MOODY-42

A Pipe Flow Calculator for the HP42s[a], Free42 and Plus42

Based on the Moody Diagram

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Introduction

Moody-42 provides a simple to use pipe flow calculator that solves directly for any of the key variables encountered in pipe hydraulics. In addition, it has extended features that help when applying the Moody Diagram to pipe hydraulics particularly when considering solutions that lie near to or within the transition from laminar to turbulent flow.

Basic Features

The five variables that are of immediate interest when analyzing the flow of fluid through a pipe are the roughness and diameter of the pipe, the flow rate, the velocity and the energy gradient. This program will calculate any one of these five variables based on values set for an appropriate selection from the remaining variables.

The five variables referred to are associated with the first 5 menu keys of the calculator. The sixth and last menu key toggles between two computation modes.

Menu Keys:

K	D	Q	S	V	>

K - Pipe roughness in mm

D - Pipe diameter in mm

Q - Flow rate in L/s

S - Slope of energy gradient as %

V - Velocity in m/s

Computation Mode:

>	Normal Friction Mode
DQV■	Continuity Mode

a While Moody-42 is designed for the HP42s class of calculator, it is not recommended to use it on the original HP product due to performance issues. Use Free42 / Plus42 instead.

In Normal Friction Mode, friction loss always forms part of the calculation. Each of the five variables can be solved based on the current values of the relevant remaining variables.

If the current values of D, Q and V are inconsistent with the state of continuity, due to data entry, then the user will be prompted to identify a dependence of the calculation on either Q or V. At the conclusion of the calculation all five terms are checked and adjusted if necessary to be sure they are consistent.

In Continuity Mode the user is able to compute any one of the three variables D, Q and V from the remaining two variables. In these cases friction does not participate in the calculation. The computation is simply solving the continuity of Q = VxA (where A is the area of the pipe). At the conclusion of the continuity calculation the program returns to Normal Friction Mode ready for the determination of K or S if required. The main purpose for the Continuity Mode is to determine the diameter needed to achieve a given combination of flow rate and velocity. See Example No 5.

Keying in a new value and then pressing one of the five menu keys stores that value into the corresponding storage register. Pressing a menu key without previously entering a value computes the value of the corresponding variable based on the current values of other relevant variables. Pressing a menu key without previously entering a value also allows the review of the current value of the variable. Both of the two previous operations usually result in calculating / re-calculating the variable value.

The units of the variables have been selected for their convenience in typical calculations for small to medium sized pipes. These units apply consistently to input and output data as controlled by the program. There is an alternate way of accessing the values of variables using the RLC and STO functions of the calculator. Note that when accessing values in this way it is important to be aware that a different set of units applies. The units applicable in this alternate method of access are more appropriate to the internal calculations of the program and may also be more convenient when further hand calculation based on program results is performed. Table 1 summarises the convention adopted for units.

TABLE 1 - Convention for Units

Variable	Program Input/Output	RCL & STO
K	mm	m
D	mm	m
Q	L/s	m^3/s
S	%	m/m
V	m/s	m/s

The program displays output values to the number of decimal places normally sufficient in practical situations. Using the calculator's SHOW function will display full precision. Alternatively setting Flag 03 will override the program's precision formatting and use the calculator's Mode setting instead.

For fluids other than water the user may revise a program step near the beginning of the program where a value is assigned to kinematic viscosity (R11).

The program runs with negligible execution times on the Free42 / Plus42 calculator emulator on modern hardware. Execution times on the original HP42s have not been tested but are likely to be excessive.

The program is supplied as a single module, namely Mo42

Advanced Features.

The Moody-42 program provides solutions for all the key variables associated with the Moody Diagram for the full scope of state covered by that diagram. The solutions therefore embrace laminar flow and turbulent flow and the transition between these two flow regimes. With respect to this transition it is important to recognise the nature of flow where it transitions from laminar to turbulent conditions and the terminology used to describe it. Moody (Ref 1) refers to this zone as the Critical zone and reserves the use of the term Transitional zone to a different region outside the Critical zone. This is illustrated on Figure 1. All further discussion in this document adopts the Moody naming convention. Within the Critical zone the actual flow conditions lie somewhere between the Laminar and Turbulent state and are heavily influenced by factors that are not addressed by the Moody Diagram. (for example, Laminar flow can to some extent be promoted to occur within the Critical zone by ensuring that pipework leading to a point of measurement is free of bends and disturbances)

For the purposes of the Moody-42 program the Critical zone is considered to lie between Reynold numbers of 2300 and 4000. The relationship between Reynolds number and Friction factor is considered to change linearly in the zone between R=2300 and R=4000 as depicted on Figure 1. The adopted limits and nature of the transition for the Critical zone serve to provide a continuum for solution, and to flag when results are falling within or near to the Critical zone thereby possibly warranting more investigation of the Laminar / Turbulent transition. Results in the Critical zone should not be inferred to have a greater accuracy than is justified.

The reported results are qualified with a code suffix which indicates where on the Moody Diagram the solution lies in terms of the regime zones indicated on Figure 1. The set of codes suffixes is listed in Table 2.

TABLE 2 - Regime Code Suffixes	
Co	Complete Turbulence
Tr	Transition Turbulence
Cr	Critical zone
La	Laminar Zone
→	Off chart – High Reynolds Number (Re>10^8)
↓	Off chart – Low Friction Factor (f<0.008)
←	Off chart – Low Reynolds Number (Re<600)
↑	Off chart – High Relative Roughness (K/D>0.05)
zz	Dormant K value

Dormant K

If solving for K and the remaining terms are recognised as being related to a Laminar state then the current value of K is reported without calculation and qualified with a “zz” suffix. This suffix serves to indicate that the current K value is retained in a “sleeping state” not needed for Laminar calculations.

No K

When attempting to determine a new value for roughness (K) you may receive the response “No K”.

For Critical and Turbulent flow, if the flow conditions specified by the current values of D, S and (Q or V) are unable to be realised regardless of the K value then “No K” will be reported.

A numeric result for K will only be reported if a solution can be found in the range

(0 >= K/D > D/10).

NoK will also be reported if the Diameter entered, or calculated, results in an out of bound K.

For Laminar flow no check is made as to whether the currently stored K is reasonable.

NoSol

In exceptional situations Moody-42 may not be able to find a solution and will display the message **NoSol.** On these occasions you can continue with alternate input data. To observe this condition you can force it to occur with K=0.001mm, D=0.19mm, S=0.002% and solve for Q. NoSol may also be reported if D is inadvertently left at zero.

Rst

In exceptional situations the Free42 equation solver may enter an endless loop. When this is detected by Moody-42 it aborts the running solve process and displays the **Rst** message, indicating that the program needs to be restarted. To observe this condition you can force it to occur with K=0.001mm, D=0.2mm, S=0.002% and solve for Q.

Extended Menu

At any time while using Moody-42 you can press the keys Δ or ∇ to bring up the extended menu. Pressing either key once more returns you to the normal menu. The extended menu looks like:

Mode: Auto -R

Re	fric	-	d	M1	M2

The line above the extended menu bar reports the current status of the Extended Modes of Moody-42 and this defaults to Auto -R each time you start the program.

The menu bar itself displays the keys that allow you to interact with the Reynolds Number and Friction Factor as well as change the Extended Modes M1 and M2 as per Table 3.

The **d** Key returns the Extended modes M1 and M2 to their default states, namely Auto -R.

TABLE 3 - Extended Modes		
M1	Auto	Automatically determine Laminar, Critical or Turbulent (Default)
	*L	Constrain calculation to Laminar equation regardless of Re
	*T	Constrain calculation to Turbulent equation regardless of Re
M2	-R	Allow Re to vary Solve among K, D, Q, S, V (Default)
	-D	Allow D to vary Enter R and solve among K, Q, S, V
	-QV	Allow Q and V to vary Enter R and solve among K, D, S

The *L and *T modes are useful when the automatic solution lands in or near the Critical Zone. The user is then able to determine the alternate solutions that might arise if turbulent or laminar flow persists into or perhaps beyond the Critical zone.

The -D and -QV modes are useful when the starting point in an analysis is a specific Reynolds Number value.

When the default M2 mode -R is selected you are able to output the Reynlods number and the Friction factor, post solution, using the Re and fric keys respectively. In this mode it is not relevant nor possible to enter Re or fric data into the program. The -D and -QV modes offer similar functionality to the -R mode and in addition allow the entry of data for the Reynolds number value to be used in calculations to follow.

When the -D and -QV modes are active and when returning to the main menu you will find one or two keys disabled. This is done to indicate that input for those keys is not required at this time. Results will be calculated for all hidden keys. Once the calculation has been performed you can inspect the "hidden" result by returning to the -R mode where all keys will be visible and available. Alternatively use the RCL function of the calculator.

Relative Roughness Option

The normal method for expressing pipe roughness in Moody42 is in the use of the Nikuradse equivalent sand roughness term K. This is an absolute value and is expressed in units of mm. You may also use a relative roughness instead and this is identified by the lower case "r" where r = K / D. To switch between using K or r you enter the special number -1 for the roughness. Once the switch has been made you need to enter a roughness value appropriate to the term now in use. The selected roughness term is retained after a restart of the program. Also be aware that the value for relative roughness is stored in the same register as K.

To Simplify

If at any time you are uncertain as to how the extended modes operate or which one is current or relevant, and your objective is a basic calculation, simply restart the program and the default state will return. All data will be retained when doing this.

Solution Method

The turbulent calculation is based on an iterative solution of the Colebrook White equation. (Ref 2)

The laminar calculation is based on an iterative solution of the Hagen-Poiseuille equation.

The transition from laminar to turbulent flow is based on a linear transition approximation.

The core equations are given in Appendix A.

Sample Data Points

A random data point has been selected in each of the four flow regimes. The location of these four points within the Moody Diagram is shown on Figure 1. The results of calculations for each of these four points is shown in Table 4. Reproducing these results is recommended in order to gain familiarity in using the program and to help verify its correct operation.

Table 4a shows the results of further investigation of hydraulic conditions at point 2. This is achieved by using the M2 Modes *L and *T. It can be seen that the energy gradient will be 0.001528% and 0.005566% for the cases of Laminar and Turbulent flow respectively potentially persisting in the Critical zone.

TABLE 4 - Sample Data Points (Use Default modes)

	INPUT DATA			OUTPUT DATA			
Point #	K mm	D mm	S %	Q L/s	V m/s	f	Re
1	0	20	0.05840	Q=0.02L/s La	V=0.063m/s La	f=0.0581314	Re=1101
2	3	100	0.00384	Q=0.30L/s Cr	V=0.039m/s Cr	f=0.0507625	Re=3378
3	3.3	300	0.00109	Q=2.69L/s Tr	V=0.038m/s Tr	f=0.0441186	Re=10030
4	18	530	2.69400	Q=475.41L/s Co	V=2.155m/s Co	f=0.0602665	Re=1001838

TABLE 4a - Constrained Laminar & Turbulent Results (use *L, *T and -QV modes)

	INPUT DATA		OUTPUT DATA				INPUT
Point #	K mm	D mm	S %	Q L/s	V m/s	f	Re
2a	3	100	S=0.001% *L	Q=0.30L/s *L	V=0.039m/s *L	f=0.0189461	Re=3378
2b	3	100	S=0.005L/s *T	Q=0.30L/s *T	V=0.039m/s *T	f=0.0652162	Re=3378

Multiple Solutions

The capability to solve directly for Diameter does give rise to the possibility of multiple solutions in some isolated situations. This can occur when solving for D and electing to base the calculation on the current Velocity and additionally when the solution lies within or near to the Critical zone. To illustrate the occurrence of multiple Diameters an example is given in Table 5a/b. Table 5a repeats the result from the Point 2 solution from Table 4. This solution was made for the Velocity in a specified 100 mm diameter pipe.

TABLE 5a - Diamater Nominated							
	INPUT DATA			OUTPUT DATA			
Case	K mm	D mm	S %	Q L/s	V m/s	f	Re
A	3	100	0.00384	Q=0.30L/s Cr	V=0.039m/s Cr	f=0.0507625	Re=3378

Table 5b re-solves the data set in Table 5a, but this time the solve request was for D based on the current V. You may need to renter data for one variable to force a full recalculation.

TABLE 5b - Diameter Sought							
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT	
Case	K mm	D mm	S %	Q L/s	V m/s	f	Re
B	3	D=61.1 mm	0.00384	Q=0.11 L/s La	0.038505	f=0.031014	Re=2064

It can be seen that two very different Diameters (100 mm and 61.1 mm) are calculated for the same input data of V=0.038505m/s, S=0.00384% and K=3mm. Both these results satisfy the equations of friction loss so in that sense they are both valid. In view of the complex behaviour resulting from competing governing factors that occur in the vicinity of the Critical zone it is not unexpected that two or maybe more different pipe diameters at the same energy gradient can produce the same velocity. The procedure adopted by Moody-42 in solving for the Diameter for a given Velocity is as follows:

- If a valid solution is found in the Laminar zone that is what gets reported.
- If no valid solution is found in the Laminar zone, the Turbulent zones are checked for a valid solution and if found, that is what gets reported.
- Failing the discovery of a valid solution in the Laminar and Turbulent zones, the first valid solution found in the Critical zone gets reported.
- If no solution is found in the Critical zone then NoSol is reported.

The multiplicity of calculated value has only been observed when solving for D based on a value of V. No guarantee can be made that it does not occur for other terms.

References:

Ref 1: Friction Factors for Pipe Flow. – Lewis F Moody, Princeton N.J. Transactions of the ASME November 1944.

Ref 2: Turbulent Flow in Pipes, with particular reference to the Transition Region between the Smooth and Rough Pipe Laws. - Cyril Frank Colebrook 1939 - Journal of the Institution of Civil Engineers (London).

Examples

1. Basic Calculation example.

What is the Discharge in a 525 mm Diameter pipe with a Roughness of 0.6 mm subject to an energy gradient of 5% ?

Enter 525 and press **D** to enter Diameter.

Enter 0.6 and Press **K** to enter Roughness.

Enter 5 and press **S** to enter Slope (gradient).

Press **Q** to calculate Discharge of 1086.82 L/s.

What Diameter change would be necessary to increase the Discharge from 1086 L/s to 2000 L/s while maintaining the same K and S.

Enter 2000 and press **Q** to enter new Discharge.

Press **D** to begin Diameter calculation.

Press **f(Q)** to base the calc on Discharge.

New Diameter is 662.4 mm.

What would the impact on the required energy gradient be if the Diameter is reduced to the nearest standard diameter below the last calculated value ? K and Q are maintained.

Enter new std Diameter of 600 mm and press **D**

Press **S** to begin Slope calculation.

Press **f(Q)** to base calc on Discharge.

The new Slope is determined to be 8.390 % compared to the previous value of 5 %.

2. Laminar Flow example.

What is the maximum Discharge that could be conveyed in a 375 mm pipe while being reasonably confident that the flow is in the Laminar regime ?

Press **▼** to bring up the Extended Menu.

Press **M2** twice to invoke the -QV mode. (This enables Re and D entry)

Enter 2300 and press **Re** to lock in the Reynolds Number of 2300, being the maximum Re for assured Laminar flow.

Press **▲** to return to the Normal Menu.

Enter 375 and press **D** to enter Diameter.

Press **S** to perform a solution. (Slope = .0000185%)

Press **▼** then **d** then **▲** to return to -R mode.

Press **Q** to reveal the maximum Discharge of 0.77 L/s.

Alternatively after the sixth step:

Press **RCL** and **Q** to reveal calculated Discharge of 0.00077 m^3/s.

3. Uncertain flow regime.

What is the flow regime to be expected in a 25 mm Diameter pipe with a Roughness of 0.25 mm subject to an energy gradient of 0.178 % ?

Enter roughness = 0.25 mm and press **K** to store Roughness.

Enter diameter = 25 mm and press **D** to store Diameter.

Enter gradient = 0.178 % and press **S** to store gradient.

Press **V** to solve for Velocity.

The result is reported as V=0.148m/s Cr.

The Cr code immediately identifies the regime as being Critical zone.

Press **▼** then **Re** to reveal the Reynolds number = 3253, placing the result towards the middle of the Critical zone.

If steps are taken to promote Laminar flow in this case, what reduction potentially could be obtained for the resulting energy gradient?

If at the Normal menu press **▼** to bring up the Extended menu.

Then press **M1** to constrain the calculation to the Laminar flow.

Press **▲** then **S** to calculate the revised energy gradient to be 0.088% for Laminar conditions, down from 0.178% in the nominal Critical zone. In the case of a pumped system, an energy and power reduction in the order of 50% could be indicated.

4. Turbulent flow regime.

What minimum Discharge and associated energy gradient is needed in order to be reasonably confident that the flow regime is in the Turbulent zone (Tr), considering a 150 mm Diameter pipe with a Roughness of 1.5 mm?

Press **▼** then **d** , then **M2** twice to enter -QV mode.

Enter Reynolds number = 4000 and press **Re** to store this lower bound value.

Press **▲** to return to the Normal menu.

Enter Diameter = 150 and press **D** to store.

Enter Roughness = 1.5 and press **K** to store.

Press **S** to perform solution and reveal required gradient of 0.0015%

Press **▼** then **d** then **▲** to return to -R mode.

Press **Q** to reveal the minimum Discharge for assured Turbulent flow.

The minimum Discharge is 0.54 L/s

5. Continuity mode example:

What Diameter and Roughness are required to produce a Discharge of 10 L/s at a Velocity of 1 m/s on a gradient of 2% ?

Press **>** to display **DQV▪** indicating Continuity mode.

Enter 10 & press **Q** to store Discharge.

Enter 1 & press **V** to store Velocity.

Press **D** to calculate Diameter of 112.8 mm that satisfies continuity.

Enter 2 and Press **S** to enter gradient.

Press **K** to calculate the required Roughness of 1.7006 mm.

Press **K | D | Q | S | V** in any order to review results.

Also:

Re = 98981

f=0.0442325

APPENDIX A

Core Equations

$$S = \frac{dH}{L}$$

$$dH = f * \frac{L}{D} * \frac{V^2}{2g}$$

{Re<2300} Laminar Zone – Hagen Poiseuille :

$$f = \frac{64}{Re}$$

{2300<Re<4000} Critical Zone – Linear transition approximation :

$$f = [-202 * r^4 + 58.1 * r^3 - 6.844 * r^2 + 0.961 * r + 0.0121] * \frac{Re - R_1}{R_2 - R_1} + 0.02783$$

{Re>4000} Turbulent Zones – Colebrook White :

$$\frac{1}{\sqrt{f}} = -2 * log_{10}\left[\frac{r}{3.7} + \frac{2.51}{Re * \sqrt{f}}\right]$$

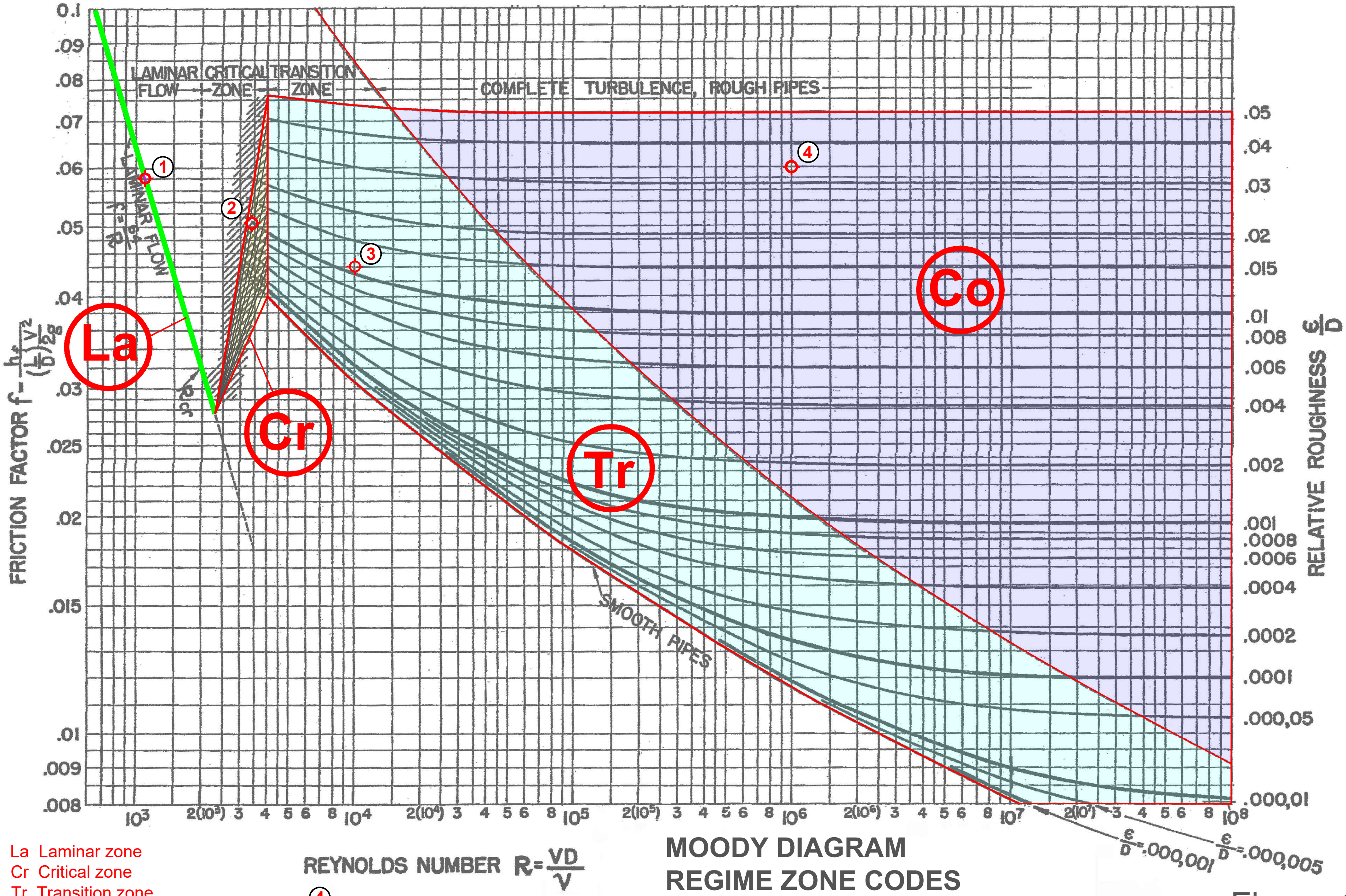
$$r = \frac{K}{D}$$

$$Re = \frac{V * D}{\nu}$$

$$Q = V * A$$

S	Energy Slope / Gradient
dH	Energy head loss
L	Pipe Length
f	Friction Factor
V	Velocity
g	Acceleration due to gravity
D	Diameter
Re	Reynolds number
r	Relative Roughness
R_1	2300
R_2	4000
K	Absolute Roughness
ν	Kinematic Viscosity
Q	Discharge
A	Pipe cross sectional Area

Note: When the M1 modes of *L and *T are invoked the relevant equations are used beyond the ranges indicated above.



La Laminar zone
Cr Critical zone
Tr Transition zone
Co Complete turbulence zone

④ Referred sample data points

MOODY DIAGRAM
REGIME ZONE CODES
REFERENCED BY Moody-42

Figure 1