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A Simplified Pipeline Calculations Program: Liquid Flow (1)

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Abstract— and Program Objective – A multi-functional single screen desktop companion program for piping calculations using Microsoft EXCEL[TM] with its Visual basic for Applications (VBA) automation tool is presented. The program can be used for the following piping geometries – circular, rectangular, triangular, square, elliptical and annular. Fluid properties are obtained from built-in fluid properties functions.

Index Terms— engineered spreadsheet solutions, liquid pipline flow, pipeline design, pipeline fluid properties, piping program, pipeline sizing.

1 Introduction

THE piping designer will often be saddled with the task of designing for different pipe configurations (circular, square ducts, etc.). Conducting such piping designs, can often involve repetitive calculations whether for simple horizontal pipelines or piping of complex terrains. Modern computer- assisted - tools are now often employed as aids in achieving these, if time and cost permits. Often times, for minor changes to existing installations or retrofitting, a customer (pipeline owner) would contract an engineering consultancy to conduct an analysis check that will involve desktop routine calculations such as determining pressure drops, or head loss, flow rate or pipe geometry (diameter, length, cross-sectional area, etc.) that can be assigned to an engineer for quick answers. Simple spreadsheet calculators can be developed to aid such small routine calculations. One such program is shown here with all required equations to assist in developing one.

2 Required General Equations for Incompressible Flow

Reynolds Number:

$$R_e = \frac{\rho V D}{\mu} \quad (1)$$

Flow Velocity:

$$V = \frac{Q}{A} \quad (2)$$

Area:

$$A = \frac{\pi D^2}{4} \quad (3)$$

Head Loss:

$$h_f = \frac{fLV^2}{2gD} = \frac{8fLQ^2}{2\pi^2 g D^5} \quad (4)$$

Friction Factor: The friction factor, *f*, is obtained as follows:

For Laminar Flow: The applicable equations for laminar flows ($R_e \leq 2100$) can be defined in terms of a *laminar flow factor*, L_f, which varies depending on the pipe geometry. The equation is of the form:

$$f.R_e = L_f \quad (5)$$

For Turbulent Flow, the friction factor, *f* is obtained by the Colebrook-White equation

$$\frac{1}{f^{\frac{1}{2}}} = -2Log\left\{\frac{\left(\varepsilon/D\right)}{3.7} + \frac{2.51}{\left(\sqrt{f}\right)R_e}\right\} \quad (6)$$

Flowrate:

For Laminar Flow:

$$Q = \frac{\pi \rho g D^4 h_f}{128 \mu L} \quad (7)$$

For Turbulent Flow:

$$Q = VA \quad (8)$$

$$Q = -0.965D^2\left(\frac{gD^5h_f}{L}\right)^{0.5} Ln\left[\frac{\varepsilon}{3.7D} + \left(\frac{3.17\mu^2L}{gD^3h_f}\right)^{0.5}\right] \tag{9}$$

Range of application: $10^{-6} \leq (\varepsilon/D) \leq 2 \times 10^{-2}$
$3 \times 10^3 \leq R_e \leq 3 \times 10^8$

Solution for Diameter:

$$D^5 = \left(\frac{8fLQ^2}{\pi^2 gh_f}\right) \tag{10}$$

$$D = 0.66\left\{\varepsilon^{1.25}\left[\frac{(LQ^2)}{(gh_f)}\right]^{4.75} + \mu Q^{9.4}\left(\frac{L}{gh_f}\right)^{5.2}\right\}^{0.04} \tag{11}$$

Range of application: $10^{-6} \leq (\varepsilon/D) \leq 2 \times 10^{-2}$
$3 \times 10^3 \leq R_e \leq 3 \times 10^8$

Pressure Drop

$$\Delta P = \gamma h_f = \rho gh_f \Rightarrow \gamma = \rho g \tag{12}$$

Shear Stress in Wall:

$$\tau = \gamma\left(\frac{f}{4}\right)\left(\frac{V^2}{2g}\right) \tag{13}$$

Power required to pump through the line:

$$P_w = Q\gamma h_f = Q\rho gh_f \tag{14}$$

3 Pipe Geometry and Friction factor

3.1 Circular section pipe:

The Laminar Flow factor is defined by the relation:

L_f = Laminar Flow factor = $f.\ R_e = 64$ (15)

For Turbulent Flow, f, is obtained by the Colebrook-White formula, "(6),".

Also, for Turbulent Flow within the limits defined below, explicit values for the friction factor, f is obtained by the Swamee-Jain relationship, "(16),".

$$f = 0.25\left[Log\left\{\frac{(\varepsilon/D)}{3.7} + \frac{5.74}{R_e^{0.9}}\right\}\right]^{-2} \tag{16}$$

Range of application: $10^{-6} \leq (\varepsilon/D) \leq 2 \times 10^{-2}$
$3 \times 10^3 \leq R_e \leq 3 \times 10^8$

The Microsoft Excel ™ Solver Add-in, has two built-in interpolation search solution methods – the Newton method and the Conjugate Gradient method. By rewriting the equation to be solved in the solution form required (see "17,") in the Microsoft Excel™ cells, the Solver Add-in option dialog box under the Tools menu, allows for desired constraints to be set as follows:

Set Target Cell:
Equal To:
Subject to: Guess value:

$$\frac{1}{f^{\frac{1}{2}}} + 2Log\left\{\frac{(\varepsilon/D)}{3.7} + \frac{2.51}{(\sqrt{f})R_e}\right\} = 0 \tag{17}$$

The Microsoft Excel™ Goal Seek option is also useful.
Furthermore, the solution method provides for limiting the number of iterations, the degree of precision desired and the level of convergence (i.e. the decimal floating points). The error margin involved in the iteration calculation is indicated by the Tolerance percentage. Care should be exercised to avoid a risk of having a circular reference – repeated recalculation of particular cell values as input and output.

Miller [1], suggest that a single iteration will produce a result within 1% of the Colebrook-White formula, if the initial estimate is calculated from the Swamee-Jain equation.

3.2 Noncircular piping sections or ducts

3.2.1 The Concept of Hydraulic Diameter

In determining the flow regime and velocity gradients in a pipeline, the wetted perimeter (the perimeter in contact with the fluid) is the consideration. For non-circular pipes, the Reynolds number is a function of a concept called a hydraulic Di-

ameter, defined as the ratio of the cross-sectional area of the piping section to the wetted perimeter.
The hydraulic diameter is defined such that it reduces to the diameter for the circular pipes (Cengel et. al., "[2],"). It is generally a parameter for generalising fluid flow in turbulent flow. The hydraulic diameter concept does not apply for laminar flow through non-circular pipe sections. The hydraulic diameter for different piping configurations is provided by Engineering Sciences Data Unit (ESDU), [3], [4].

3.2.2 Square section pipe

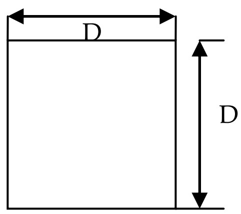


Fig. 1: geometry of square pipe section- *Source*: [3], [4]

$$A = D^2 \qquad (17)$$

$$D_h = D = \text{hydraulic diameter} \qquad (18)$$

For laminar flow, "(5)", is applied, as follows,

$$L_f = \text{Laminar Flow factor} = f.R_e = 14.2 \qquad (19)$$

Thus,

$$f = \frac{14.2}{R_e} \qquad (19a)$$

3.2.3 Triangular pipe section of the Isosceles type

$$A = ½\left(d^2 \sin\theta\right) \qquad (20)$$

$$D_h = \frac{d\sin\theta}{\left[1+\sin\left(\theta/2\right)\right]} \qquad (21)$$

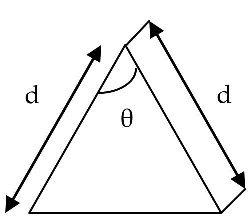


Fig 2: geometry of isosceles triangular pipe section
Source: [3], [4]

The laminar flow factors vary as a function of the isosceles angle, in line with the values in Table 1.
Note that angles falling between those in the table can be obtained by straight line interpolation.

Table 1: Laminar flow factors for Isosceles duct type pipes
Source: ESDU, [3], [4]

θ	$f.R_e$
10	12.5
30	13.1
45	13.3
60	13.3
90	13.2
120	12.7
150	12.5

3.2.4 Rectangular section pipe

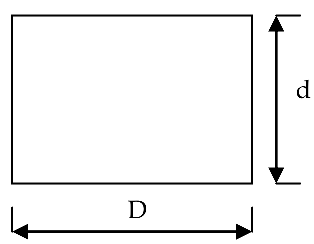


Fig 3: geometry of Rectangular pipe section-*Source*: [3], [4]

$$A = Dd \qquad (22)$$

$$D_h = \frac{2Dd}{(D+d)} \qquad (23)$$

$$f.R_e = 16\left\{0.67 + 0.46\left(\frac{d}{D}\right)\left(2-\frac{d}{D}\right)\right\} \qquad (24)$$

The Laminar flow factor, ($f.R_e$) is defined in terms of the (D/d) ratio by "(24),"

The Variation of Laminar Flow factors for different (D/d) values is as shown in Table 2.

Again, duct side ratios falling between those in the table can be obtained by straight line interpolation.

Table 2: Laminar flow factors for Rectangular duct type pipes
Source: ESDU, [3], [4]

D/d	f.R_e
1	14.2
2	15.8
5	19.2
10	21.1

3.2.5 Elliptical pipe section

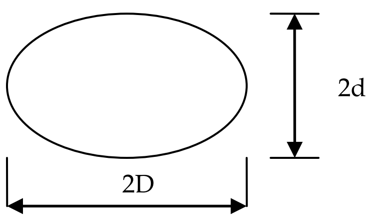


Fig 4: geometry of elliptical pipe section- *Source*: [3], [4]

$$A = \pi D d \qquad (25)$$

Hydraulic diameter,

$$D_h = \frac{4Dd\left(64-16c^2\right)}{\left[(d+D)\left(64-3c^4\right)\right]} \qquad (26)$$

Where, for, 0.1 < (D/d) < 10

$$c = \frac{(D-d)}{(D+d)} \qquad (27)$$

The Laminar flow factor for elliptical pipe sections is obtained from "(28),".

$$f.R_e = \frac{2D_h^2\left(D^2+d^2\right)}{\left(d^2D^2\right)} \qquad (28)$$

3.2.6 Right-angled Triangular pipe section

Laminar flow factors for triangular pipe sections of the right-angled type, for variations in the angle θ, defined by "(31)," is shown in Table 3.

Again, angles falling between those in the table can be obtained by straight line interpolation.

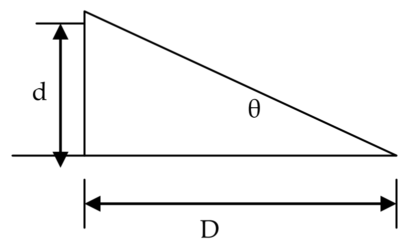


Fig 5: geometry of right-angled triangular pipe section
Source: [3], [4]

$$A = \frac{dD}{2} \qquad (29)$$

$$D_h = \frac{2dD}{\left[d+D+\left(d^2+D^2\right)^{0.5}\right]} \qquad (30)$$

$$\theta = \tan^{-1}\left(\frac{d}{D}\right) \qquad (31)$$

Table 3: Laminar flow factors for Right-angled duct type pipes
Source:ESDU, [3], [4]

θ	f.R_e
10	12.5
30	13.0
45	13.2
60	13.0
70	12.8
90	12.0

4 Fluid Properties Functions

Microsoft Excel™ Functions category (under the Insert menu option) can be used to develop a database of mouse click, drop-down physical properties of typical pumping liquids. Yaws, [5], [6], [7], [8], provides density, viscosity, and vapour pressure data as a function of temperature in line with the mathematical relation, *function*(Temperature), i.e f(T).
For example, [8], derived general curve-fitted density relationships for certain fluid types as functions of reduced temperature. As an example, for Chlorobenzene (C6H6Cl), the following relations for liquid density apply:

$$\rho_L = AB^{-(1-T_r)^{2/7}} \qquad (32)$$

Where the constants are: A= 0.3706, B= 0.2708
T_r is the reduced temperature = T/T_c
T_c = Critical temperature of Chlorobenzene = 359.2°C
The constant terms vary from one fluid type to another.
The liquid density value is in g/cm³. Conversion to kg/m³ can be made in the program by multiplying by 1000.
When developing a fluid properties function data pack in Microsoft Excel™, it is recommended to follow a structured naming convention to allow for an error free process in selection using the drop-down list button. One useful method given by ALIGNAgraphics [9], is:

Name of property_ (temperature)

For water: **rhoWater**(temperature)
viscWater(temperature)

Where r**hoWater**, and **viscWater** are the function names for water density and Liquid viscosity respectively.

5 Writing the Fluid Properties Functions Program

Writing the VBA Module Function code procedure, for example for Chlorobenzene liquid density using "(32)," is of the form:

```
Function rhoChlorobenzene (temperature)
    Tr=T/359.2          'returns reduced temperature value'
    C=(-(1-Tr))^(2/7)          'returns the exponent value'
    rhoChlorobenzene=(0.3706)*(0.2708)^C
End Function
```

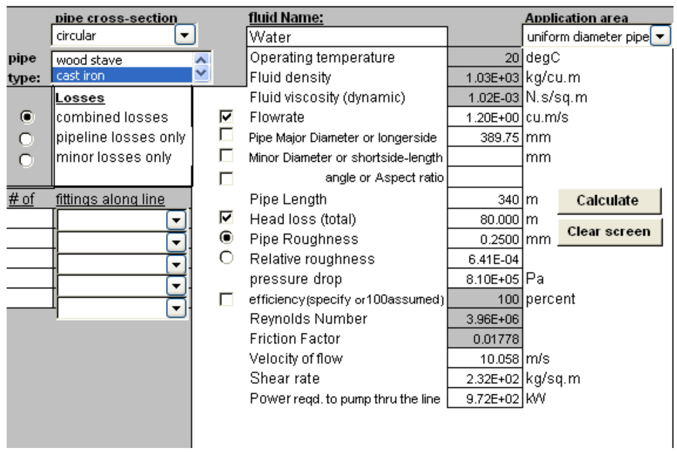
Compared to a VBA subroutine (SUB) procedure, a FUNCTION procedure has a return value. Thus, by entering the function procedure name into a cell, a return value can be obtained by referencing the function dependent cell. In this case the functions are dependent on temperature.

6 Method of Solution and Screen Formatting

The Excel worksheet screen shot shown in Fig. 10 shows link cells with the built in Excel developed formulae. The Interface Excel screen is formatted using the Excel VBA icons which are directly pasted on the sheet. The outputs obtainable for different piping parameter inputs are displayed using the VBA Worksheet subroutine macros shown in the program clip of the Appendix.

7 Program Application Examples

Example 1: Circular Pipes



Water at 20 °C flows through a cast iron pipe at the rate of 1.2 m³/s. The pipe is 340 m long and the head loss through the line is 80 m. What size pipe is required? Also determine the power lost to friction, the pressure drop and the shear rate in the wall?

Fig. 5: A clip of Excel Screen Solution for the Example 1

Example 2: Square Pipe Cross-section

A 350 m long square cross-section duct is used to transport air. Evaluate the pipeline given the following? Take that: Pipe Roughness = 0.008 mm; Air density = 1.22 kg/m³; Viscosity = 1.81×10^{-5} N.s/m², headloss = 35 m; flow rate = 0.5 m³/s.

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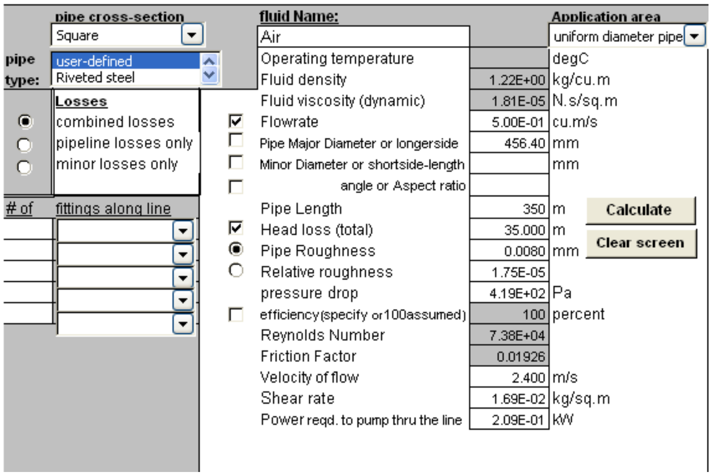
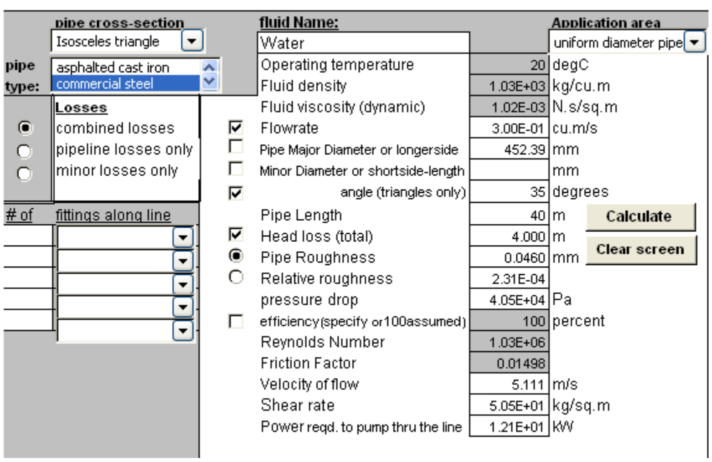


Fig 6: A clip of Excel Screen Solution for the Example 2

Example 3: Triangular Ducts

A 40 m long triangular conduit made of commercial steel is used to carry water at 20 ^{o}C, at the rate of 0.3 m^3/s. If the head loss is 4 m, and the triangular section is shaped in the form of an isosceles triangle with ¸=35^o, find the length of the longest side, x?



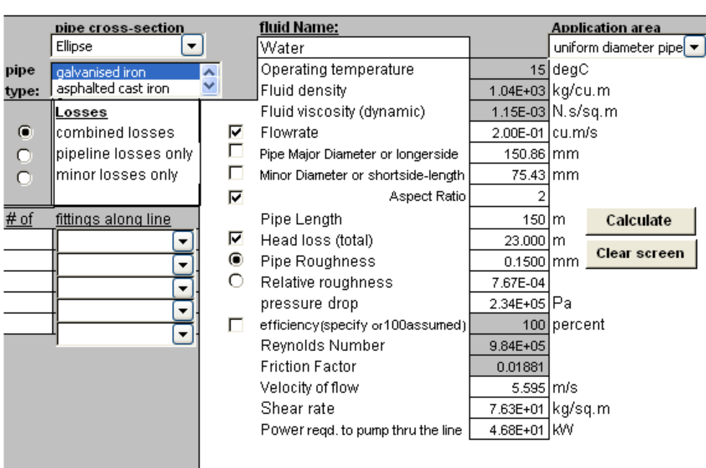


Fig. 7: A clip of Excel Screen solution for the Example 3

Example 4: Elliptical Ducts

A galvanized pipe, elliptical cross-section of 2:1 aspect ratio is used to transport water at 15^{o}C at the rate of 0.2 m^3/s through a 150 m line. If head loss is 23 m, evaluate the pipeline?

Fig. 8: A clip of Excel Screen solution for the Example 4

Example 5: Circular pipe with fittings along line

Ethanol at 20 ^{o}C flows from *tank 1* to *tank 2* at the rate of 0.024 m^3/s through a 100 mm-diameter, 100 m long pipe. Compute the total head loss, if the fittings along the pipe include a 90^o Long Radius Elbow, and a gate valve. (ε/D=0.00065)

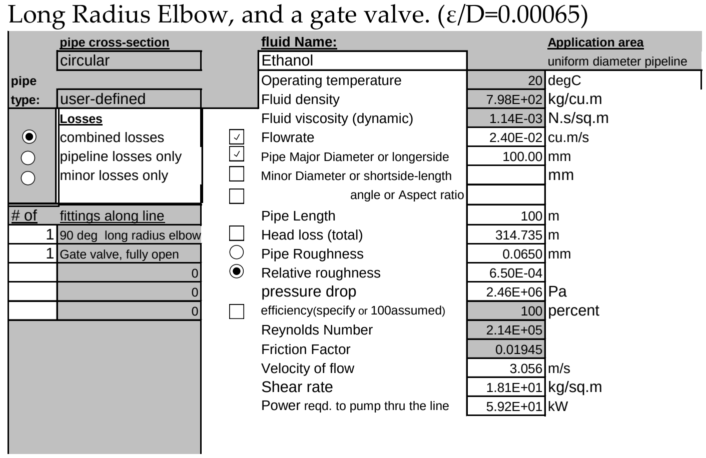


Fig. 9: A clip of Excel Screen solution for Application Example 5 – Pipes with fittings along the line

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solverSolve	solution	reciprocal of sqr. frictionfactor	reciprocal of sqr. frictionfactor
sngRecipfric		7.170320286	7.890194064
Relative Roughness2			
			D=
sngFricfunction		1.26738E-06	-0.747686295
sngFriction		0.019450147	0.016062925
sngFriction for Re>4000			
		circular	circular
		given(Q,D,e/D,L,u,*p*)	given(Q,D,e,L,u,*p*)
PipetypeRougness	0.0650	0.0650	0.0650
RelativeRoughness		0.00065	0.00065
Flowrate		0.02	0.02
Diameter major or LongSide or Dh		100.00	100.00
Diameter minor or ShortSide			
Area		0.00785	0.00785
Velocity		3.06	3.056
Length		100.00	100.00
HeadLoss-total		314.73535	259.9245283
Pipelosses only		9.256922059	7.644839068
Minorlosses		305.478427954	252.279689233
Reynolds Number		213635.3371	213635.3371
FrictionFactor		0.019450147	0.01606
Shear rate		18	15
Power reqd. to pump thru the line		59.15	48.85
efficiency		100	100
pressure drop		2464727.216	2035497.63

Fig. 10: Excel Screen showing Non-Display link Cells with built in formula for Circular pipe section

Nomenclature

P_1	Upstream pressure (kPa).
P_2	Downstream pressure (kPa).
P_w	Power Required (kW)
Q	Flowrate (KN/s).
g	Gravity constant (m/s²).
h_f	Head loss (m or J/kg)
A	Area (m²).
f	Friction factor
D	Pipe Major or Minor diameter (m)
D_h	Hydraulic diameter (m)
L	Pipe section length (m).
V	Velocity of flow (m/s).
ε	Pipe Rougness (mm)
γ	Specific weight (kN/m³).
ρ	liquid density (kN-s²/m⁴).
τ	Shear rate

APPENDIX

A Clip of Microsoft Excel VBA Cells – Link Worksheet Subroutines for Display Interface

```
Sub pipeType()
   If ActiveSheet.Range("M13") = 1 Then
   ActiveSheet.Range("F13") = ""
   ElseIf 2 <= ActiveSheet.Range("M13") And ActiveSheet.Range("M13") <= 10 Then
      ActiveSheet.Range("F13") = ActiveSheet.Range("Q17")
   End If

End Sub

'Perform pipe sizing calculations
'Circular pipeline section calculations
Sub circular()
   Rho = ActiveSheet.Range("F5")
   visc = ActiveSheet.Range("F6")
   D = ActiveSheet.Range("F8")
   d1 = ActiveSheet.Range("F9")
   AspectAngle = ActiveSheet.Range("F10")
   L = ActiveSheet.Range("F11")
'pipe sizing for circular section given relative roughness, headloss unknown
If ActiveSheet.Range("M17").Value = 2 And (ActiveSheet.Range("M6").Value = 1 Or ActiveSheet.Range("M6").Value = 2 Or ActiveSheet.Range("M6").Value = 3) And ActiveSheet.Range("M9").Value = True And ActiveSheet.Range("M10").Value = True And ActiveSheet.Range("M15").Value = 1 Then
   ActiveSheet.Range("F13") = ActiveSheet.Range("R17")
   ActiveSheet.Range("F19") = ActiveSheet.Range("R23")
   ActiveSheet.Range("F17") = ActiveSheet.Range("R28")
  Sheets("incompressible flow").Range("R11").GoalSeek Goal:=0, ChangingCell:=Sheets("incompressible flow").Range("R7")
   ActiveSheet.Range("F18") = ActiveSheet.Range("R29")
   ActiveSheet.Range("F12") = ActiveSheet.Range("R25")
   ActiveSheet.Range("F20") = ActiveSheet.Range("R30")
   ActiveSheet.Range("F21") = ActiveSheet.Range("R31")
   ActiveSheet.Range("F16") = ActiveSheet.Range("R32")
   ActiveSheet.Range("F15") = ActiveSheet.Range("R33")

'same as above but given PipeRoughness not relative roughness
ElseIf ActiveSheet.Range("M17").Value = 2 And (ActiveSheet.Range("M6").Value = 1 Or ActiveSheet.Range("M6").Value = 2 Or ActiveSheet.Range("M6").Value = 3) And ActiveSheet.Range("M9").Value = True And ActiveSheet.Range("M10").Value = True And ActiveSheet.Range("M15").Value = 2 Then

   ActiveSheet.Range("F14") = ActiveSheet.Range("S18")
   ActiveSheet.Range("F19") = ActiveSheet.Range("S23")
   ActiveSheet.Range("F17") = ActiveSheet.Range("S28")
  Sheets("incompressible flow").Range("S11").GoalSeek Goal:=0, ChangingCell:=Sheets("incompressible flow").Range("S7")
   ActiveSheet.Range("F18") = ActiveSheet.Range("S29")
   ActiveSheet.Range("F12") = ActiveSheet.Range("S25")
   ActiveSheet.Range("F20") = ActiveSheet.Range("S30")
   ActiveSheet.Range("F21") = ActiveSheet.Range("S31")
   ActiveSheet.Range("F16") = ActiveSheet.Range("S32")
   ActiveSheet.Range("F15") = ActiveSheet.Range("S33")
'pipe sizing for circular section given relative roughness diameter unknown
   ElseIf ActiveSheet.Range("M17").Value = 2 And (ActiveSheet.Range("M6").Value = 1 Or ActiveSheet.Range("M6").Value = 2 Or ActiveSheet.Range("M6").Value = 3) And ActiveSheet.Range("M9").Value = True And ActiveSheet.Range("M11").Value = True And ActiveSheet.Range("M15").Value = 1 Then
   ActiveSheet.Range("F13") = ActiveSheet.Range("T17")
End If
```

End Sub

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BIOGRAPHICAL NOTES

T. K. Jack is a Registered Engineer, and ASME member. He worked on rotating equipment in the Chemical Fertilizer industry, and on gas turbines in the oil and gas industry. He has Bachelors degree in Mechanical Engineering from the University of Nigeria, and Masters Degrees in Engineering Management from the University of Port Harcourt, and in Rotating Machines Design from the Cranfield University in England. He was the Managing Engineer of a UK Engineering Software Company, ALIGNagraphics and the developer of a Pipeline sizing program, "*PipeDi*". He is a University Teacher in Port Harcourt, Rivers State, Nigeria, teaching undergraduate classes in mechanical engineering. He can be reached by Email: - tonyekjack@yahoo.com