, and the calculation of the friction factor using Equation (3.1) includes these individual losses. It should be noted that individual components over which there is a large pressure loss at steady-state may have a significant effect on the transient flow conditions.

If friction factors for lengths of pipes in a system are not known, the program can calculate an effective friction factor for each length of pipe. It is assumed that friction losses arise from both the roughness of the pipe wall surface and the pressure losses over individual components in the pipe. The losses due to pipe wall roughness are represented by the pipe wall friction factor, f_w, which is calculated within the program. For turbulent flows, f_w is calculated using the equation (given in Reference 7)

$$\frac{1}{\sqrt{f_w}} = -4\log_{10}\left[\frac{1}{3.7605}\left(\frac{\varepsilon}{D}\right) - \frac{5.0452}{Re}\log_{10}\left\{\frac{1}{2.8257}\left(\frac{\varepsilon}{D}\right)^{1.1098} + \frac{5.8506}{Re^{0.8981}}\right\}\right], \tag{3.2}$$

where ε is the effective roughness of the pipe wall surface and Re is the Reynolds number of the flow, given by the expression

$$Re = \frac{\rho V_0 D}{\mu}, \tag{3.3}$$

where μ is the dynamic viscosity of the liquid. Typical values of ε for a number of common pipe wall surfaces are given in Figure 1. Typical values of dynamic viscosity for a number of common liquids are given in ESDU*78040 and 66024 (for water at 15°C and atmospheric pressure, $\mu = 10^{-3}$ kg/m s or 6.491×10^{-7} lbf s/ft^2). Further guidance on the calculation of f_w and on flow conditions where Equation (3.2) does not apply is given in ESDU 66027 (Derivation 1).

The sum of the pressure losses in a straight length of pipe due to both surface roughness effects and local losses is represented by the equation

$$,\Delta p_f = \frac{2\rho f_w L V_0^2}{D} + \frac{\rho V_0^2 \Sigma k_l}{2} \tag{3.4}$$

where the second term on the right-hand side of the equation is the pressure loss in the pipe due to the sum of the local losses. In this equation, Σk_l is the sum of the pressure loss factors for all components and bends in the pipe. Pressure loss factors for pipe bends, branches and junctions may be estimated using ESDU† 73022, 73033, 77009 and 77029. Pressure loss factors for duct fittings and equipment may be estimated using ESDU† 66030, 72009, 81021 and 81039.

If all local losses are distributed equally along the line, Equations (3.1) and (3.4) may be used to estimate the friction factor, f, for a straight length of pipe, giving

$$f = f_w + \frac{D\Sigma k_l}{4L}. \tag{3.5}$$

* ESDU 78040, 'Viscosity of water and steam' and ESDU 66024, 'Approximate data on the viscosity of some common liquids' are located in the Physical Data, Mechanical Engineering Series.

† These Data Items are located in the Fluid Mechanics, Internal Flow Series.

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3.3.2 Wave speed representation

The speed of propagation of pressure waves or wave speed, a, is dependent upon both the properties of the fluid and the elasticity of the pipe that contains it.

For the computer program, the value of wave speed is required for each pipe in the system. If all pipes are circular and thin-walled (*i.e.* the pipe wall thickness is less than approximately 10 per cent of the internal diameter), the program provides the option of calculating the approximate wave speed in each pipe using the equation

$$a = \left[\rho\left(\frac{1}{K} + \frac{D}{tE}\right)\right]^{-1/2}. \tag{3.6}$$

In this equation, ρ and K are the density and bulk modulus of the liquid respectively, t is the pipe wall thickness and E is the modulus of elasticity of the pipe wall material. For the wave speed calculation, values of t and E are required for each pipe.

The wave speed in water contained in circular pipes may be estimated from Figure 2. These data are given for a ranges of values of t/D, the ratio of the pipe wall thickness to internal diameter, and E/E_{ref} (where E_{ref} = 10 GN/m^2 or 2.09×10^8 lbf/ft^2). Typical values of liquid density and bulk modulus, and the modulus of elasticity of some common pipe materials, are tabulated in ESDU 83046 (Reference 14). For water at 15°C and atmospheric pressure, K = 2.148 GN/m^2 or 4.49×10^7 lbf/ft^2. Further details on wave speed estimation are also given in that Item. The program allows single values of the above parameters to be specified for each pipe in the system.

3.4 Component Parameters

The operating conditions of the components at the upstream and downstream ends of the pipe, referred to as the boundary components, need to be specified. The upstream boundary component may be either a constant pressure point or a pump (either running at constant speed or tripped). Similarly, the downstream boundary component may be either a constant pressure point or a valve (either opening, closing or at constant open or closed position). The prediction of pressure and flow changes following pump trip and valve operation requires careful and accurate simulation of the behaviour of these devices. The following information may be of assistance when modelling the boundary components.

3.4.1 Constant pressure points

It is assumed that the pressure in the tank does not change over the considered flow period. Pressure losses at the inlet to the pipe are usually small and are neglected in this analysis.

3.4.2 Pumps

The pump pressure and flow at a given speed are calculated using the pump characteristic curves. The head, flow and power of a pump at any speed can be estimated from the curves of head versus flow and power versus flow at a reference speed (or rated speed). This reference speed is usually the predicted operating speed of the pump, and corresponding values of head, flow and power at that speed can be obtained from the characteristic curves.

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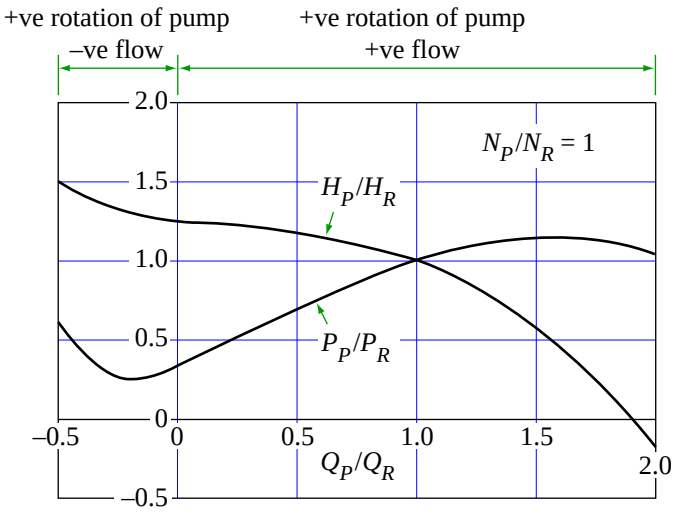
Typical non-dimensional centrifugal pump characteristic curves are shown in Sketch 3.2, from References 5 and 6. The data required by the program to model these curves are as follows.

(i) Non-dimensional values of pump head, H_P/H_R, and power, P_P/P_R, at zero flow, $Q_P/Q_R = 0$.

(i) Non-dimensional values of pump head H_P/H_R, and power, P_P/P_R, at half-rated flow, $Q_P/Q_R = 0.5$.

(ii) Non-dimensional values of pump head, H_P/H_R, power, P_P/P_R, and flow, Q_P/Q_R at a suitable point on the pump characteristic such that $1 < Q_P/Q_R \leq 2$. A value corresponding to $Q_P/Q_R = 1.5$ is recommended for convenience.



Sketch 3.2 Typical centrifugal pump characteristics

The rated conditions of the pump are required in the analysis. These are the pump rated head, H_R, flow rate, Q_R, and rotational speed, N_R. The steady-state operating speed of the pump, N_{SS}, is also required.

The pump inertia, I_P, is required for run-down calculations and is usually available from the manufacturer. However, an estimate of the inertia may be made from data presented in Figure 3. In this figure, values of inertia are presented for a range of values of the ratio of pump shaft input power to pump rotational speed at rated conditions. For this estimation, the pump rated efficiency, η_R, is required, and is in the range 0 to 1 (usually between 0.65 and 0.9). Figure 3 shows a mean line and a band containing the measured data. A smaller value of I_P usually leads to higher values of transient pressure changes. Figure 3 was derived using data for British and U.S. pumps (see ESDU 87027).

It is assumed that the pump is protected by a one-way valve, commonly referred to as a check valve or non-return valve, which is fitted at the pump outlet. In practice, some reverse flow normally occurs and the subsequent pressure rise due to valve slam can increase greatly the peak pressures and values of structural response parameters. The program allows the effects of backflow through the pump to be investigated by specifying a percentage of the steady-state flow velocity (or flow rate) through the pump that is allowed to flow back through the pump. An upper limit of 30 per cent of the steady-state forward flow velocity is recommended to ensure the estimates of flow changes due to backflow are realistic. A means of estimating the magnitude of the reverse flow velocity, V_R, in the absence of structural motion is given in ESDU 87027. It is prudent to try different values of allowable reverse flow velocity to gauge the effects of backflow.

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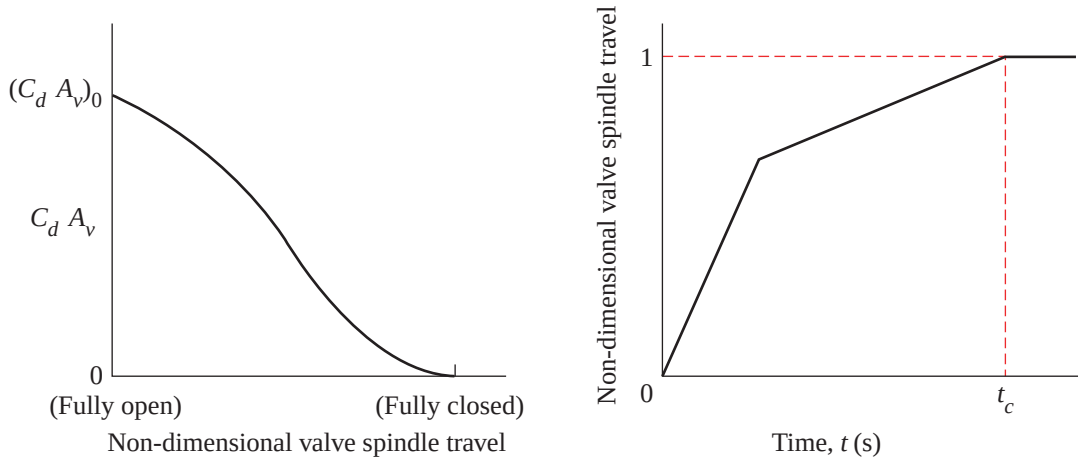
3.4.3 Valves

The magnitudes of pressure changes resulting from the closure of valves are dependent upon the type of valve and the time of closure in relation to the pipeline period, $2L/a$, where L refers to the total length of the pipeline. For example, the way in which a valve shuts off may lead to a gentle decrease in the flow velocity and a small increase in pressure as the valve starts to close, followed by a rapid decrease in velocity and increase in pressure as the valve nears total closure. In such a situation, the maximum pressure change is likely to be greater than that obtained for a linear rate of decrease of flow velocity (assuming total closure in the same period). The valve closure may be described by the variation of values of a dimensional parameter, $C_d A_v$, with time, which are instantaneous values of the effective flow area of the valve.

The flow velocity on the upstream side of the valve, V, can be attained from the pressure drop across the valve, Δp_d, through the equation

$$V = \frac{C_d A_v}{A}\sqrt{\frac{2}{\rho}\Delta p_d}. \tag{3.7}$$

It may be necessary in some cases to construct the valve characteristic curve, particularly when non-linear valve operation, such as two-stage closure, is specified. The characteristic curve may be constructed by combining the curves of effective valve area versus valve spindle travel and of spindle travel versus non-dimensional time. Example curves of these types are shown in Sketch 3.3. The procedure for estimating the valve characteristic curve is as follows.



Sketch 3.3 Typical valve closure curve

(i) From a plot of the effective flow area versus spindle movement, determine the effective valve area, $(C_d A_v)_0$, at steady-state conditions (corresponding to time $t = 0$).

(ii) Determine the values of the non-dimensional spindle movement at a suitable number of points on the time scale from a plot of the non-dimensional spindle movement versus non-dimensional time.

(iii) For each value of spindle movement determined from (ii), estimate the corresponding value of the effective flow area, $C_d A_v$, from the sketch of effective area versus spindle movement.

(iv) Plot these values of $C_d A_v$ against time.

A valve characteristic curve for valve closure is shown in Sketch 3.4. This curve has been obtained from information given in Sketch 3.3 using the above procedure.

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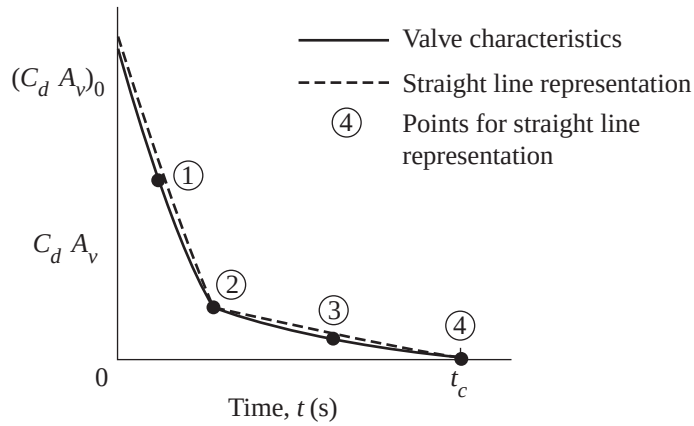

Sketch 3.4 Valve closure characteristics

If the shape of the valve characteristic is to be modelled accurately in the computer analysis, values of $C_d A_v$ are input as a series of points at different values of time after time zero (the time at which the transient analysis begins). The value of $C_d A_v$ at any time t on the valve characteristic is calculated, within the program, by linear interpolation between the given values of $C_d A_v$. It may be seen that the closure characteristic on Sketch 3.4 may be described with reasonable accuracy for a fluid/structure interaction analysis by four values of $C_d A_v$ [denoted by $(C_d A_v)_p$ at time t_p].

3.5 Method of Solution

The computer program calculates instantaneous values of pressure, flow velocity, structural displacement, velocity and acceleration, and piping forces. The program uses an iterative method to calculate, for each time step, the flow and structural parameters. The flow parameters and piping forces are first calculated throughout the piping system using the method of characteristics. Values of the structural parameters associated with the calculated forces throughout the piping system are then estimated using the method of modal superposition. Using the principles of conservation of mass and momentum, the flow and structural parameters are coupled at the junctions, and new values calculated within the iterative procedure. A full explanation of the method of analysis is given in Appendix B.

3.6 Limitations of the Method

3.6.1 Additional pressure change due to axial strain in pipe walls (Poisson coupling)

In the piping system model of this Item, structural motion is generated by unbalanced pressure forces across valves and bends. The magnitude of the pressure changes resulting from structural motion, over and above those calculated assuming no structural motion, can be estimated using the computer program of this Item. However, the effects on the liquid pressure of axial stress waves in the walls of the pipeline are neglected in this analysis.

Axial stress waves propagate along the pipe walls following a flow disturbance, initially in the direction away from the source of that disturbance. The speed of propagation of axial stress waves in the pipe wall is greater than that of the pressure waves in the contained liquid. For metallic pipes containing water, the ratio of these two wave speeds is typically of the order of 2.5 to 3.5. For simple steel pipes containing water, the additional pressure change generated by the axial strain can be of the order of 15 per cent of the value calculated assuming no structural motion.

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The importance of axial strain effects is greater for piping systems in which the dynamic response is dominated by axial modes of vibration. This is often the case in piping systems without bends (or containing only very shallow bends). These effects, and the effects of torsional waves, are included in the third Item of this group of Data Items (see Section 2.1). Further guidance on axial strain effects is given in References 8, 19, 21, 26, 28 and 29.

3.6.2 Small deformations

It is assumed that all deformations of piping and supports are small and remain linear throughout the system. Changes in damping and wave speed can occur as a result of large deformations, and are not accounted for in the analysis.

3.6.3 Homogeneous liquids

Contained liquids are assumed to be, and remain, homogeneous, with no changes in wave speed as the pressure fluctuates in the system.

3.6.4 Gas release and cavitation

The onset of gas release and cavitation is predicted by the program, although the subsequent effects on the pressure, flow and structural motion of these phenomena are not modelled. If the pressure in the system falls below a specified gas release pressure (required as input to the computer program), a warning is printed by the program that the remainder of the calculated values may not be realistic.

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4. DERIVATION AND REFERENCES

Derivation

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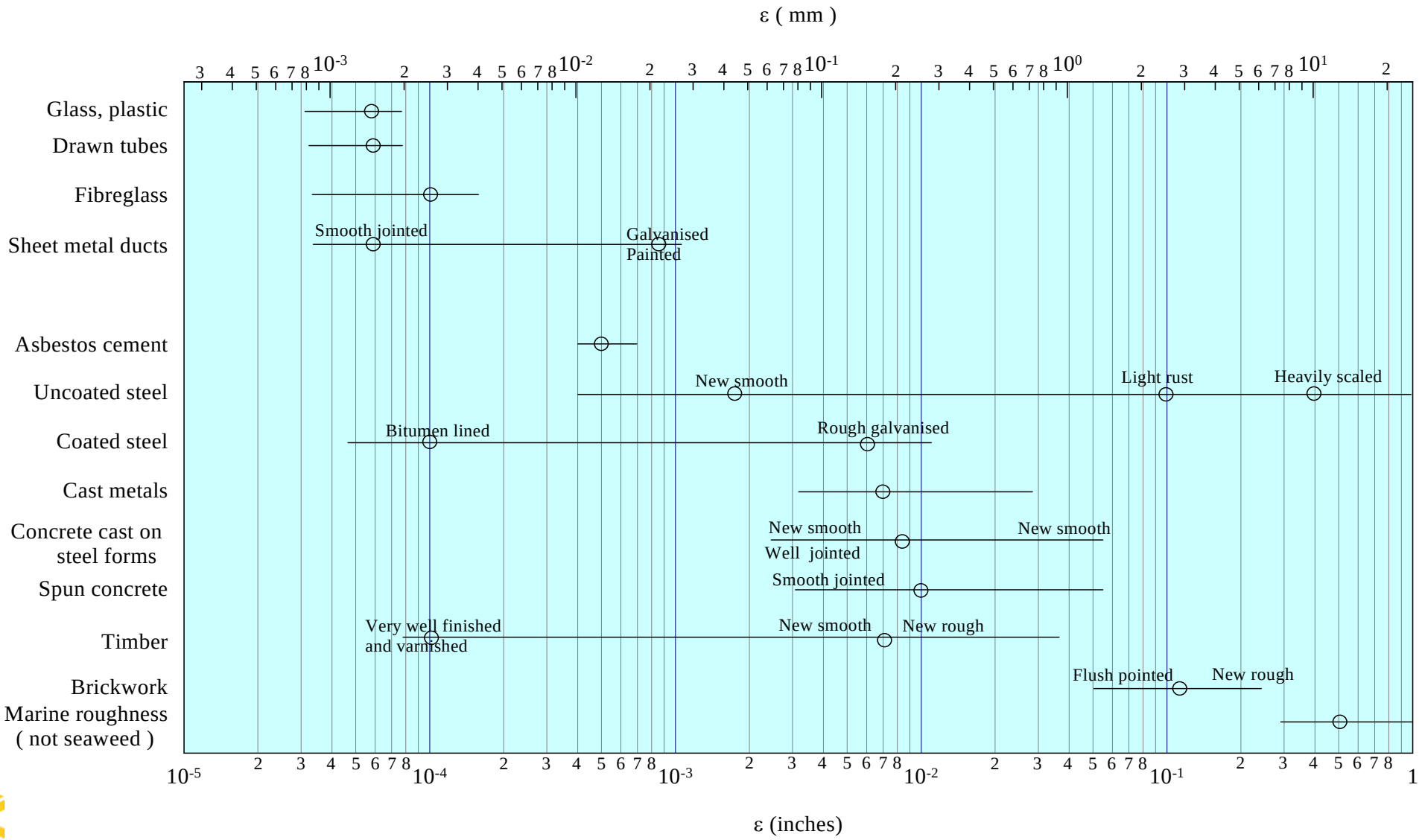

It is emphasised that the variations in surface roughness between specimens of the same basic surface can be large.
A range of roughness values and recommended average values (--o--) are shown above for several common surfaces. These data are presented for guidance and the results of tests on a specimen piece of pipework are to be preferred if they are available.

FIGURE 1 EFFECTIVE ROUGHNESS HEIGHT OF A NUMBER OF COMMON SURFACES

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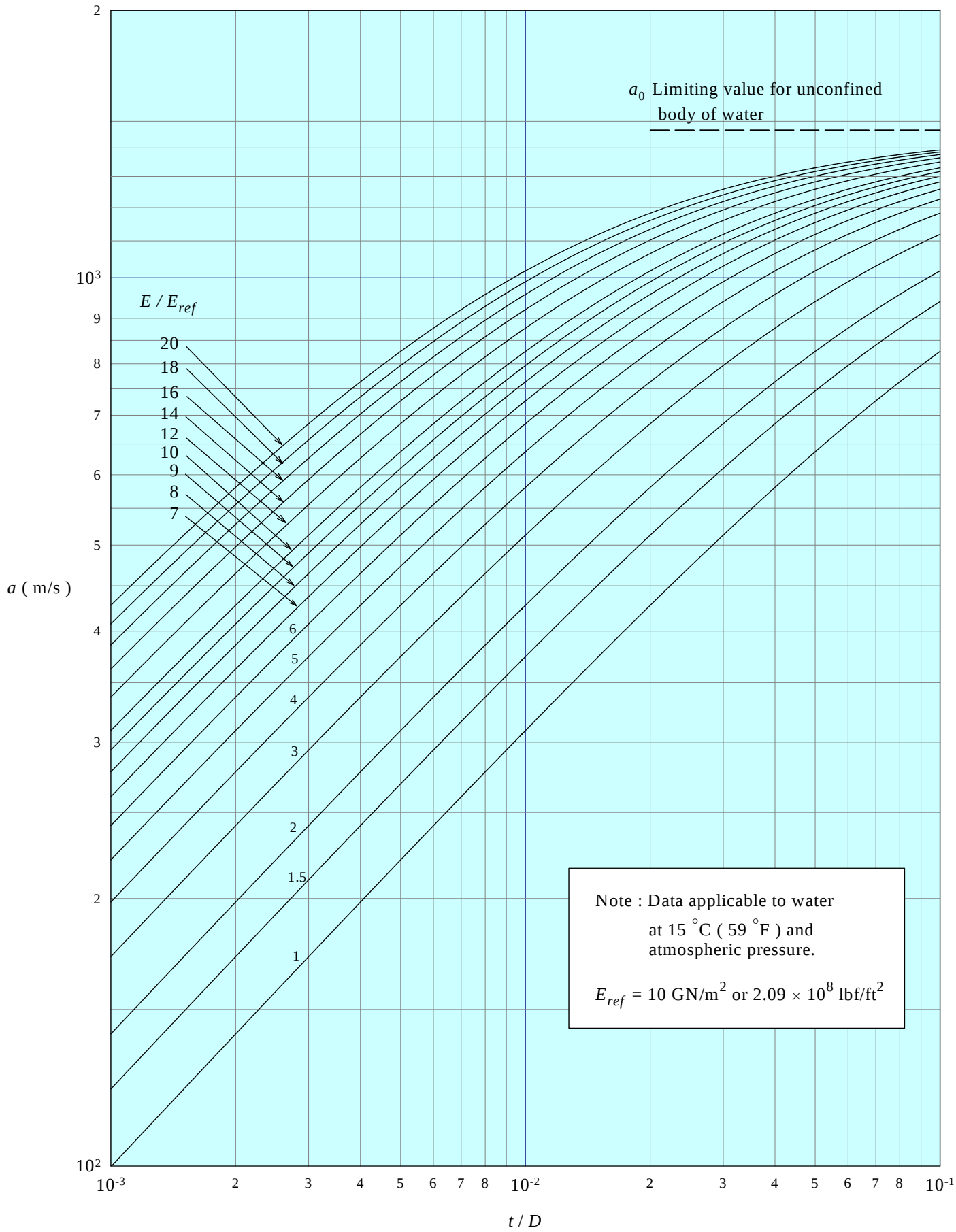

FIGURE 2 WAVE SPEED IN WATER IN CIRCULAR PIPES

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