A note on selection of resistance coefficients for empirical pipe flow formulas. May 1986.

Author:
Fietz, T. R.

Publication details:
Report No. UNSW Water Research Laboratory Report No. 166
0858241552 (ISBN)

Publication Date:
1986

DOI:
https://doi.org/10.4225/53/579806e7cf9dc

5

THE UNIVERSITY OF NEW SOUTH WALES

water research laboratory

Manly Vale N.S.W. Australia

A NOTE ON SELECTION OF RESISTANCE COEFFICIENTS
FOR EMPIRICAL PIPE FLOW FORMULAS

by

T.R. FIETZ

Research Report No. 166
May 1986

https://doi.org/10.4225/53/579806e7cf9dc

BIBLIOGRAPHIC DATA SHEET	1. REPORT No. 166	2. I.S.B.N. 0/85824/155/2

3. TITLE AND SUBTITLE	4. REPORT DATE
A NOTE ON SELECTION OF RESISTANCE COEFFICIENTS FOR EMPIRICAL PIPE FLOW FORMULAS	MAY 1986

5. AUTHOR (S)

T.R. FIETZ

6. SPONSORING ORGANISATION

7. SUPPLEMENTARY NOTES

8. ABSTRACT

Methods of finding resistance coefficients for the Hazen-Williams and Manning formulas are discussed. Coefficients are selected to maximise agreement with the Colebrook-White equation, using pipe data from Australian Standard codes.

9. DISTRIBUTION STATEMENT

This report has been published by The University of New South Wales, Water Research Laboratory.

10. DESCRIPTORS

Colebrook-White Equation ; Hazen-Williams Formula ; Manning Formula

11. IDENTIFIERS

Pipe Flow ; Flow Friction ; Hydraulic Roughness

12. CLASSIFICATION	13. NUMBER OF PAGES	14. PRICE
	33	

A NOTE ON SELECTION OF RESISTANCE COEFFICIENTS FOR EMPIRICAL PIPE FLOW FORMULAS

by

T.R. Fietz

Abstract:

Methods of finding resistance coefficients for the Hazen-Williams and Manning formulas are discussed. Coefficients are selected to maximise agreement with the Colebrook-White equation, using pipe data from Australian Standard codes.

Notation

C^1	Resistance coefficient in an empirical formula
C_1	A parametric value for C_{hw}
C_{hw}	Hazen-Williams resistance coefficient
d	Pipe diameter (bore)
d_{hw}	Pipe diameter from Hazen-Williams formula
d_m	Pipe diameter from Manning formula
$\left(\frac{df}{d\mathbb{R}}\right)_{cw}$	Slope of $\frac{k}{d}$ = constant line on Moody Chart
$\left(\frac{df}{d\mathbb{R}}\right)_{hw}$	Slope of C_{hw} = constant line on Moody Chart
f	Darcy friction factor
f_{cw}	Friction factor from Colebrook-White equation
f_{hw}	Friction factor from rearranged Hazen-Williams formula
f_m	Friction factor from rearranged Manning formula
f_r	Friction factor for wholly rough wall turbulent flow
f_T	Friction factor at tangent point
F	Function of
g	Gravitational acceleration
h_f	Frictional head loss
k	Equivalent sand grain roughness
K_1	A parametric value of $\frac{k}{d}$
ℓ	Pipe length
n	Manning's n

N_1	A parametric value of n
Q	Discharge
Q_{hw}	Discharge from Hazen-Williams formula
Q_m	Discharge from Manning formula
$\mathbb{R}$	Reynolds Number $= \frac{Vd}{\nu}$
$\mathbb{R}_T$	Reynolds Number at tangent point
R_h	Hydraulic radius
S	Energy (friction) gradient $= \frac{h_f}{\ell}$
S_{cw}	Energy gradient from Darcy-Weisbach and Colebrook-White equations
S_{hw}	Energy gradient from Hazen-Williams formula
S_m	Energy gradient from Manning formula
V	Mean velocity $= \frac{4Q}{\pi d^2}$
α	R_h exponent in an empirical formula
β	S exponent in an empirical formula
ϕ	Function of
ν	Kinematic viscosity

INTRODUCTION

The Darcy-Weisbach formula, with friction factor f given by the Colebrook-White equation, is generally recognised as the preferable, universal method for predicting frictional head loss in water supply pipes.

Older empirical formulas, such as Hazen-Williams and Manning, still persist, however, in textbooks, handbooks and standard codes.

Their main advantage compared to the preferred formula is ready manipulation to find head loss, discharge, or diameter for single pipe problems. Also they are easily differentiated, which saves computation in pipe network analysis.

The empirical formulas rely on specifying a resistance coefficient for a particular pipe material; C_{hw} is used in the Hazen-Williams formula and n in the Manning formula.

This report discusses selection of the empirical coefficients C_{hw} and n in order to maximise the agreement between the empirical formulas and the preferred formula. Firstly, areas of agreement are defined and charts are presented to relate C_{hw} and n to diameter d and equivalent sand grain roughness k for single pipes. Secondly, typical values of C_{hw} and n for common pipe materials are derived for a range of pipe diameters and flowrates. The methods for selecting C_{hw} and n are applied to pipe data shown in Australian Standard Codes.

BASIC EQUATIONS

Frictional (or surface resistance) head loss for steady flow under pressure in prismatic circular pipes is given by the Darcy-Weisbach equation:

$$h_f = \frac{f \ell V^2}{d 2g} \tag{1}$$

The friction factor f is a function of the relative roughness $\frac{k}{d}$ and the Reynolds Number $\mathbb{R}$, i.e. $f = \phi(\frac{k}{d}, \mathbb{R})$. The most popular expression for ϕ is given by the Colebrook-White equation (Ref. 8):

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{k}{3.7d} + \frac{2.51}{\mathbb{R}\sqrt{f}}\right) \tag{2}$$

Plotting log f vertically against log $\mathbb{R}$ horizontally for parametric values of $\frac{k}{d}$ gives the Moody Chart (Ref. 13).

At high $\mathbb{R}$ values equation (2) is asymptotic of the "Rough Law":

$$\frac{1}{\sqrt{f}} = 1.74 + 2 \log_{10}\left(\frac{d}{2k}\right) \tag{3}$$

Earlier empirical expressions for frictional head loss are often in the form (Ref. 1):

$$V = C' R_h^{\alpha} S^{\beta} \tag{4}$$

The most popular empirical formulas used in Australia (Ref. 4) are the Hazen-Williams formula:

$$V = 0.849\, C_{hw} R_h^{0.63} S^{0.54} \tag{5}$$

and the Manning formula:

$$V = \frac{1}{n} R_h^{0.67} S^{0.5} \tag{6}$$

Using $Q = \frac{\pi}{4}d^2 V$ and $R_h = \frac{d}{4}$ in equation (5) gives alternative forms of the Hazen-Williams formula:

$$Q = 0.2784\, C_{hw}\, d^{2.63} S^{0.54} \tag{7}$$

$$S = \frac{6.824\, V^{1.852}}{C_{hw}^{1.852}\, d^{1.167}} \tag{8}$$

$$S = \frac{10.676\, Q^{1.852}}{C_{hw}^{1.852}\, d^{4.87}} \tag{9}$$

Similarly, alternative forms of the Manning formula are:

$$Q = \frac{0.3102\, d^{2.67} S^{0.5}}{n} \tag{10}$$

$$S = \frac{6.409\, n^2 V^2}{d^{1.34}} \tag{11}$$

$$S = \frac{10.39\, n^2 Q^2}{d^{5.34}} \tag{12}$$

Lamont (Ref. 12) has made a comprehensive review of the above and many other empirical equations.

OPERATING ZONES ON THE MOODY CHART

k and d ranges for some clean water supply pipes are shown in Table 1. The k and d data in Table 1 have been used with a velocity range of 0.2 to 6 $m.s^{-1}$ to plot operating zones on the Moody chart. These are shown as Figures 1 and 2, and will be used subsequently for assessing the empirical formulas.

METHODS OF COMPARISON OF PIPE FLOW EQUATIONS

In the following comparisons the Darcy-Weisbach equation (1) [in conjunction with the Colebrook-White equation (2)] has been taken as the preferred formula for pipe flow calculations. Results from the Hazen-Williams and Manning equations are compared with those from the preferred formula.

The first problem is to examine single pipes of given d and k to see if there is a velocity, or range of velocities, where the empirical formulas are in agreement with the preferred formula. By considering several pipe diameters a line, or zone, of agreement may be mapped on the Moody chart for the Hazen-Williams and Manning formulas. The errors involved in operating away from these lines, or zones, of agreement may also be shown on the Moody chart.

The second problem is to select a typical (or single) value of either C_{hw} or n for a pipe material so as to maximise the agreement with the preferred formula over the available range of pipe diameters and the normal range of velocities. Most of the typical C_{hw} and n values given in textbooks, handbooks and codes fall in this category.

FINDING EMPIRICAL COEFFICIENTS FOR A SINGLE PIPE

Using the Hazen-Williams Formula

Equation (8), with extended constants and exponents, may be manipulated to obtain $\frac{V^2}{2gd}$ as a variable group:

$$S = \frac{6.824263 \times 2g}{C_{hw}^{1.85185} \, (Vd)^{0.14815} \, d^{0.01852}} \left(\frac{V^2}{2gd}\right) \tag{13}$$

Using $S = \frac{hf}{l}$ in equation (1):

$$S = f\left(\frac{V^2}{2gd}\right) \tag{14}$$

Taking $g = 9.8\ m.s^{-2}$, then equations (13) and (14) are equivalent when:

$$f = \frac{133.7556}{C_{hw}^{1.85185}\ V^{0.14815}\ d^{0.1667}} \qquad (15)$$

A Reynolds Number $\mathbb{R}$ may be introduced when combining equations (13) and (14):

$$f = \frac{133.7556}{C_{hw}^{1.85185}\ d^{0.01852}} \left(\frac{\nu}{Vd}\right)^{0.14815} \left(\frac{1}{\nu^{0.14815}}\right) \qquad (16)$$

Taking $\nu = 1.0038 \times 10^{-6}\ m^2.s^{-1}$ for water at 20 degrees Celsius gives:

$$f = \frac{1035.1}{C_{hw}^{1.85185}\ d^{0.01852}\ \mathbb{R}^{0.14815}} \qquad (17)$$

Equation (17), with slight variations in coefficient and exponents, has been derived previously by numerous authors (Refs. 9, 12, 5, 14, 6, 15).

Equation (17) plots as a family of straight lines of slope −0.14815 on the log f vs. log $\mathbb{R}$ Moody Chart. Note that variation of the water temperature will affect the numerator and shift the location of the plotted lines. Equation (17) is shown plotted on the Moody Chart in Figure 3, for C_{hw} from 80 to 160 and $d = 0.3\,m$. Also plotted near the $C_{hw} = 80$ line are lines for $d = 0.05\,m$ and $d = 2\,m$ which show that the diameter has a slight effect on the location of a C_{hw} = constant line.

Diskin (Ref. 9) has shown that the Hazen-Williams formula and Colebrook-White equation are in agreement at the point where a C_{hw} = constant line is tangential to a $\frac{k}{d}$ = constant line on the Moody Chart. On Figure 4(A) the tangent point is at T where the slope of the $\frac{k}{d}$ = constant line is equal to the slope of the C_{hw} = constant line.

From the Colebrook-White equation (1), for a specified value of $\frac{k}{d}$, the slope is:

$$\left(\frac{df}{d\mathbb{R}}\right)_{cw} = -\left(0.062\ \frac{k}{d}\ \frac{\mathbb{R}^2}{f} + 0.5756\ \frac{\mathbb{R}}{f^{1.5}} + \frac{\mathbb{R}}{2f}\right)^{-1} \qquad (18)$$

For any $\mathbb{R}$ value, f is found from the Colebrook-White equation by Yao's method (Ref. 16).

From equation (16) the slope is:

$$\left(\frac{df}{d\mathbb{R}}\right)_{hw} = \frac{-133.7556 \times 0.14815}{C_{hw}^{1.85185}\, d^{0.01852}\, \nu^{0.14815}\, \mathbb{R}^{1.14815}} \qquad (19)$$

or

$$\left(\frac{df}{d\mathbb{R}}\right)_{hw} = \frac{-f \times 0.14815}{\mathbb{R}} \qquad (20)$$

The tangent point T was found by applying the method of bisection (or interval halving) (Ref. 7) about $\mathbb{R}$ to the equation:

$$F(\mathbb{R}) = \left(\frac{df}{d\mathbb{R}}\right)_{cw} - \left(\frac{df}{d\mathbb{R}}\right)_{hw} = 0 \qquad (21)$$

Note that C_{hw}, the coefficient being sought, is required to find the derivative from equation (19). The solution may be simplified by using the Colebrook-White $f = f_{cw}$ in equation (20), as f_{cw} and the Hazen-Williams $f = f_{hw}$ converge as the tangent point is approached.

The tangent point occurs at ($\mathbb{R}_T$, f_T) and at any other $\mathbb{R}$ value f_{cw} exceeds f_{hw}. The useful range of $\mathbb{R}$ values may be extended by specifying an arbitrary difference in f_{hw} and f_{cw}. In this case f_{hw} is allowed to be within $\pm$ 2.5% of f_{cw}. The $C_{hw} = C_1$ line is then taken through the point ($\mathbb{R}_T$, 1.025 f_T) as shown on Figure 4(A). The value for C_1 is found by putting $f = 1.025\ f_T$ and $\mathbb{R} = \mathbb{R}_T$ in a rearranged equation (16):

$$C_{hw} = \frac{14.067}{f^{0.54}\, d^{0.01}\, \mathbb{R}^{0.08}\, \nu^{0.08}} \qquad (22)$$

The above method has been applied for a range of d and k values to produce Figure 5, which may be used to find a C_{hw} value for a single pipe of known d and k. Pipe velocity V for $\mathbb{R}_T$ at the tangent point is also plotted for the range 0.2 to 6 $m.s^{-1}$.

To show the difference between f_{hw} and f_{cw} when operating away from the tangent point, f_{hw} is found from equation (16) for a given $\mathbb{R}$ value as shown on Figure 4(A). The ratio $\frac{f_{hw}}{f_{cw}}$ is then plotted at the point ($\mathbb{R}$,f_{cw}), and from numerous points the contour lines of Figure 6 have been obtained.

Equation (22) for finding C_{hw} is a rearranged form of equation (16), used for finding f_{hw}. The diameter effect is eliminated so Figure (6) applies to all pipe diameters. Comparison of Figure 6 with Figures 1 and 2 indicates the degree of agreement between the Hazen-Williams formula and the preferred formula for different pipes.

Using the Manning Formula

Following the argument of Barnes et al (Ref. 6), equations (11) and (14) are equivalent when:

$$\frac{6.409\, n^2 V^2}{d^{1.34}} = \frac{f\, V^2}{d\, 2g} \tag{23}$$

Taking g = 9.8 $m.s^{-2}$ gives:

$$f = \frac{125.616\, n^2}{d^{0.34}} \tag{24}$$

Equation (24) plots as a family of horizontal lines on the Moody Chart, so the Manning equation agrees with the preferred formula in the zone of wholly rough wall turbulent flow, where equation (3) applies. Rearranging equation (3):

$$f = 0.25\left[\log_{10}\left(3.707\,\frac{d}{k}\right)\right]^{-2} \tag{25}$$

For equations (24) and (25) to be equivalent:

$$\frac{125.616\, n^2}{d^{0.34}} = 0.25\left[\log_{10}\left(3.707\,\frac{d}{k}\right)\right]^{-2} \tag{26}$$

Giving:

$$n = \frac{d^{0.17}}{22.416}\left[\log_{10}\left(3.707\,\frac{d}{k}\right)\right]^{-1} \tag{27}$$

If f from equation (25) is called f_r then equation (27) becomes:

$$n = \frac{f_r^{\,0.5}\; d^{0.17}}{11.208} \tag{28}$$

For given d and k, and $\frac{k}{d} = K_1$, the value of Manning's n is N_1 for agreement of the Manning and the preferred formula. N_1 is found from equation (27). The corresponding curves are shown plotted on Figure 4(B).

For flow in the transition zone the Manning friction factor $f_m = f_r$ underestimates f_{cw} from the preferred formula. The value of $\frac{f_m}{f_{cw}}$ has been determined for numerous points on the Moody chart, and these points were used to plot the contour lines of Figure 7. Comparison of Figures 1 and 2 with Figure 7 indicates the degree of agreement between the Manning and the preferred formulas for various pipes.

Equation (27) has been applied to a d range from 0.05 to 2 m and for numerous k values to produce Figure 8. Also shown (as broken lines) are velocity contours for $\frac{f_m}{f_{cw}} = 0.99$ indicating the lower limit of velocity for various d and k values. Note that Figure 8 is an alternative to the chart of Barnes et al (Ref. 6, Figure 3.8) which plots n against d (both linear scales) for parametric values of k.

FINDING EMPIRICAL COEFFICIENTS FOR AN OPERATING ZONE

Using the Hazen-Williams Formula

The operating zone is covered by a mesh of points as shown partially in Figure 9. The V range is from 0.2 to 6 $m.s^{-1}$, in increments of 0.25 $m.s^{-1}$, giving 24 values. The d range is given in Table 1 for various pipes and this was divided to give 23 values. The total number of grid points is then 552.

For a given pipe material of known k value, a value is chosen for C_{hw} and water temperature is taken as 20 degrees Celsius. If friction gradient S is the pertinent variable then the following procedure is used to compare the Hazen-Williams and the preferred formulas:

(i) At any mesh point compute $\mathbb{R} = \frac{Vd}{\nu}$ and $\frac{k}{d}$. Use Yao's method (Ref. 16) to find f from equation (2), then S_{cw} from equation (14).

(ii) Calculate S_{hw} from equation (8).

(iii) Find $\frac{S_{hw}}{S_{cw}}$ and increment the count for the appropriate range, e.g. from 0.9 to 0.95.

(iv) Repeat for all mesh points then the number of points in any range divided by the total number of points represents the proportion of the chart area covered by that range, e.g. for the range $\frac{S_{hw}}{S_{cw}}$ = 0.95 to 1.05, a chart area of 45% indicates that over 45% of the operating zone the Hazen-Williams and the preferred formulas agree within ±5% for finding the friction gradient.

An alternative method is to plot contour lines on the operating zone mesh and to measure areas by planimeter. Contour lines for one pipe material are shown on Figure 9.

Various C_{hw} values were tried for each pipe in Table 1 to maximise agreement with the preferred formula. The effect of varying C_{hw} on the ±5% and ±10% agreement ranges for one pipe is shown in Figure 10(A).

The other dependent variables of interest are d and Q. To find d_{hw} for a given mesh point (d,V), and specified C_{hw} value, the procedure is:

(i) Compute $\mathbb{R} = \frac{Vd}{\nu}$ and $\frac{k}{d}$, and find f by Yao's method (Ref. 16). Find S_{cw} from equation (14).

(ii) Find d_{hw} from a rearranged equation (5) with $\mathbb{R}_h = \frac{d}{4}$:

$$d_{hw} = \frac{5.1866}{S_{cw}^{0.857}} \left(\frac{V}{C_{hw}}\right)^{1.5873} \tag{29}$$

To find Q_{hw} for a given mesh point (d,V) and specified C_{hw} value, the procedure is:

(i) Compute S_{cw} as above.

(ii) Find Q_{hw} from equation (7):

$$Q_{hw} = 0.2784\, C_{hw}\, d^{2.63}\, S_{cw}^{0.54} \tag{30}$$

$\frac{d_{hw}}{d}$ may be expressed as a function of $\frac{S_{hw}}{S_{cw}}$ by rearranging equation (8) to get d:

$$d = \frac{5.1866}{S_{hw}^{0.857}} \left(\frac{V}{C_{hw}}\right)^{1.5873} \tag{31}$$

Dividing equation (29) by equation (31) gives $\frac{d_{hw}}{d}$:

$$\frac{d_{hw}}{d} = \left(\frac{S_{hw}}{S_{cw}}\right)^{0.857} \tag{32}$$

Applying a similar argument to a rearranged equation (9) and equation (30) gives $\frac{Q_{hw}}{Q}$:

$$\frac{Q_{hw}}{Q} = \left(\frac{S_{hw}}{S_{cw}}\right)^{-0.54} \tag{33}$$

Equations (32) and (33) show that $\frac{S_{hw}}{S_{cw}}$ is more sensitive to change in C_{hw} than the Q and d ratios. For investigating the effect of C_{hw} change only the S ratio needs to be examined. On Figure 9 the contour lines for the three ratios $\frac{S_{hw}}{S_{cw}}$, $\frac{Q_{hw}}{Q}$, $\frac{d_{hw}}{d}$ would coincide at 1.0. At other contours of $\frac{S_{hw}}{S_{cw}}$ the corresponding values for $\frac{d_{hw}}{d}$ and $\frac{Q_{hw}}{Q}$ are found from equations (32) and (33) and shown in the table on Figure 9.

The results of trying various C_{hw} values for the pipes in Table 1 are presented in Table 2. The explanatory diagram for the points A, B, etc. used in the "Notes" columns of Table 2, is shown as Figure 11.

Using the Manning Formula

A similar procedure to that used above for the Hazen-Williams formula has been adopted. Additional equations required are shown below.

Diameter d_m [corresponding to equation (29)] is found by rearranging equation (6) with $R_h = \frac{d}{4}$:

$$d_m = \frac{4(Vn)^{1.49254}}{S_{cw}^{0.74627}} \tag{34}$$

Flow rate Q_m [corresponding to equation (30)] comes from equation (10):

$$Q_m = \frac{0.3102\, d^{2.67}\, S_{cw}^{0.5}}{n} \tag{35}$$

The diameter and flowrate ratios [corresponding to equations (32) and (33) respectively] are:

$$\frac{d_m}{d} = \left(\frac{S_m}{S_{cw}}\right)^{0.746} \tag{36}$$

and:

$$\frac{Q_m}{Q} = \left(\frac{S_m}{S_{cw}}\right)^{-0.5} \tag{37}$$

The effect of varying n on the ±5% and ±10% agreement ranges for one pipe is shown in Figure 10(B). The results of trying various n values for the pipes in Table 1 are shown in Table 3.

CONCLUSIONS

Finding Empirical Coefficients for a Single Pipe Using the Hazen-Williams Formula

For a single pipe of given d and k values (and water temperature 20 degrees Celsius) C_{hw} may be found from Figure 5.

The C_{hw} values on Figure 5 correspond to those along the $\frac{f_{hw}}{f_{cw}} = 1.025$ contour line on Figure 6. For operation away from this line the $\frac{f_{hw}}{f_{cw}}$ values of Figure 6 apply.

Comparison of Figure 6 with Figures 1 and 2 indicates that the pipes with operating zones closer to the smooth pipe curve may utilise the Hazen-Williams formula with an error in f of -5% to +2.5% compared to the preferred formula. For the rougher (high k value) pipes the error in f becomes unacceptable over much of the operating zone.

Using the Manning Formula

The Manning formula agrees with the preferred formula when the flow is wholly rough wall turbulent. For known values of d and k Manning's n may be found from Figure 8 to give agreement in this zone of flow.

For operation in the transition zone the Manning formula underestimates f and the $\frac{f_m}{f_{cw}}$ contours of Figure 7 apply.

Comparison of Figure 7 with Figures 1 and 2 indicates that it is only for rougher (high k value) pipes of poor quality that the Manning formula may be used. For these pipes an error in f of -5% compared to the preferred formula may result over part of their operating zone.

Finding Empirical Coefficients for an Operating Zone

For a V range of 0.2 to 6 $m.s^{-1}$, and the d ranges shown in Table 1 for the various pipes, the recommended C_{hw} and n values (extracted from Tables 2 and 3) are shown in Table 4.

In Tables 2 and 3 the point A conditions (also shown on Figure 11) correspond to maximum V (i.e. 6 $m.s^{-1}$), and maximum d for the particular pipe (from Table 1). Maximum V and maximum d may be used as a rough criterion for finding C_{hw} and n, as follows:

(i) To find C_{hw} for given V, d and k, calculate IR and $\frac{d}{k}$ and find f from the Moody Chart, or use Yao's method (Ref 16). Then find C_{hw} from equation (22).

(ii) To find n for given V, d and k use equation (27).

Application to Other Empirical Formulas and Pipe Data

The methods demonstrated above for a single pipe may be applied to any other empirical formula in the general form of equation (4). Such equations may be reduced to a form suitable for plotting on the Moody Chart, giving a family of straight lines which attempt to approximate portion of the chart (Ref. 12).

The method used above for finding a single value of an empirical coefficient for a given operating zone may be used for any pipe or range of V and d. The operating zone should be specified when a single value of an empirical coefficient is quoted for a pipe material.

REFERENCES

[1] Ackers, P., Resistance of fluids flowing in channels and pipes. 1958. (Great Britain - Hydraulics Research Station. Hydraulics Research Paper No. 1).

[2] Precast concrete pressure pipes. (AS A124 - 1962). Sydney: Standards Association of Australia, 1962.

[3] Centrifugally cast iron pressure pipes for water, gas and sewage. (AS A145 - 1970). Sydney: Standards Association of Australia, 1970.

[4] Design charts for water supply and sewerage. (AS 2200 - 1978). Sydney: Standards Association of Australia, 1978.

[5] Barlow, J.F.; Markland, E. "Converting the Hazen-Williams equation to the Colebrook function." Water Power & Dam Construction 27 (1975), 331-334.

[6] Barnes, D.; Bliss, P.J.; Gould, B.W.; Vallentine, H.R. Water and wastewater engineering systems. London: Pitman Books Ltd., 1981.

[7] Carnahan, B.; Luther, H.A.; Wilkes, J.O. Applied numerical methods. New York: John Wiley & Sons, 1969.

[8] Colebrook, C.F. "Turbulent flow in pipes with particular reference to the transition region between the smooth and rough pipe laws." J.I.C.E. 11 (1938-39), 133-156.

[9] Diskin, M.H. "The limits of applicability of the Hazen-Williams formula." La Houille Blanche 15, 6 (1960), 720-723.

[10] Hardie's Pipelines, Flow resistance chart, A.C. pressure pipes. Sydney: James Hardie & Co Pty Ltd, 1975.

[11] Hardie's Pipelines, Flow resistance chart, UPVC pressure pipes. Sydney: James Hardie & Co Pty Ltd, 1975.

[12] Lamont, P. "The choice of pipe flow laws for practical use." Water and Water Engineering 63 (1969), 9-17, 55-63.

[13] Moody, L.F. "Friction factors for pipe flow." T.A.S.M.E. 66(1944), 671-678.

[14] Streeter, V.L.; Wylie, E.B. Fluid mechanics. 7th Ed. New York: McGraw-Hill Book Co., 1979.

[15] Vennard, J.K.; Street, R.L. Elementary fluid mechanics. 6th Ed., S.I. Version. New York: John Wiley & Sons, 1982.

[16] Yao, K.M. "Pipe friction factor calculations." Water & Sewerage Works 110(1963), 91-95.

TABLE 1: DATA FOR TYPICAL CLEAN WATER SUPPLY PIPES

Material	d(m) Range	Ref.	Quality	Roughness and Coefficients k(mm)	C_{hw}	n	Ref.
Smooth, Brass Copper, UPVC, Polyethylene	0.015 to 0.25	11	Good	0.003	160	0.008	4
			Poor	0.015	155	0.009	4
Asbestos Cement	0.05 to 0.6	10	Good	0.015	155	0.008	4
			Poor	0.06	145	0.011	4
Concrete, spun	0.1 to 1.83	2	Good	0.03	150	0.009	4
			Poor	0.15	140	0.012	4
Cast Iron, uncoated	0.08 to 0.625	3	Good	0.15	140	0.010	4
			Poor	0.6	125	0.013	4

TABLE 2: RESULTS OF APPLYING HAZEN-WILLIAMS FORMULA TO PIPE OPERATING ZONES

V range 0.2 to 6 $m.s^{-1}$, Water at 20 deg. C.

Material & Quality	d (m) Range	k (mm)	C_{hw}	Notes (see Fig.11)	% Area for S_{hw}/S_{cw} Range 0.95 to 1.05	0.9 to 1.1
Smooth, Good	0.015 to 0.25	0.003	150		38.5	97.7
			152.5	Mean of pts. A & B	89.3	95.8
			155.8	Pts. A & C coincide	76.8	91.5
			156		75.5	91.3
			160	AS Code (Ref. 4)	10.5	79
Smooth, Poor	0.015 to 0.25	0.015	143.1	Mean of Pts. A & B	25.3	93.3
			145		56.3	98.9
			148.1	Pts. A & C coincide	86.6	94.4
			150		78.6	92.9
			155	AS Code (Ref. 4)	4.5	74.2
Asbestos Cement, Good	0.05 to 0.6	0.015	146.5	Mean of Pts. A & B	60	99.8
			148.8	Pts. A & C coincide	97.1	99.5
			150		93.7	99.5
			155	AS Code (Ref. 4)	32.6	91.8
Asbestos Cement, Poor	0.05 to 0.6	0.06	131.6	Mean of Pts. A & B	16.6	48.3
			136	Pt. A	51.8	79
			140		56	93.7
			145	AS Code (Ref. 4)	33.3	65.2
			146.8	Pt. C	22.4	50.5

Concrete, Good	0.1 to 1.83	0.03	143.6	Pt. A	53.9	93
			145		68.2	99.9
			147.5	Mean of Pts. A & C	88.3	99.9
			150	AS Code (Ref. 4)	61.7	97.8
			150.9	Pt. C	51.8	96.5
Concrete, Poor	0.1 to 1.83	0.15	122.2	Mean of Pts. A & B	8	32.3
			127.1	Pt. A	41.3	63.4
			130		49.9	73.6
			140	AS Code (Ref. 4)	20.3	43.7
			147	Pt. C	6.4	16.4
Cast Iron, Good	0.08 to 0.625	0.15	124.9	Pt. A	43.8	67.1
			127.5		46.5	74.3
			134.3	Mean of Pts. A & C	26.1	55.3
			140	AS Code (Ref. 4)	14.2	28
			143.6	Pt. C	6	16
Cast Iron, Poor	0.08 to 0.625	0.6	100.1	Mean of Pts. A & B	12.3	27.6
			106.4	Pt. A	37.7	60.3
			110		32.3	61.5
			125	AS Code (Ref. 4)	5.6	13.2
			132.2	Pt. C	0	0

TABLE 3: RESULTS OF APPLYING MANNING FORMULA TO PIPE OPERATING ZONES

V range 0.2 to 6 $m.s^{-1}$. Water at 20 deg. C.

Material & Quality	d (m) Range	k (mm)	n	Notes (See Fig. 11)	% Area for S_m/S_{cw} Range 0.95 to 1.05	0.9 to 1.1
Smooth, Good	0.015 to 0.25	0.003	.0068	Mean of Pts. A & B	8.5	20.3
			.0073		25.9	48.6
			.0075	Pt. A	29.3	50.7
			.0077		23.5	44.3
			.008	AS Code (Ref. 4)	14	29
Smooth, Poor	0.015 to 0.25	0.015	.0076		29.6	60.4
			.0078	Pt. A	34.7	57
			.009	AS Code (Ref. 4)	4	8.6
Asbestos Cement, Good	0.05 to 0.6	0.015	.008	AS Code (Ref. 4)	22.6	47.5
			.0082		29.7	55.3
			.0084	Pt. A	32.9	54.1
			.0086		25.2	48
Asbestos Cement, Poor	0.05 to 0.6	0.06	.0089		38.3	66.6
			.0091	Pt. A	39.7	61.8
			.0093		27.9	51.3
			.011	AS Code (Ref. 4)	1.3	2.4

Concrete, Good	0.1 to 1.83	0.03	.009	AS Code (Ref. 4)	21.4	45.3
			.0094		35.2	58.7
			.0096	Pt. A	33.5	54.5
Concrete, Poor	0.1 to 1.83	0.15	.01		24.1	51.3
			.0107	Pt. A	40.2	62
			.012	AS Code (Ref. 4)	1.7	2.6
Cast Iron, Good	0.08 to 0.625	0.15	.01	AS Code (Ref. 4)	37.7	62.8
			.0095		38.4	79.5
			.0097		51	77.8
			.0099	Pt. A	45.5	69.2
Cast Iron, Poor	0.08 to 0.625	0.6	.011		49.2	93.2
			.01125		74.5	98.3
			.0115	Pt. A	56.3	86.2
			.01175		23.1	61.5
			.013	AS Code (Ref. 4)	0	0

TABLE 4: RECOMMENDED EMPIRICAL COEFFICIENTS FOR PIPE OPERATING ZONES

V range 0.2 to 6 $m.s^{-1}$. Water at 20 deg. C.

Material & Quality	d (m) Range	k (mm)	Coefficient C_{hw}	Coefficient n
Smooth,	0.015 to 0.25			
Good		0.003	152.5	.0075
Poor		0.015	148	.0078
Asbestos Cement,	0.05 to 0.6			
Good		0.015	149	.0084
Poor		0.06	140	.0091
Concrete,	0.1 to 1.83			
Good		0.03	147.5	.0094
Poor		0.15	130	.0107
Cast Iron,	0.08 to 0.625			
Good		0.15	127.5	.0099
Poor		0.6	106.5	.0113

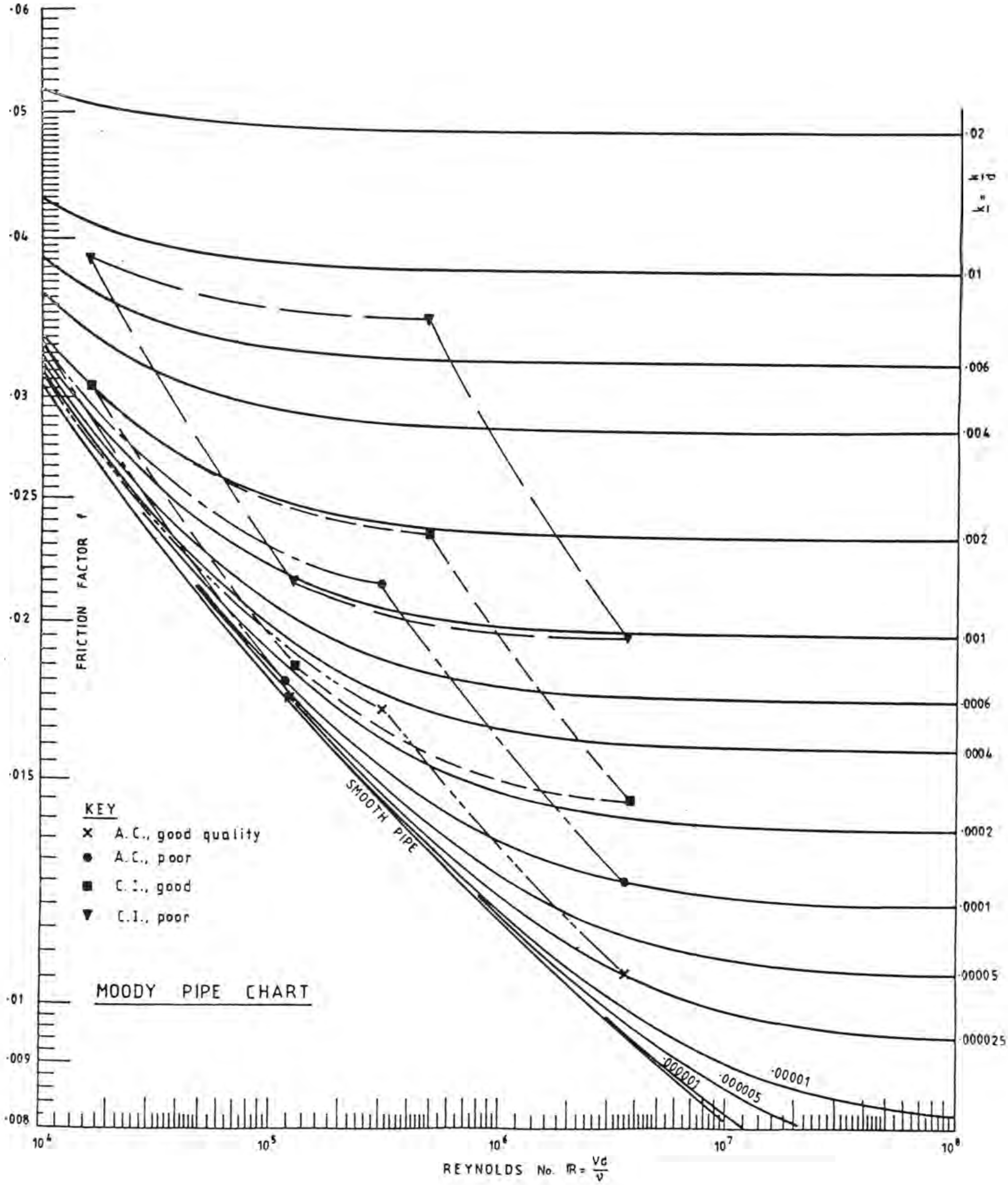


FIG. 1. OPERATING ZONES FOR CLEAN PIPES

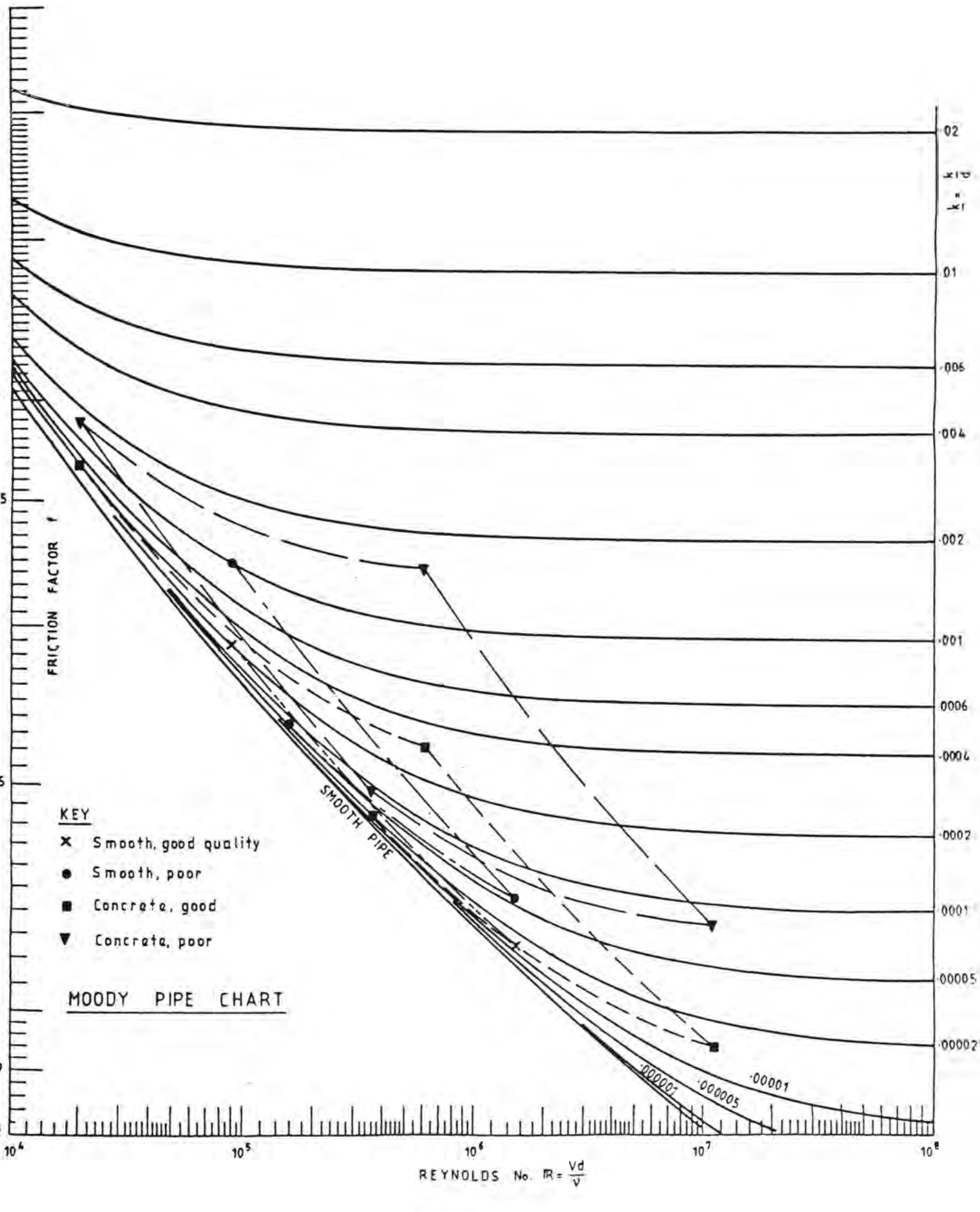


FIG. 2. OPERATING ZONES FOR CLEAN PIPES

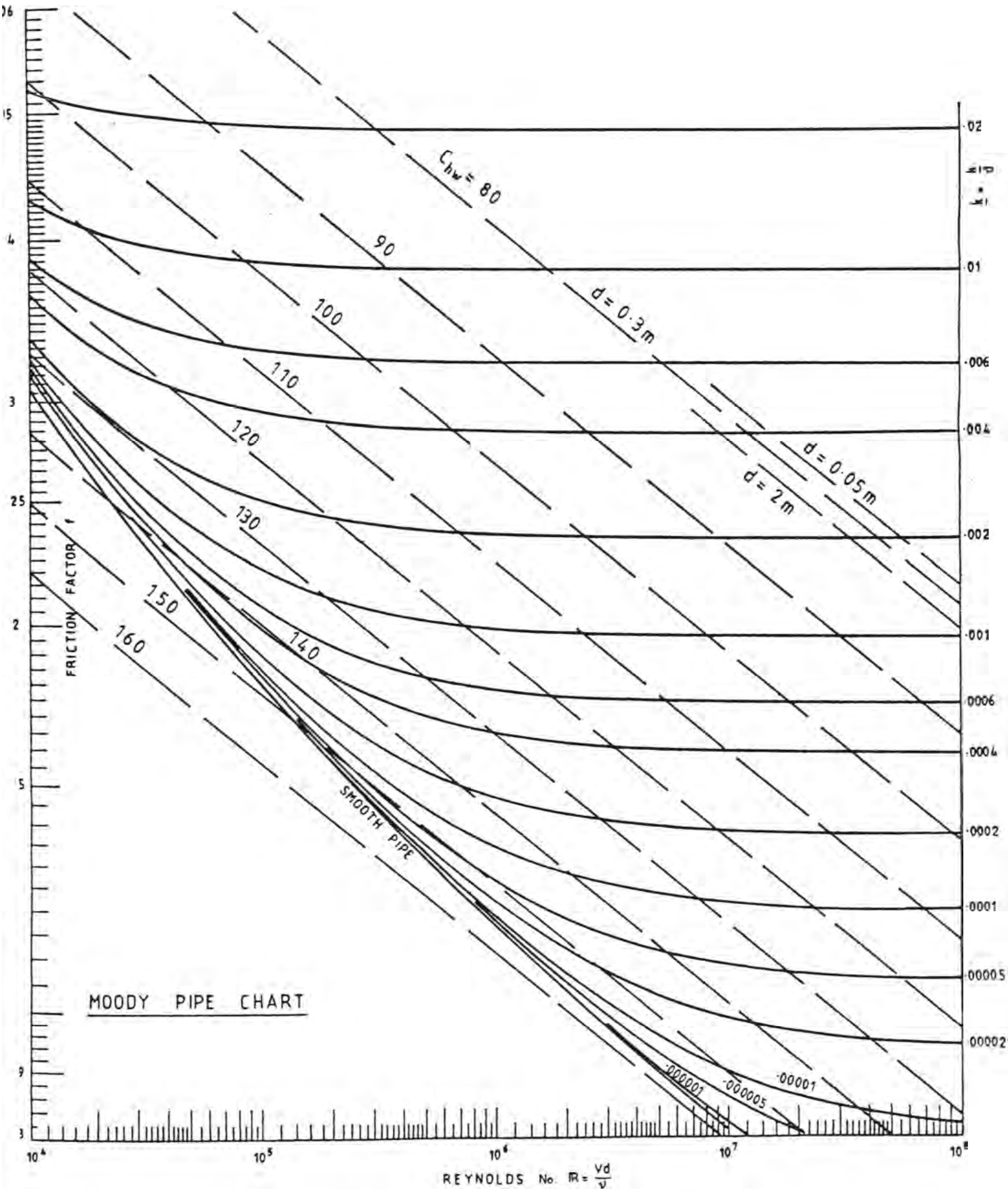


FIG. 3. C_{hw} = CONSTANT LINES
d = 0·3m, WATER AT 20°C

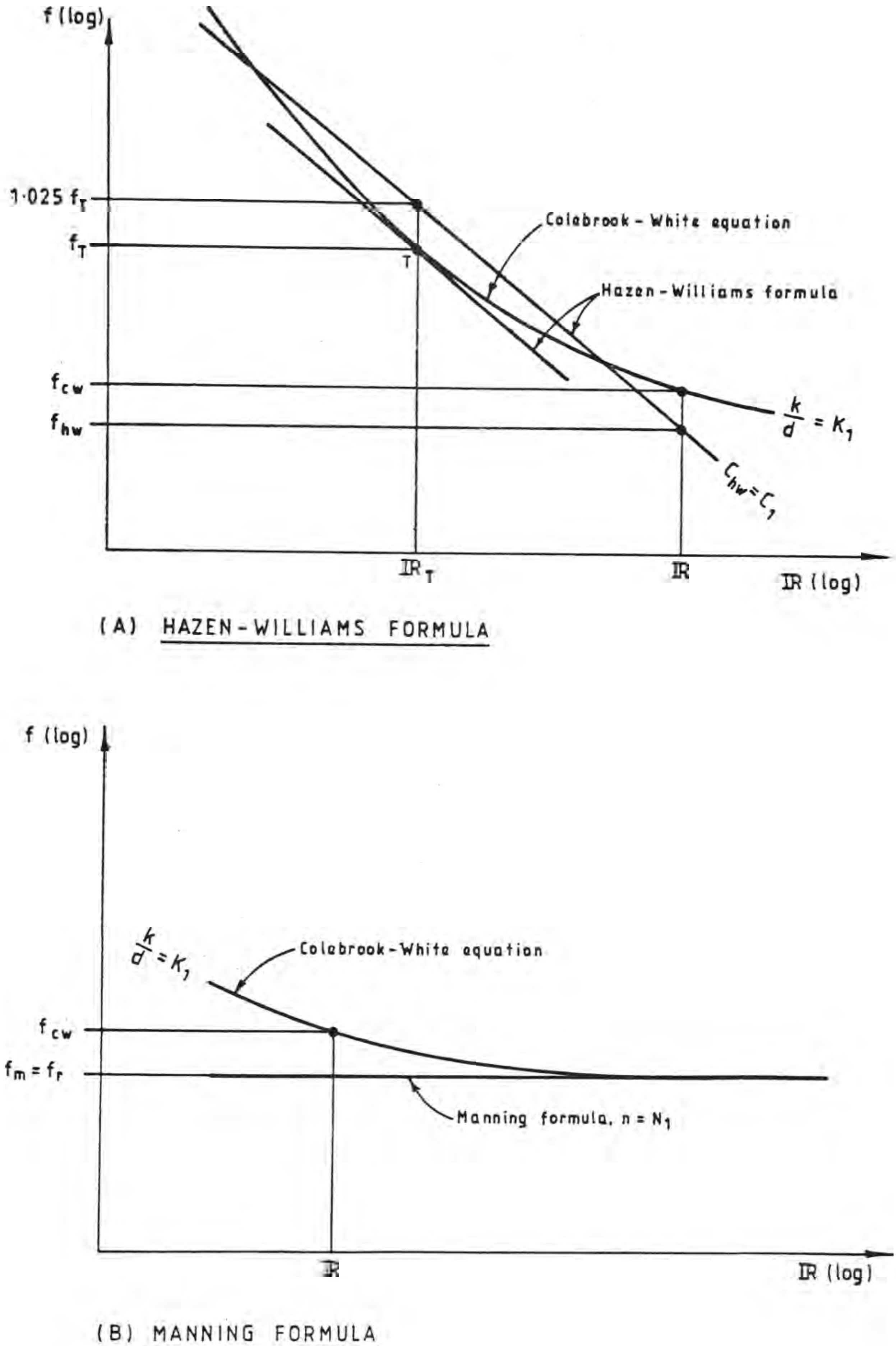


FIG. 4. FITTING EMPIRICAL FORMULAS TO COLEBROOK - WHITE EQUATION FOR SINGLE PIPES

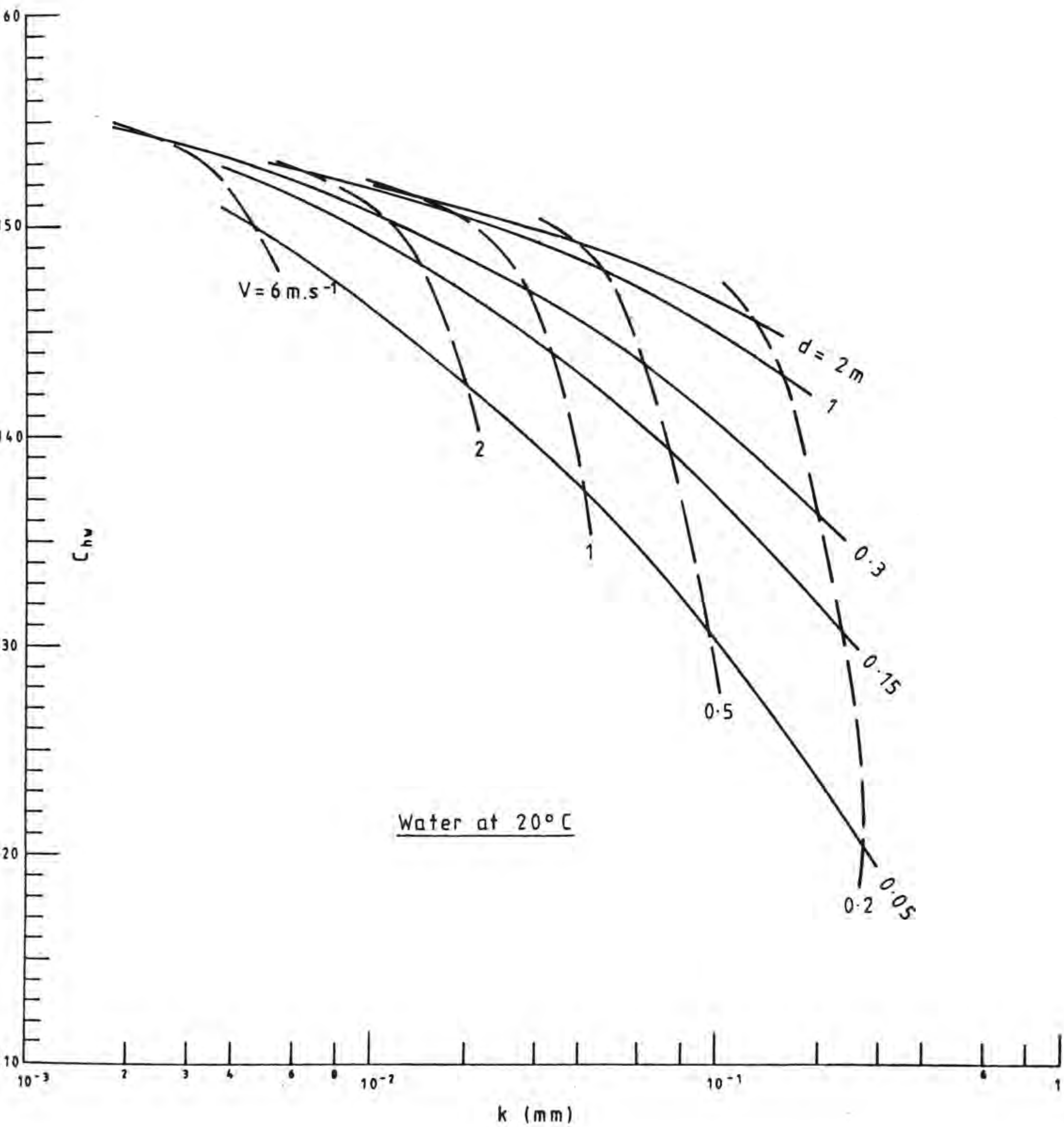


FIG. 5. HAZEN-WILLIAMS COEFFICIENT C_{hw} FOR A SINGLE PIPE

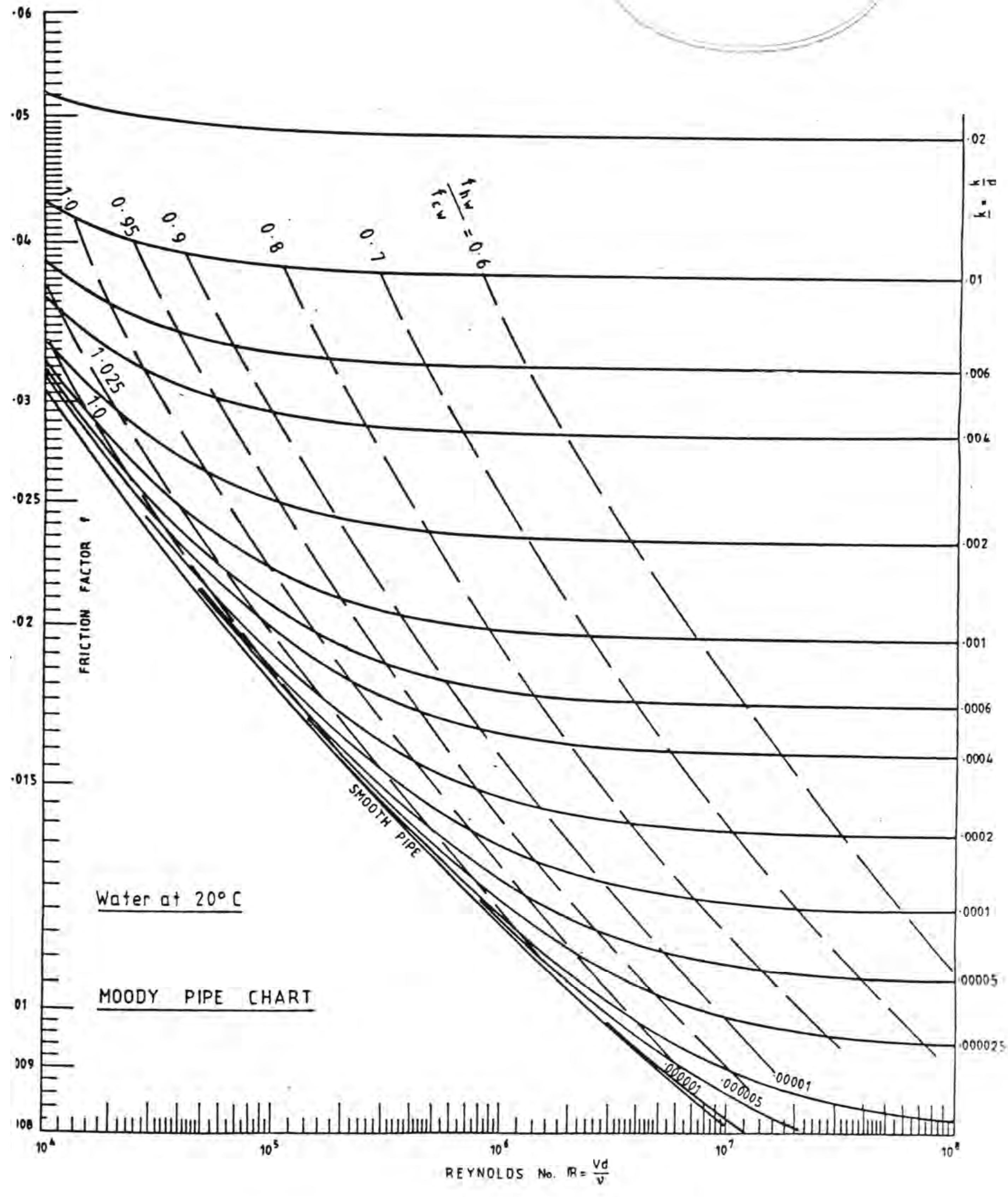


FIG. 6. HAZEN-WILLIAMS FORMULA

$$\frac{f_{hw}}{f_{cw}} = \text{CONSTANT CONTOURS}$$

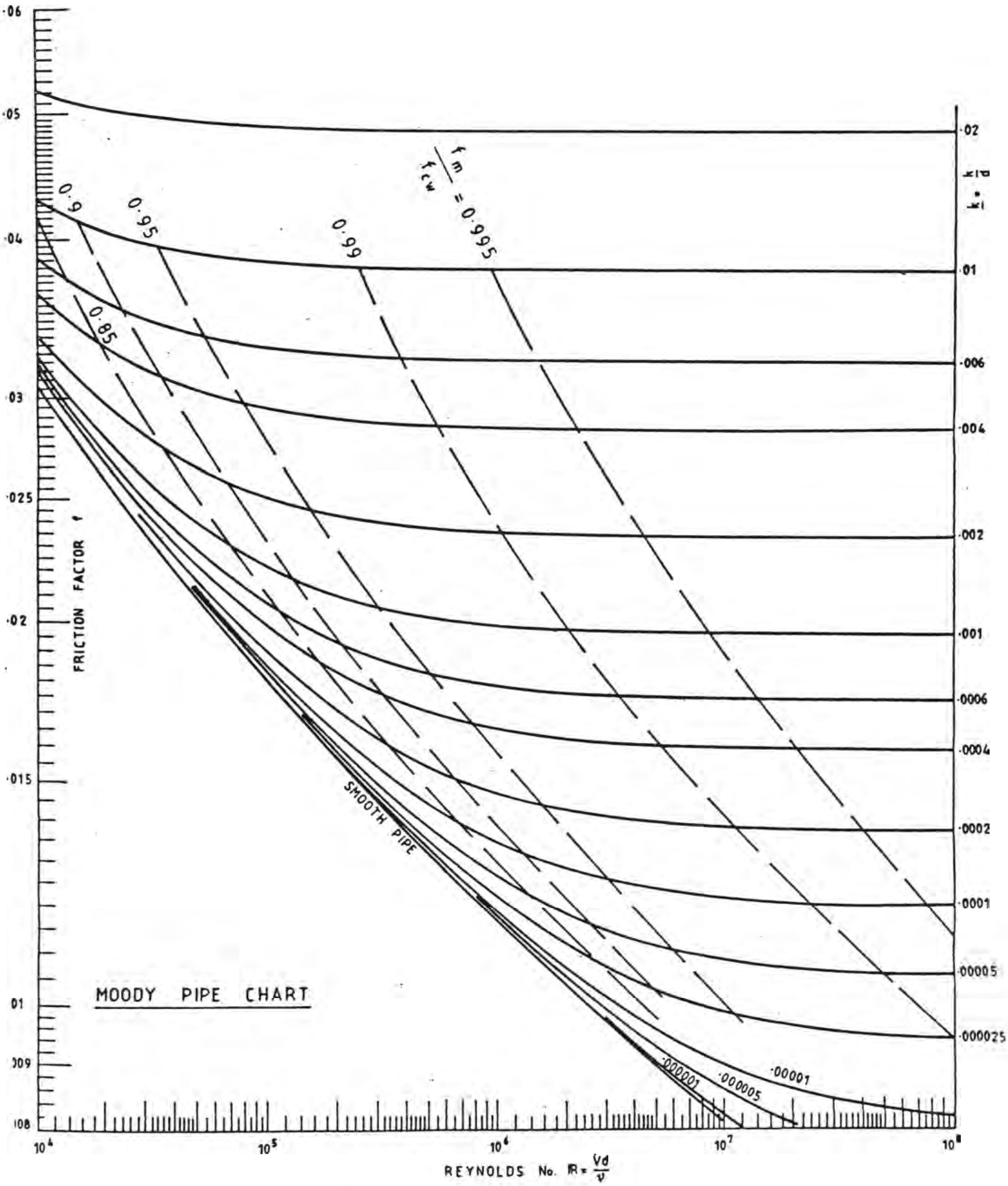


FIG. 7. MANNING FORMULA

$\frac{f_m}{f_{cw}}$ = CONSTANT CONTOURS

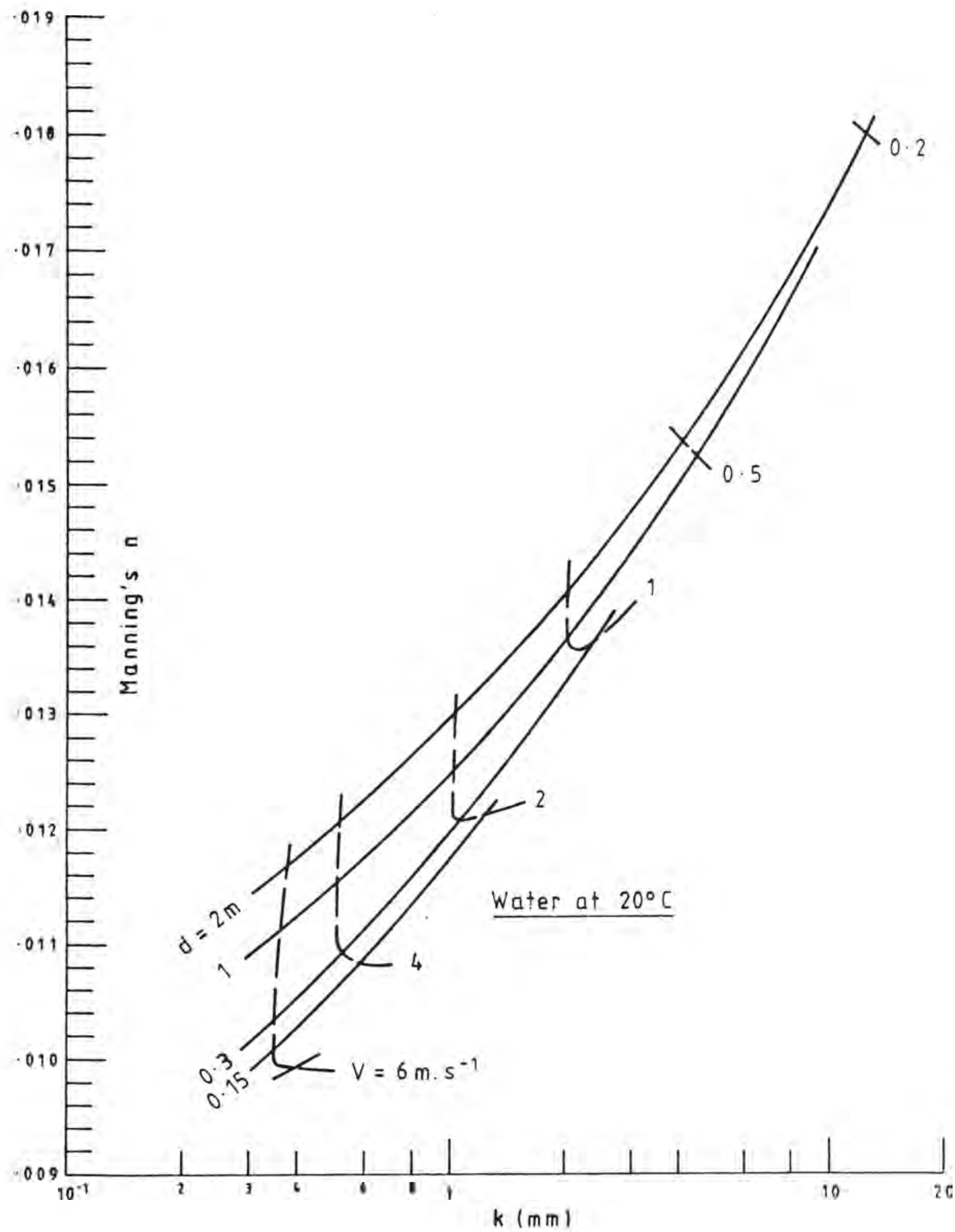
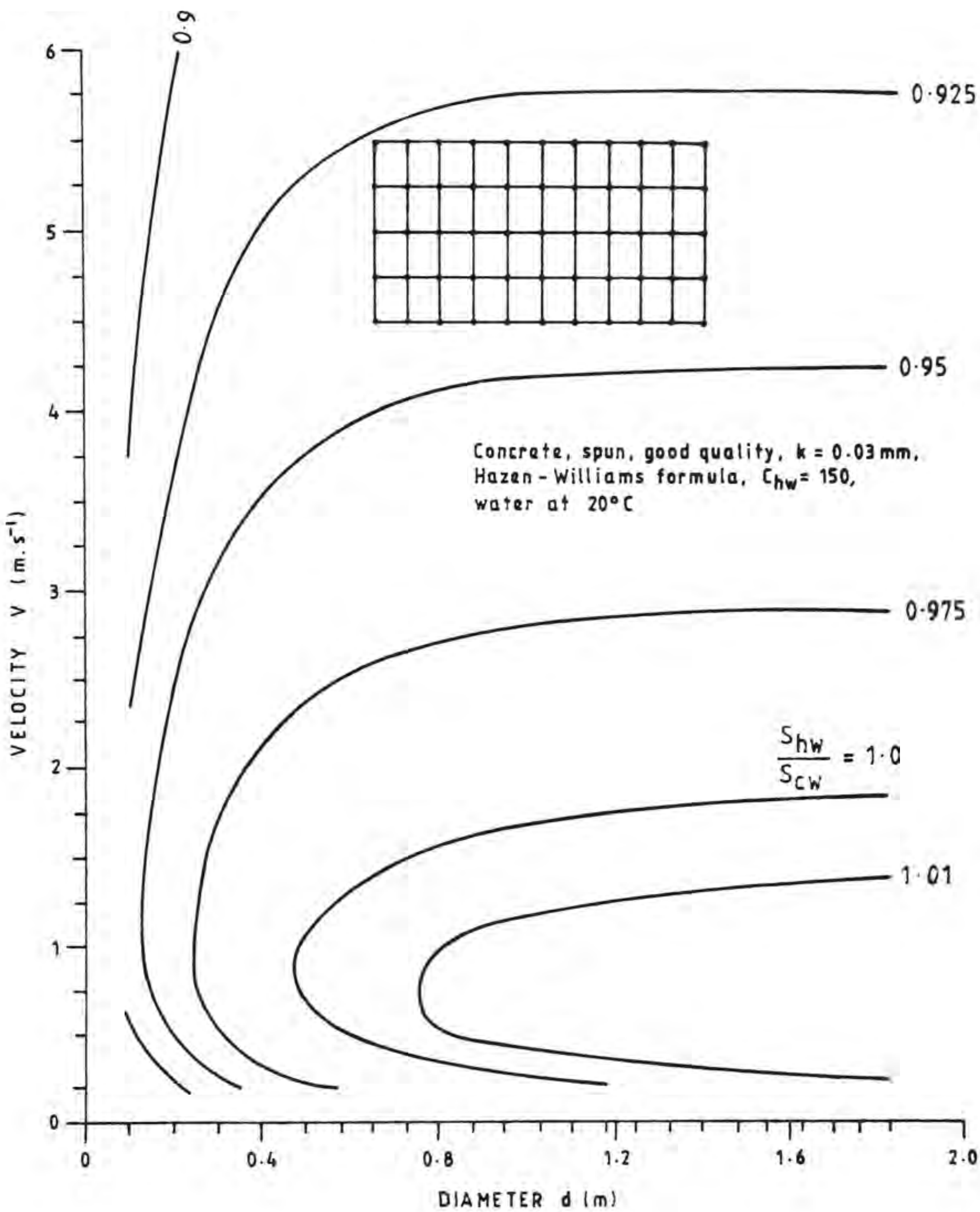


FIG. 8. MANNING'S n FOR A SINGLE PIPE



$\frac{S_{hw}}{S_{cw}}$	0·9	0·925	0·95	0·975	1·0	1·01
$\frac{Q_{hw}}{Q}$	1·059	1·043	1·028	1·014	1·0	0·995
$\frac{d_{hw}}{d}$	0·914	0·935	0·957	0·979	1·0	1·009

FIG. 9. EMPIRICAL FORMULA APPLIED TO AN OPERATING ZONE

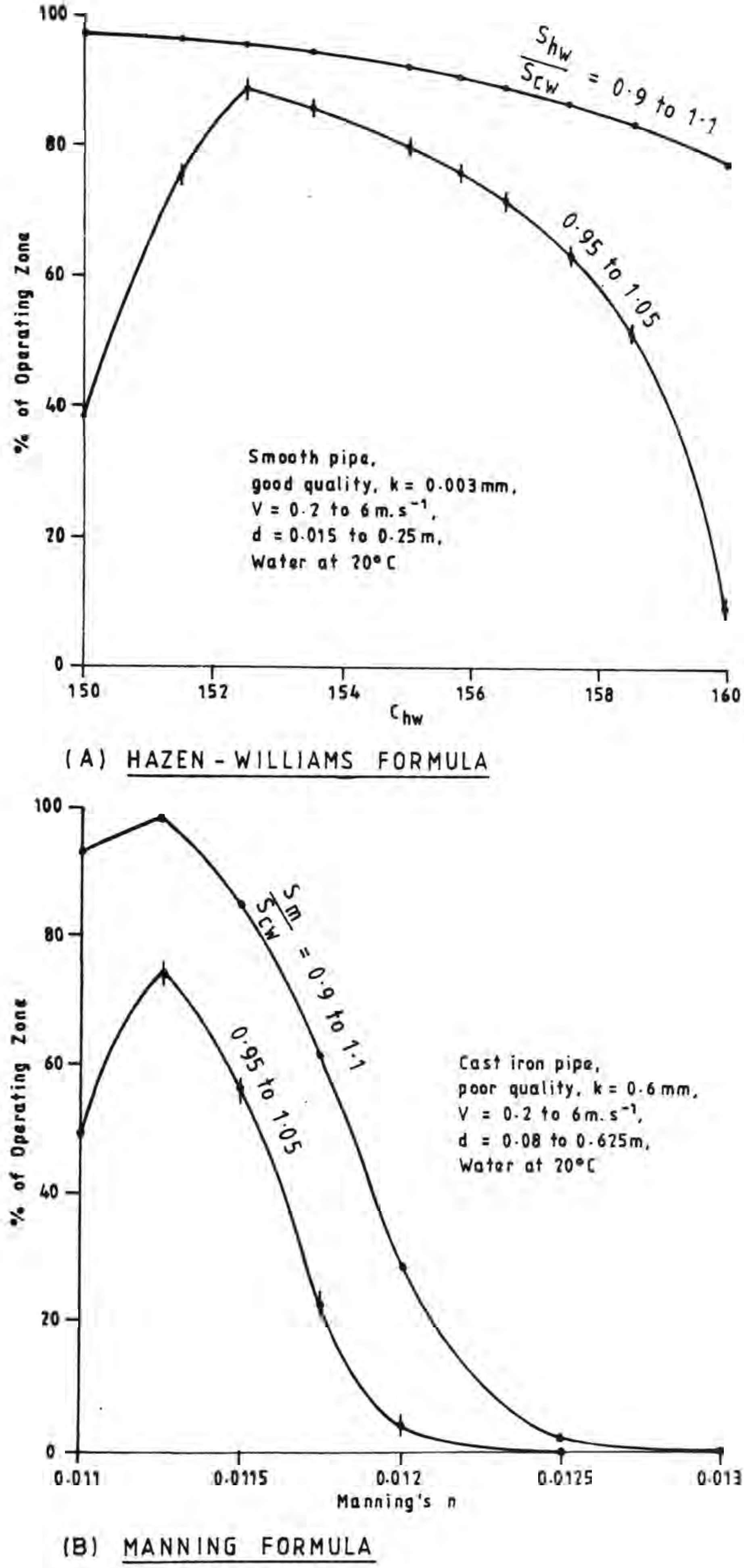


FIG. 10. FINDING EMPIRICAL COEFFICIENTS FOR AN OPERATING ZONE

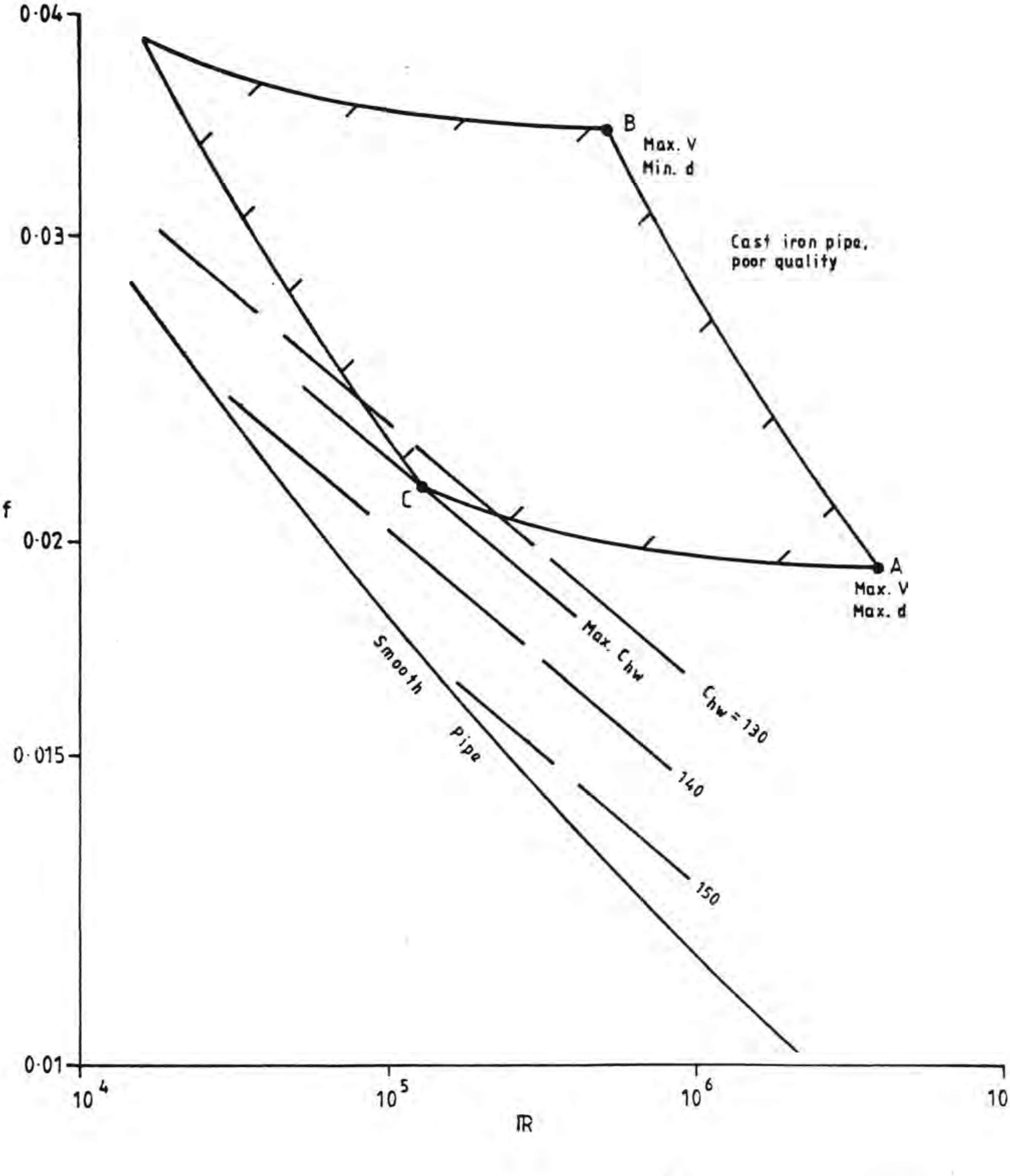


FIG.11. POINTS FOR TESTING EMPIRICAL COEFFICIENTS FOR AN OPERATING ZONE