

# USING EXCEL FOR ENHANCING ANALYSIS OF SERIAL PIPING SYSTEMS

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## Introduction

Fluid flow analysis in a piping system is governed by the principle of conservation of energy. Every fluid particle has energy from three sources, namely energy due to pressure, potential energy and kinetic energy. Pumps add energy to the system, and friction takes energy out of the system. Additionally, some piping systems are designed to provide fluid for doing work. Once fluid does work, its energy is reduced.

Friction losses are a function of fluid velocity. Consequently, if the velocity of fluid at every point in the system is known, the energy balance equations can be used to obtain the piping system equations and the number of independent equations and unknowns will be equal and the equations can be solved by standard algebraic techniques.

However, since friction losses are a function of velocity, and velocity is a function of fluid flow rates and pipe sizes, if either the flow rates or the pipe sizes are unknown, there will be more unknowns than number of available independent equations. In such situations the equations cannot be solved by standard algebraic techniques, and iterative techniques must be used that are time consuming if done by classical techniques (hand calculation). Efficient iterative solution of these problems require use of computers.

The theme of this article is to use EXCEL to automate routine labor intensive calculations, and then using the EXCEL files to produce sufficient data points to be able to use the graphical capabilities of EXCEL to solve piping scenarios that require iterative techniques.

The article contains 3 examples. In Example 1, flow velocities are defined and the problem can be solved by the use of a standard algebraic procedure, namely the “N equations and N unknowns” technique. In Examples 2 & 3, flow velocities are not known and standard algebraic solutions are not applicable and EXCEL graphical techniques are used to solve the problems without resorting to iterative techniques.

The examples in this article are limited to serial piping systems. However, the techniques can also be used on parallel piping systems with minor modifications.

It must be emphasized that pumps can cavitate as flow rates decrease and the calculations in this article do not address this condition. This article emphasizes the mathematics of solving fluid flow equations without taking into account pump cavitation considerations.

## Nomenclature

P: Pressure (pound force per square ft).  
Y: Weight density (pound force per cubic ft).  
V: Velocity (ft / sec).  
g: Specific gravity constant ( 32.2 ft / sec<sup>2</sup>).  
Z: Elevation (ft).  
h<sub>A</sub>: Added head by pumping action (ft).  
h<sub>R</sub>: Removed head due to work performed by fluid system (ft).  
h<sub>L</sub>: Head lost due to friction (ft).  
K: Coefficient for determination of head loss due to friction (dimensionless).  
L: Length of straight pipe (ft).  
D: Pipe inside diameter (ft).  
f: Friction factor for straight pipes (dimensionless).  
N<sub>R</sub>: Reynolds number (dimensionless).

$\nu$ : Fluid kinematic viscosity ( $\text{ft}^2/\text{sec}$ ).  
 $\epsilon$ : Pipe material roughness (ft).  
 $Q$ : Rate of fluid flow ( $\text{ft}^3/\text{sec}$ ).  
 $A$ : Cross sectional area of fluid flow ( $\text{ft}^2$ ).  
 $x, y$  &  $N$ : Component data for a second degree polynomial fit.

### Theoretical Background

Flow of fluids in a piping system is governed by the principle of conservation of energy. There are three types of energy associated with a fluid particle at any location in a piping system. They are:

- Energy due to internal fluid pressure.
- Energy due to fluid velocity.
- Energy due to fluid elevation.

Additionally energy can be added to a fluid system by using a pump, and energy is removed from the system when work is done by the system. Furthermore, energy is always lost due to frictional losses. The conservation of energy principle in a piping system can be mathematically represented by equation (1).[1]

$$P_A/\gamma + (V_A^2/2g) + Z_A + h_A - h_R - h_L = P_B/\gamma + (V_B^2/2g) + Z_B \quad (1)$$

Subscripts A and B for P, V and Z represent points of interest in a fluid system.

Figure 1 is an illustration of a fluid system where equation (1) can be applied for system analysis.

Friction losses in a system can be determined by a general relationship shown in equation (2).[1]

$$h_L = K (V^2/2g) \quad (2)$$

Coefficient K in equation (2) for a straight pipe can be determined by equation (3).[1]

$$K = fL/D \quad (3)$$

Flow in a pipe is either classified as laminar or turbulent. The classification is determined by calculating a quantity referred to as Reynolds number for the flow of fluid in a pipe. If the Reynolds number is less than 2000 the flow is

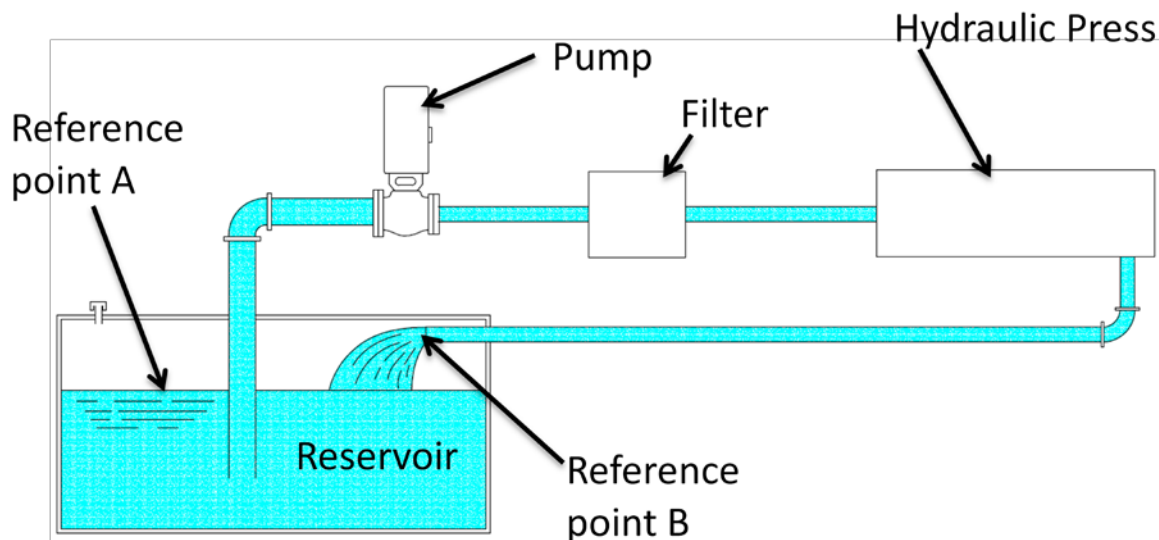


Figure 1: Representation of a fluid system clarifying equation (1)[1].

laminar. Between Reynolds numbers of 2000 and 4000, it is not possible to determine the flow classification. For Reynolds numbers greater than 4000, the flow is turbulent. Reynolds number for flow in a pipe can be determined from equation (4).[1]

$$N_R = VD / \nu \quad (4)$$

By having the relative roughness of a pipe ( $D/\epsilon$ ) and the Reynolds number of fluid flow in a pipe, the friction factor can be read from Moody's diagram. However, use of Moody's diagram is not suitable for computerized analysis of piping systems. In place of Moody's diagram formulas (5) and (6) can be used. Formula (5)<sup>1</sup> is for laminar flow conditions and formula (6)<sup>2</sup> is for turbulent flow conditions. Generally fluid flow is considered to be laminar below a Reynolds number of 2000 and turbulent above a Reynolds number of 4000, and flow condition is unknown between Reynolds numbers of 2000 and 4000. Since the theme of this article is computerized analysis, an unknown region will lead to programming errors. Consequently, an approximate compromise has been chosen by considering flow to be laminar below a Reynolds number of 3000, and turbulent above it.

$$f = 64 / N_R \quad (5)$$

$$f = 0.25 / \{[\log(1 / 3.7 (D/\epsilon)) + (5.74 / N_R^{0.9})]^2\} \quad (6)$$

Fluid flow rate and velocity of flow and cross sectional area of a pipe are related as shown in equation (7).

$$Q = VA \quad (7)[1]$$

The apparent power output by a pump (ignoring pump efficiency) can be calculated by equation (8). The unit of power calculated by equation (8) is in "ft-lb/sec". Dividing "ft-lb/sec" by 550 results in the power being presented in units of Horse Power (HP).

$$\text{Power} = h_A Y Q \quad (8)[1]$$

Exact solutions are not possible for many classes of serial piping systems because there are more unknowns than independent equations. This situation can be addressed by repeating the calculations at frequent assumed conditions by using EXCEL. The results of EXCEL runs can be plotted and polynomial curves can be fitted (interpolated) through the points for selected intervals. Excel can be used for calculating the polynomial equations.

### Examples

There are 3 examples in this article. The examples demonstrate that all fluid systems can be solved by the use of techniques described in section III. The examples will also show that without using a computerized technique such as using EXCEL, the solutions will be time consuming to the point of becoming impossible for moderately complex scenarios.

In all the examples, K values for entrance into tanks and exit from tanks, elbows, valves and sudden enlargement and/or contractions have been obtained from reference [1]. These values are a function of their size and geometry and are not related to fluid flow rate in the system and their values are summarized in various hydraulics handbooks.

#### Example 1:

For the system shown in Figure 2, calculate the vertical distance between the surfaces of the two reservoirs when fluid flows from A to B at a rate of 0.03 ft<sup>3</sup>/sec (13.47 gallons per minute). The inside diameter of the 3 inch pipe is assumed to be 3 inch and the inside diameter of the 6 inch pipe is assumed to be 6 inch. The total length of 3 inch pipe is 330 ft and the total length of the 6 inch pipe is 990 ft. Fluid kinematic viscosity is assumed to be 14X10<sup>-6</sup> ft<sup>2</sup>/sec.

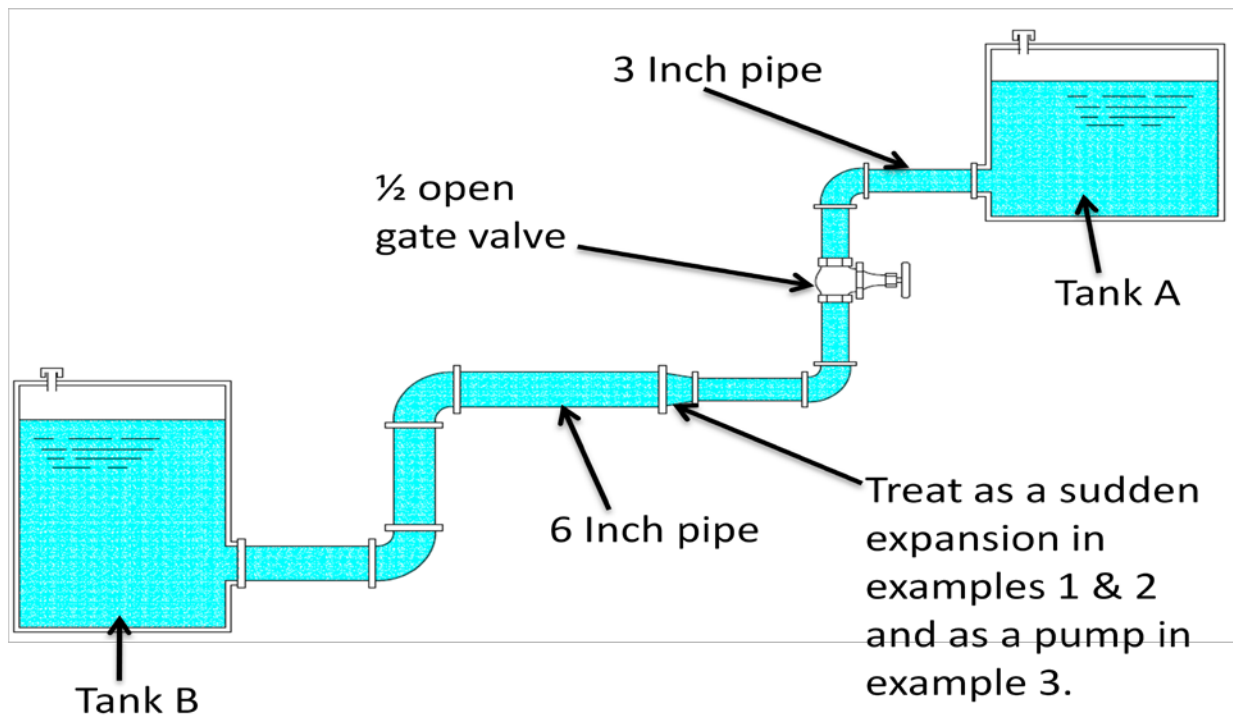


Figure 2: schematic diagram of examples 1, 2 & 3 (not to scale)[1].

Solution:

The energy balance relationship shown in formula (1) can be used to determine the required height difference between fluid surfaces. Since the velocities at points A and B are approximately zero, the velocity terms drop out. Since the pressures in both tanks are atmospheric, the pressure terms drop out. Consequently, the required height turns out to be the total lost head which is the sum of the head losses in the 3 inch and the 6 inch sections of the piping system.

Head loss in the straight portion of pipe is a function of pipe roughness, pipe diameter and Reynolds number. Reynolds number is a function of fluid properties, flow velocity and pipe diameter.

Head losses for entrance from a tank, exit from a tank, elbows, valve and sudden enlargement are constants and not dependent on flow rate. Values of these k coefficients are obtained from reference [1] and they are:

- K for exit from a tank = 0.5
- K for entrance into a tank = 1.0
- K for 3 inch elbow = 0.54
- K for 6 inch elbow = 0.45
- K for 1/2 gate valve attached to a 3 inch pipe = 2.88
- K for sudden enlargement from a 3 inch pipe into a 6 inch pipe = 0.5625

Value of pipe roughness for coated ductile iron pipe ( $\epsilon$ ) is also taken from reference [1] and it is 0.0004 ft.

By determining the K values for various components in the piping system and using equation (2) for head loss calculation for each component and adding the head loss components, the total frictional head loss can be determined.

The following calculations have been obtained from an EXCEL file that is specifically setup for expediting the calculations for the piping system shown in Figure 2. The constants and formulas discussed earlier are used in the EXCEL file.

*Beginning of EXCEL calculations*

*(Note: Details of the calculations performed by EXCEL are shown in appendix A).*

Inside diameter of 3 inch pipe (inch)=	3
Inside diameter of 6 inch pipe (inch)=	6
Length of 3 inch pipe (ft)=	330
Length of 6 inch pipe (ft)=	990
K for exit from tank A=	0.5
k for 3 inch elbow =	0.54
k for 6 inch elbow =	0.45
K for sudden enlargement from 3 inch pipe to 6 inch pipe =	0.5625
K for entrance into tank B=	1
Cross sectional area for 3 inch pipe (square feet)=	0.0490625
Cross sectional area for 6 inch pipe (square feet)=	0.19625
Fluid flow rate (cubic feet per second) =	0.03
Velocity of fluid flow in 3 inch pipe (ft/sec)=	0.611464968
Velocity of fluid flow in 6 inch pipe (ft/sec)=	0.152866242
ε for coated ductile iron pipe (ft)=	0.0004
Fluid viscosity (square feet/ sec) =	0.000014
Reynolds number for 3 inch pipe =	10919.01729
Reynolds number for 6 inch pipe =	5459.508644
f for 3 inch pipe=	0.032977148
f for 6 inch pipe=	0.037900659
K value for straight portion of 3 inch pipe=	43.52983543
K value for straight portion of 6 inch pipe=	75.04330559
K value for 1/2 open gate valve attached to a 3 inch pipe=	2.88
Total k for 3 inch part of piping system excluding the pipe itself consists of sum of "K for exit from tank A" + "K for 1/2 open gate valve" + "K for 2 '3 inch' elbows" + "k value for sudden enlargement"	5.0225
Total k for 6 inch part of piping system excluding the pipe itself consists of sum of "k for entrance into tank B" + "K for 2 '6 inch elbows' =	1.9
total head loss for 3 inch pipe portion (ft)=	0.281882048
total head loss for 6 inch pipe portion (ft)=	0.027919533

*End of EXCEL calculations*

Required vertical distance (ft) = Total head loss for 3 inch section (ft) + Total head loss for 6 inch section (ft) = 0.28188 + 0.027919 = 0.31 ft

Discussion of Example 1:

The implementation of the formulas shown is time consuming without the use of EXCEL. However, for a scenario such as Example 1

where the flow rate is defined this task is possible. However, the task becomes very time consuming for a problem similar to Example 1 if the flow rate is to be calculated for a given height. The reason for the additional complexity resulting from the unknown flow rate is that the losses are a function of the velocity in the piping system, and the velocity is a function of flow rate. Consequently, there will be more unknowns than the number of available

equations and iterative procedures must be used to arrive at a solution. However, by using the EXCEL file created for Example 1, a table of heights versus flow rates can be quickly generated, and then a plot of height versus flow rate can be created. The combination of the table and plot will define the system performance.

Example 2:

Create a table of height difference and flow rate for the system of Example 1. Use the table to obtain an approximate formula relating fluid flow rate to fluid height difference (HD).

Solution:

The EXCEL file created for Example 1 can be used to perform the calculations quickly. Table 1 is showing the flow rates corresponding to the height difference between fluid top surfaces for the piping system shown in Figure 2. The EXCEL file of Example 1 is used to create Table 1. Figure 3 is a plot of data in Table 1. Such tables and figures can be used to determine flow rates for conditions that do not have a closed form solution because there are more unknowns than independent equations. Use of such graphical techniques eliminate the need for iterative hand calculation or computerized iterative techniques.

Equation (9) is a second degree polynomial relationship that has been calculated for the data of table 1 using EXCEL.

$$Q = -5 (10)^{-6} (HD)^2 + 0.0021 (HD) + 0.0249$$

(9) (HD in inches)

Figure 4 shows the data of Table 1 and the results obtained from equation (9) on the same plot. Figure 4 shows that the equation determined by the second degree polynomial

curve fitting technique closely resembles the piping system behavior.

Table 1

Flow rate versus surface height difference for the piping system of Figure 2.

Height difference between points A & B (Inch)	Flow rate (ft <sup>3</sup> /sec)
0	0
0.5	0.01
1.8	0.02
3.7	0.03
6.3	0.04
9.4	0.05
13.2	0.06
17.5	0.07
22.4	0.08
28.0	0.09
34.1	0.10
40.8	0.11
48.0	0.12
55.9	0.13
64.3	0.14
73.3	0.15
82.9	0.16
93.1	0.17
103.8	0.18
115.1	0.19
127.0	0.20
139.5	0.21
152.5	0.22
166.1	0.23
180.3	0.24
195.0	0.25

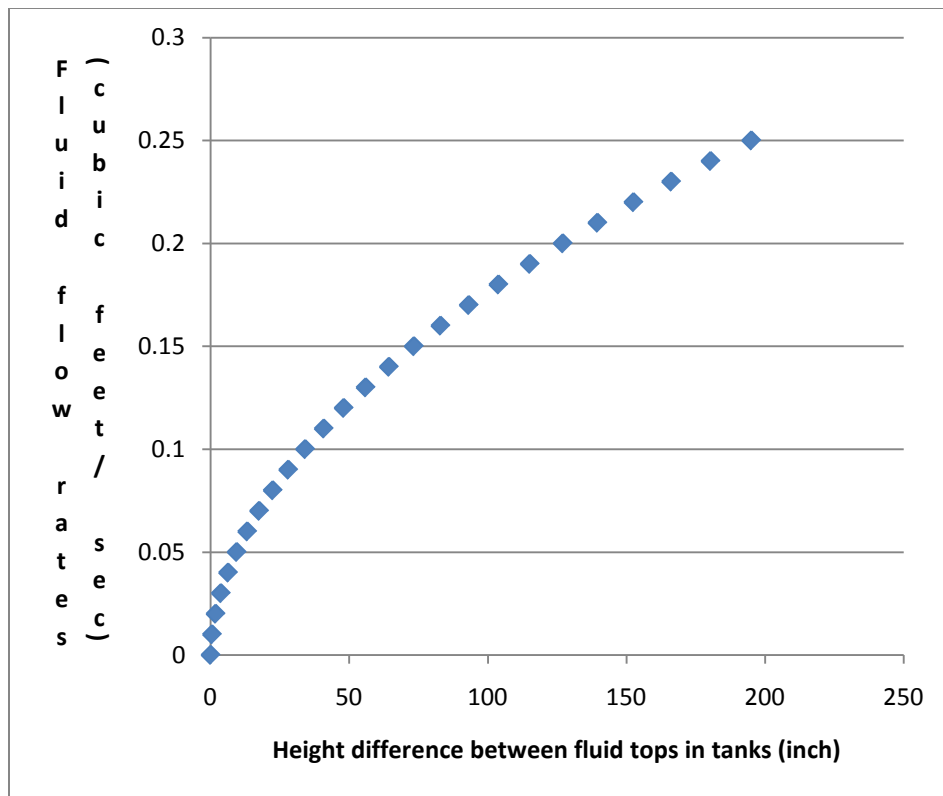


Figure 3: Plot of data of Table 1.

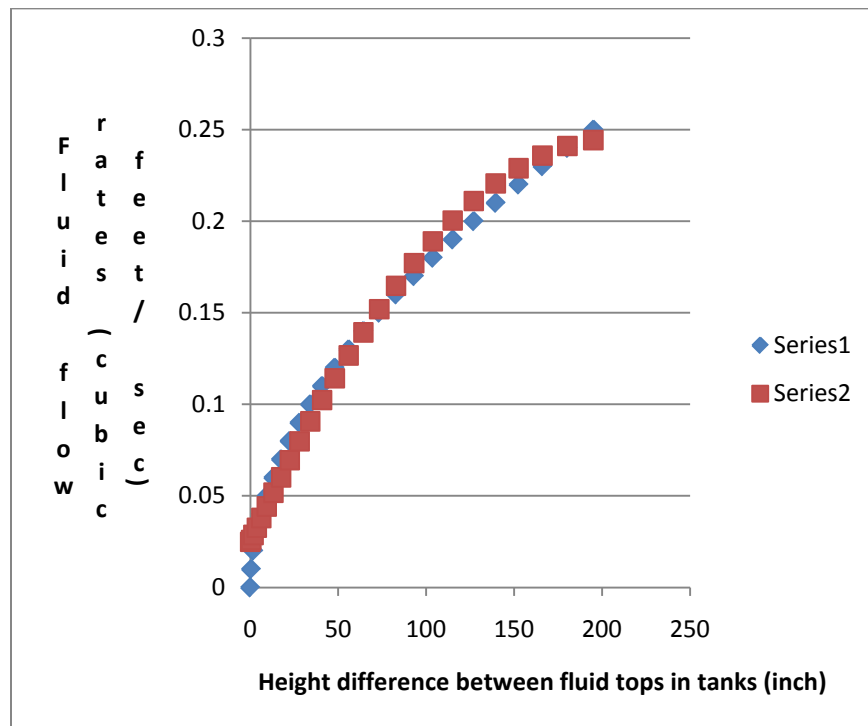


Figure 4: plot of data of Table 1 and second degree polynomial fit for data of Table 1. “Series 1” is a plot of data of Table 1 and “series 2” is a second degree polynomial fit of data of Table 1.

Example 3:

Change the system of Example 1 by replacing the sudden enlargement device by a 3 horse power pump that is used to pump the fluid from tank B into tank A. Assume the fluid surfaces are initially 0.3 ft apart in vertical direction. As pumping continues fluid height in tank B decreases resulting in less potential energy helping the pump, and fluid height in tank A increases resulting in more potential energy opposing the pump. Calculate the fluid flow rate as a function of height difference between fluid top levels in tanks A & B.

Solution:

Formula (8) can be used to start the solution.

$$\text{Power} = h_A \gamma Q$$

$$3 \times 550 = (h_A)(62.4)(Q)$$

$$h_A = \text{Friction head loss} + \text{Distance between fluid tops} = h_L + HD$$

$$1650 = (h_L + HD)(62.4)(Q) \quad (10)$$

Equation (10) is the only independent equation available.  $h_L$  and  $Q$  are related. However, there is no general fixed formula for the relation because the relationship is unique for each piping system. Therefore, there are more unknowns than equations.

Since the layout of the piping system of this example is similar to Example 1, the EXCEL file of Example 1 can be used to determine a number of data points relating  $h_L$  and  $Q$ . Table 2 summarizes such results. These results can then be used to establish a relationship (by interpolation) between  $h_L$  and  $Q$  for the piping system. Such a relationship is shown in equation (11).

$$h_L = 236.58 Q^2 + 6.81Q - 0.24 \quad (11)$$

Table 2  
Summary of friction losses as a function of flow rate.

Flow rate (ft <sup>3</sup> /sec)	Friction head losses (ft)
0.05	0.78
0.10	2.83
0.15	6.10
0.20	10.56
0.25	16.21
0.30	23.06
0.35	31.09
0.40	40.31
0.45	50.71
0.50	62.30
0.55	75.07
0.60	89.02
0.65	104.15
0.70	120.47
0.75	137.97
0.80	156.65
0.85	176.51
0.90	197.54
0.95	219.76
1.00	243.16
1.05	267.74
1.10	293.51
1.15	320.44
1.20	348.56

Figure 5 is a plot of data of Table 2 along with results obtained from equation (11). As it can be observed on Figure 5, the interpolation formula of equation (11) is an accurate representation of data for the chosen range of fluid flow.

Equations (10) and (11) can then be combined to get equation (12).

$$26.44 - 237Q^3 - 6.8 Q^2 + 0.24Q = (HD) Q \quad (12)$$

(HD is in feet and Q is in ft<sup>3</sup>/sec)



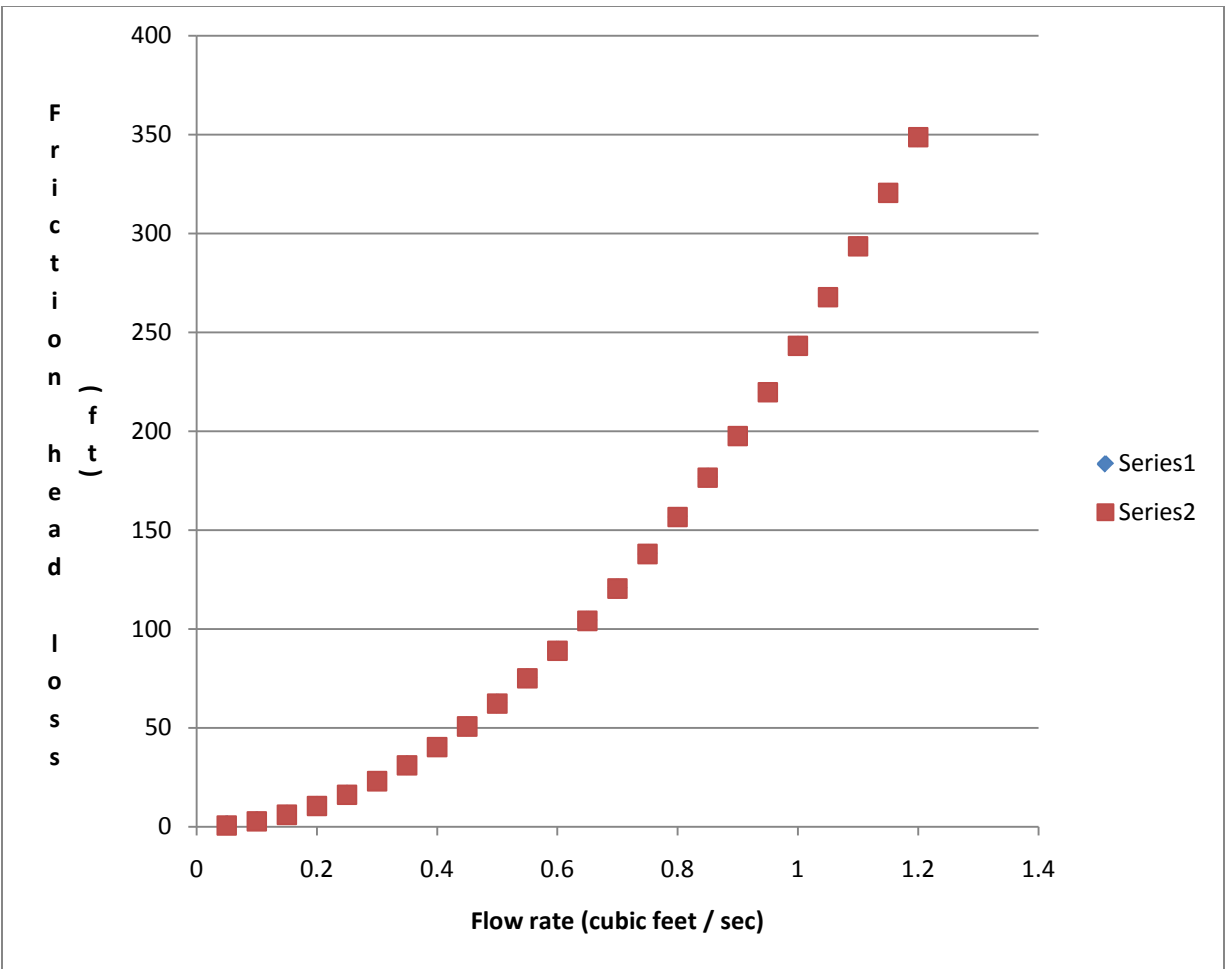


Figure 5: Plot of flow rate versus friction head loss for piping system of Table 2, and the corresponding second degree polynomial fit for data of Table 2 (equation (11)). Series 2 data are from equation (11) and series 1 data are from Table 2. The data from series 1 and 2 are so close that they cannot be distinguished on the plot.

Equation (12) cannot be readily solved in the form of “Q= function (HD)”.

Equation (12) can be rearranged as shown in equation (13).

$$HD = (26.44 - 237Q^3 - 6.8Q^2 + 0.24Q) / Q \quad (13)$$

(HD is in feet and Q is in ft<sup>3</sup>/sec)

Table 3 is the results obtained from equation (13) and Figure 6 is the plot of the data summarized in Table 3. As expected, as the height difference increases, flow rate slows down for a constant power input, and eventually

the pump will not be able to push the fluid in the desired direction.

Figure 7 is a second degree polynomial fit for the data of Table 3. It can be observed that the second degree polynomial fit is not a good one especially for lower flow rates. Figure 8 is a third degree polynomial fit for the data of Table 3. The polynomial fit of Figure 8 is acceptable.

The formula for the third degree polynomial fit of Figure 8 is shown in equation (14). It must be emphasized that equation (14) applies only for the conditions of Example 3. If conditions change, a new formula must be calculated.

Table 3  
Summary of fluid flow as a function of height difference (HD) for piping system of Example 3.

Height difference (ft)	Fluid flow rate (ft <sup>3</sup> /sec)
0.9	0.47
11.4	0.44
22.1	0.41
33.0	0.38
44.4	0.35
56.4	0.32
69.5	0.29
84.1	0.26
101.1	0.23
121.6	0.20
147.8	0.17
183.5	0.14
237.0	0.11
328.7	0.08
528.1	0.05

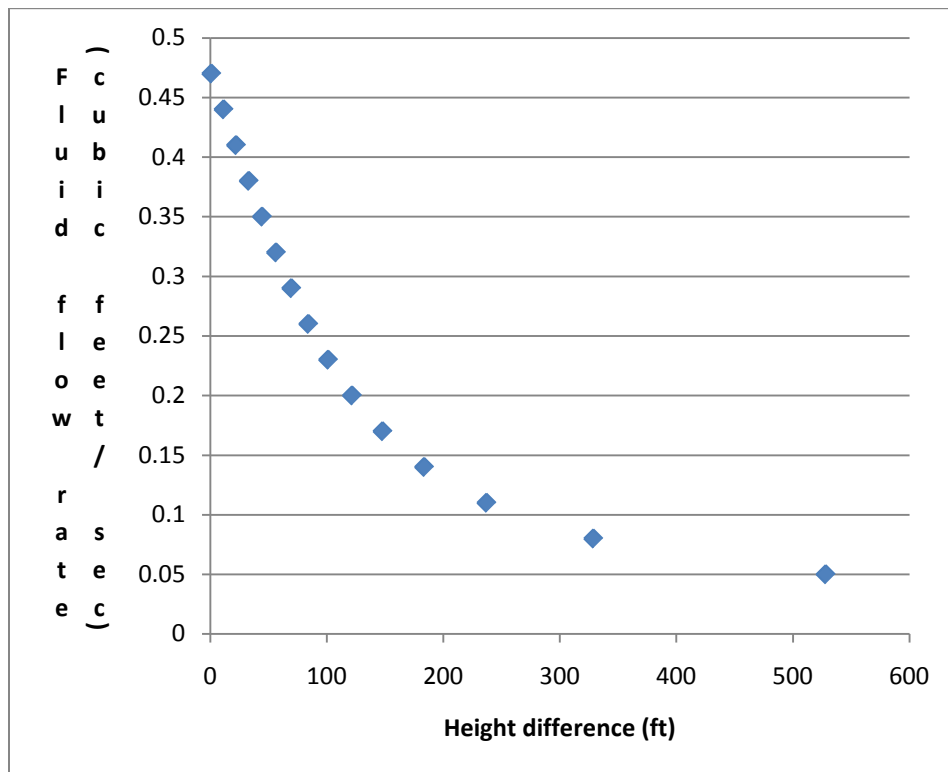


Figure 6: Plot of height difference versus flow rate for data of Table 3.

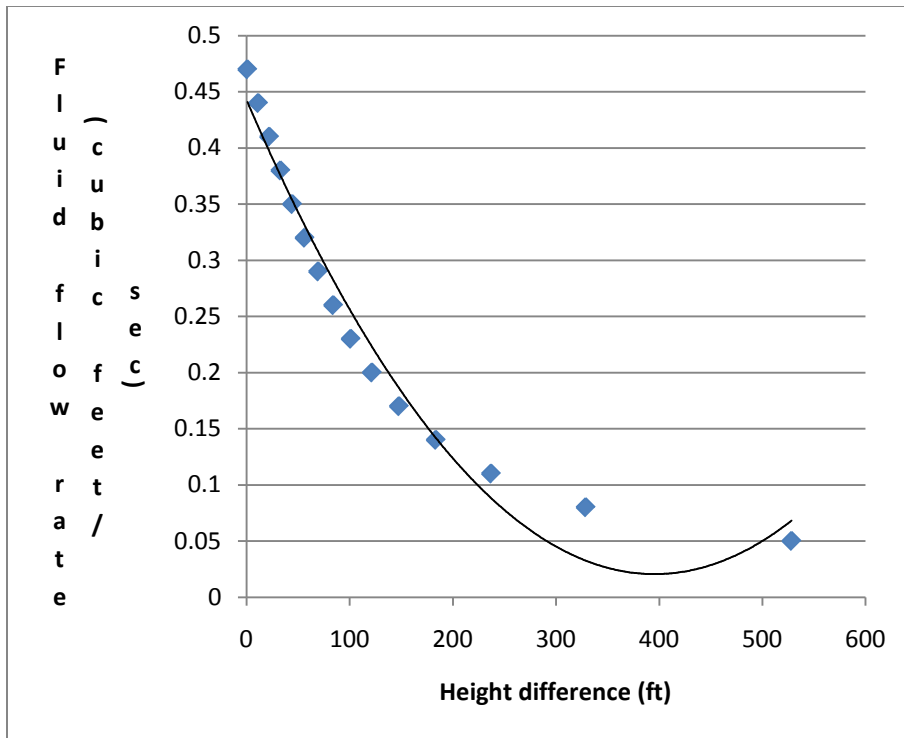


Figure 7: Plot of data of Table 3 along with a second degree polynomial fit.

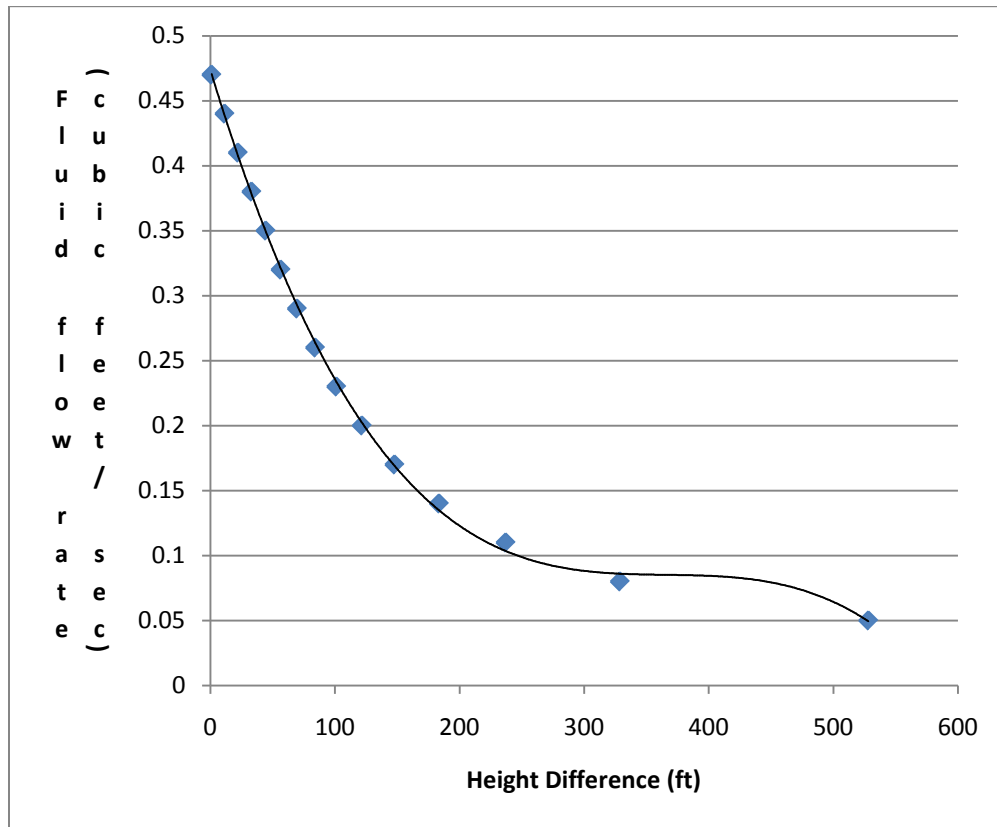


Figure 8: Plot of data of Table 3 along with a third degree polynomial fit.

$$\text{Flow rate} = -(8)(10)^{-9}(\text{HD})^3 + (9)(10)^{-6}(\text{HD})^2 - (0.0032)(\text{HD}) + 0.4733 \quad (14)$$

(Flow rate in equation (14) is in ft<sup>3</sup>/sec & HD is in ft)

### Summary and Conclusion

In this article it was shown that EXCEL can be used to significantly expedite the solution to piping problems that can be solved by classic algebraic techniques, and additionally the EXCEL files can be used to efficiently get sufficient data points for a graphical representation of system performance.

Since frictional losses in a piping system are a function of fluid velocities, there are more unknowns than independent equations when fluid velocities are not known. These problems

require either specialized computer programs or time consuming iterative techniques (hand calculation).

Through the examples presented in this article, techniques for using EXCEL for solving piping problems with unknown velocities are presented. These techniques are efficient replacements for the iterative procedures.

### References

1. Robert Mott, Applied Fluid Mechanics, Sixth Edition.
2. Swamee, P.K. and A.K. Jain, 1976. Explicit Equations for Pipe flow Problems. Journal of the Hydraulics Division 102(HY5): 657-664. New York: American Society of Civil Engineers.

### Appendix A

This appendix contains a step by step calculation presenting all the calculations performed for the EXCEL file of Example 1. Values defined by superscript \* are given.

Inside diameter of 3 inch pipe (inch) = 3\*

Inside diameter of 6 inch pipe (inch) = 6\*

Length of 3 inch pipe (ft) = 330\*

Length of 6 inch pipe (ft) = 990\*

K for exit from tank A = 0.5\*

K for 3 inch elbow = 0.54\*

K for 6 inch elbow = 0.45\*

K for sudden enlargement from 3 inch pipe to 6 inch pipe = 0.5625\*

K for entrance into tank B = 1\*

Cross sectional area for 3 inch pipe (square feet) = (pi) \* (radius of 3 inch pipe in feet)<sup>2</sup> = pi \* (3/24)<sup>2</sup> = 0.0490625

Cross sectional area for 6 inch pipe (square feet) = (pi) \* (radius of 6 inch pipe in feet)<sup>2</sup> = pi \* (6/24)<sup>2</sup> = 0.19625

Fluid flow rate (cubic feet per second) = 0.03\*

Velocity of fluid flow in 3 inch pipe (ft/sec) =

(fluid flow rate (cubic feet per second) / cross sectional area of 3 inch pipe (square feet)) = .03 / .0490625 = 0.611464968

Velocity of fluid flow in 6 inch pipe (ft/sec) =

(fluid flow rate (cubic feet per second) / cross sectional area of 6 inch pipe (square feet)) = .03 / .19625 = 0.152866242

ε for coated iron pipe (ft) = 0.0004\*

Fluid viscosity (square feet / sec) = 0.000014\*

Reynolds number for 3 inch pipe =

$$\{(\text{velocity in 3 inch pipe (ft/sec)} * (\text{Diameter of 3 inch pipe (ft)}) / \text{Fluid viscosity (square ft. /sec)} = (6.11464968 * (3/12)) / .000014 = 10919.01729$$

Reynolds number for 6 inch pipe =

$$\{(\text{velocity in 6 inch pipe (ft/sec)} * (\text{Diameter of 6 inch pipe (ft)}) / \text{Fluid viscosity (square ft. /sec)} = (.152866242 * (6/12)) / .000014 = 5459.508644$$

$$f \text{ for 3 inch pipe} = 0.25 / \{[\log (1 / 3.7 (\text{Diameter of 3 inch pipe (ft)} / \epsilon (\text{ft}))) + (5.74 / (\text{Reynolds no of 3 inch pipe}^{0.9}))^2]\} = 0.25 / \{[\log (1 / 3.7 (3/12) / 0.0004)) + (5.74 / 10919^9)]^2\} = 0.032977148$$

$$f \text{ for 6 inch pipe} = 0.25 / \{[\log (1 / 3.7 (\text{Diameter of 6 inch pipe (ft)} / \epsilon (\text{ft}))) + (5.74 / (\text{Reynolds no of 6 inch pipe}^{0.9}))^2]\} = 0.25 / \{[\log (1 / 3.7 (6/12) / 0.0004)) + (5.74 / 5459^9)]^2\} = 0.037900659$$

K value for straight portion of 3 inch pipe =

$$\{(f \text{ for 3 inch pipe}) * (\text{length of 3 inch pipe})\} / \text{diameter of 3 inch pipe (ft)} = (0.0329977148 * 330) / (3/12) = 43.52983543$$

K value for straight portion of 6 inch pipe =

$$\{(f \text{ for 6 inch pipe}) * (\text{length of 6 inch pipe})\} / \text{diameter of 6 inch pipe (ft)} = (.037900659 * 990) / (6/12) = 75.04330559$$

K value for ½ open gate valve attached to a 3 inch pipe = 2.88\*

Total K for 3 inch part of piping system excluding the pipe itself consists of sum of “K for exit from tank A” + “K for ½ open gate valve” +

“K for 2 ‘3 inch’ elbows + “K value for sudden enlargement” =

$$0.5 + 2.88 + (2 * 0.54) + 0.5625 = 5.0225$$

Total K for 6 inch part of piping system excluding the pipe itself consists of sum of “K for entrance into tank B” + “K for 2 ‘6 inch elbows’ =

$$1 + (2 * 0.45) = 1.9$$

$$\text{Total head loss for 3 inch pipe portion (ft)} = \{(\text{‘K for straight portion of 3 inch pipe’} + \text{‘K for non straight portion of 3 inch pipe’) * (\text{velocity in 3 inch pipe in feet per second})^2\} / (2 * 32.2) = \{(43.52983543 + 5.0225) * 0.611464968^2\} / (2 * 32.2) = 0.281882048$$

$$\text{Total head loss for 6 inch pipe portion (ft)} = \{(\text{‘K for straight portion of 6 inch pipe’} + \text{‘K for non straight portion of 6 inch pipe’) * (\text{velocity in 6 inch pipe in feet per second})^2\} / (2 * 32.2) = \{(73.04330559 + 1.9) * 0.152866242^2\} / (2 * 32.2) = 0.027919533$$

## Biographical Information

Dr. Hagigat is an associate professor in the college of engineering of University of Toledo, and he is teaching engineering technology courses. Dr. Hagigat has an extensive industrial background, and he is continuously emphasizing the practical applications of engineering material covered in a typical engineering technology course.