

**Piping Networks**  
**Computer Project Number One**

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## Table of Contents

List of Figures and Tables.....	ii
Project Description.....	1
Project Objectives.....	2
Report Requirements.....	2
Problem Formulation.....	3
Node and Line numbering.....	6
Solution Strategy.....	8
Assumptions.....	9
Physical Properties and Base Case Parameters.....	10
MATLAB Requirements.....	11
Project Requirements.....	12
Appendix I. Nomenclature.....	13
Appendix II. Documentation for MATLAB code, “piping_network.m”.....	14
References.....	16

**List of Figures**

Figure 1. Sample piping network schematic.....	1
Figure 2. Lines involved in mass balance around node b.....	3
Figure 3. Nodes involved in the mechanical energy balance over pipe j.....	3
Figure Four. Node and Pipe numbering (odd number of rows case).....	6
Figure Five. Node and Pipe numbering (even number of rows case).....	7

## I. Problem Description

We wish to model the flow behavior of a piping network, using material balances and mechanical energy balances. Our fluid is incompressible, so the density is constant and we do not need to consider changes in temperature. The piping network of interest is a rectangular grid of pipes with outlets at each intersection, as we might find in (i) the fire-protection sprinkler system of a building, or (ii) the lawn-maintenance sprinkler system of a yard. A sample piping network schematic with 3 rows and 4 columns of sprinklers is shown below. The lines represent pipes and the circles represent nodes, intersection of two or more pipes.

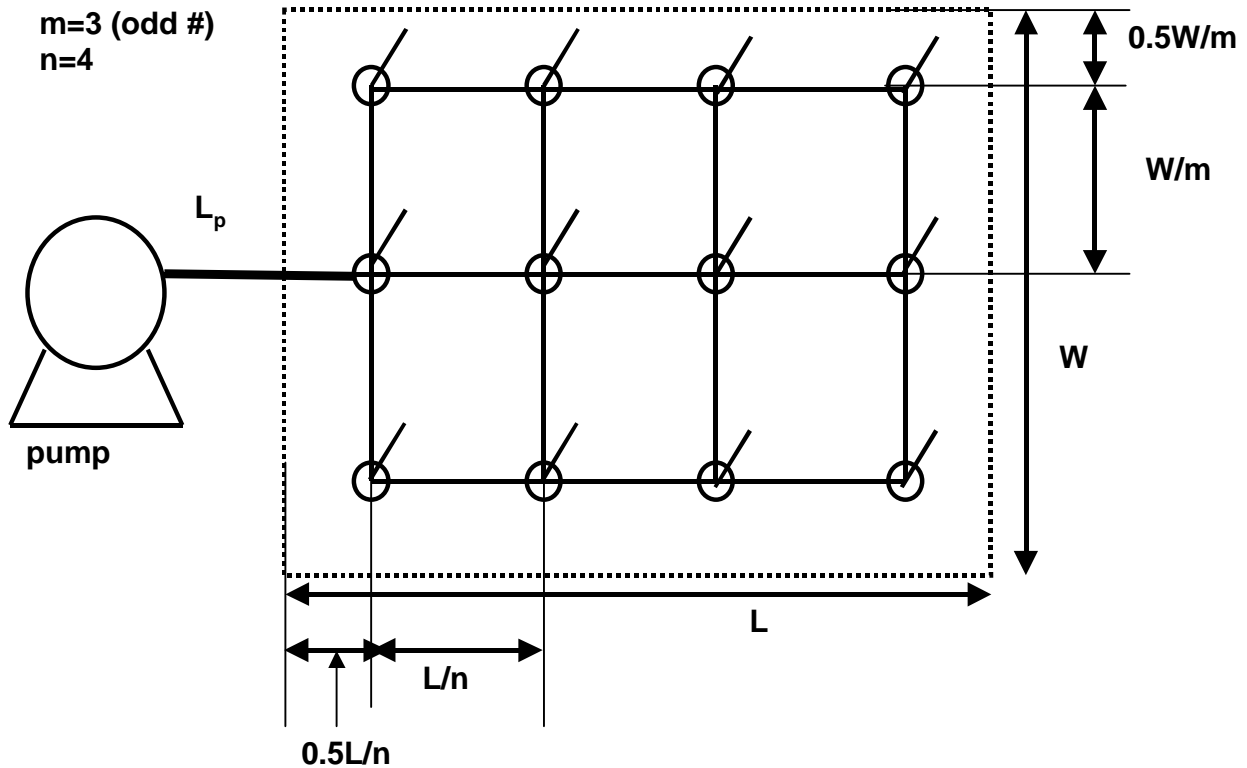


Figure 1. Sample piping network schematic.

## II. Project Objectives

The objectives of this project are

- (1) Write material and mechanical energy balances which describe this system. (In other words to properly pose the problem.)
- (2) Use a MATLAB routine to solve the system of algebraic equations arising from the system of steady state material and mechanical energy balances.
- (3) Identify the (i) pressure at each node, (ii) the mass flow through each pipe, and (iii) the Reynolds number in each pipe.
- (4) Modify and use the MATLAB code to fit the pipes and/or size the pump to obtain various design specifications, such as minimum mass flow through each of sprinkler heads.

## III. Report Requirements

The project requires a typed report. A collection of papers including MATLAB routines, plots, and numbers stapled together is unacceptable.

The report should follow the “Writing Guidelines for ChE 310 & 410” as composed by Dr. Weber and Dr. Bruns. If you do not have a copy of the handout, it is posted on the web at <http://clausius.engr.utk.edu/che310/index.html> . That procedure should be followed as closely as possible. Where the word “experimental” occurs in the report, substitute “numerical”, such as “experimental methods” becomes “numerical methods” for this project.

Some features of the “Writing Guidelines for ChE 310 & 410” will not apply to this project. In that case, use your common sense and omit sections where necessary.

Briefly, the following components from the “Writing Guidelines for ChE 310 & 410” are required:

1. Title Page
2. Table of Contents, List of Figures, and List of Tables
3. Summary
4. Introduction and Background
5. Experimental Methods or Numerical Methods
6. Results and Discussion
7. Conclusions
8. Nomenclature (if at all different from the nomenclature used in this handout)
9. Literature cited (if references beyond this handout were used)
10. Appendices (This is where MATLAB routines would go.)
11. Figures

You do not need to attach a copy of this handout to the report. The report need not be wordy. Short and sweet is best. You do not need to repeat the derivations given in this handout.

#### IV. Problem Formulation

For a piping network system, as shown in Figure One, we have several choices as how to proceed with our analysis. The procedure outlined here is one promoted by the late Dr. Gerald B. Westermann-Clark of the Chemical Engineering Department at the University of Florida. This procedure is based on the concept of Kirchoff's First Law, (as taken from electrical engineering). Kirchoff's First Law states that, "The net mass flow-rate into a node is zero." This is equivalent to saying that in our generalized material balance, namely,

$$\text{accumulation} = \text{in} - \text{out} + \text{generation} - \text{consumption}$$

that there are no accumulation terms (we make the steady-state assumption) and there are no generation or consumption terms (we assume there is no chemical reaction in the system). Both of these assumptions are reasonable for a sprinkler system.

If we apply Kirchoff's First Law to a given node, b, as shown in Figure Two, we have that the sum of the mass flow-rates must be zero. We sum over all pipes, j, which connect from a dummy node a to the node of interest, b.

$$\sum_{j \text{ a} \rightarrow \text{b}} \dot{m}_j = \sum_{j \text{ a} \rightarrow \text{b}} \rho \bar{v}_j A_j = 0 \quad (1)$$

See the nomenclature section for the definition of each variable. We must apply Kirchoff's First Law to each and every node, where a node is defined to be any point where two or more pipes join.

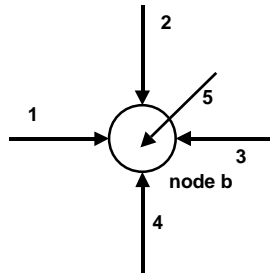


Figure 2. Lines involved in mass balance around node b.

For flow in a single pipe j between nodes a and b, as shown in Figure Three, the mechanical energy balance is as follows:

$$\frac{(P_b - P_a)}{\rho} + g(Z_b - Z_a) + h_j = 0 \quad (2)$$

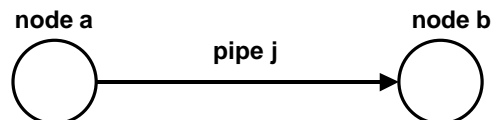


Figure 3. Nodes involved in the mechanical energy balance over pipe j

The frictional head-loss in pipe  $j$ ,  $h_j$ , has units of [energy/mass or length<sup>2</sup>/time<sup>2</sup>]. It is defined as the sum of all frictional components in the pipe, including friction due to the pipe wall, as well as friction due to expansions, contractions, T's, and bends in the pipe. In general,  $h_j$  has the form:

$$h_j = \left[ \frac{4f_j L_j}{D_j} + (\sum k)_j \right] \left( \frac{\bar{v}_j^2}{2} \right) \quad (3)$$

where the first term accounts for friction due to the pipe wall and the remaining summation accounts for all expansions, contractions, T's, and bends.

We can make the substitution:

$$K_j = \left[ \frac{4f_j L_j}{D_j} + (\sum k)_j \right] \quad (4)$$

so that

$$h_j = K_j \left( \frac{\bar{v}_j^2}{2} \right) \quad (5)$$

It is going to prove useful to define a quantity,  $Q_b$ , for node  $b$ , as

$$Q_b = P_b + \rho g Z_b \quad (6)$$

For computation simplicity, we define  $B_j$ , for pipe  $j$ , as

$$B_j = \frac{2\rho A_j^2}{K_j} = \frac{2\rho \left( \pi \frac{D_j^2}{4} \right)}{\left[ \frac{4f_j L_j}{D_j} + (\sum k)_j \right]} \quad (7)$$

In this case, the mechanical energy balance of equation (2) becomes:

$$|\Delta Q_j| = |Q_a - Q_b| = \frac{\dot{m}_j^2}{B_j^2} \quad (8)$$

We can solve explicitly for the mass flow rates

$$\dot{m}_j = B_j \sqrt{|\Delta Q_j|} X_{ba} \quad (9)$$

where

$$X_{ba} = \frac{Q_a - Q_b}{|Q_a - Q_b|} \quad (10)$$

The factor,  $X_{ba}$ , takes either the value of 1.0 or -1.0. It is included to get the direction of flow right. If  $X_{ba} = 1.0$ , flow goes from node a to node b. If  $X_{ba} = -1.0$ , flow goes from node b to node a. If there is no flow in line j, reaching from node a to node b, then  $X_{ba} \equiv 0$ .

Substituting equation (9) in for  $\dot{m}_j$  in the mass balance, equation (1), yields

$$\sum_{\substack{j \\ a \rightarrow b}} B_j \sqrt{|\Delta Q_j|} X_{ba} = 0 \quad (11)$$

Equation (11) is a function only of the pressure,  $P_j$  and elevation,  $Z_j$ , of each node. There is no longer a velocity or mass flow in equation (11).

The point of this derivation has been reached. We have one mass balance of the form of equation (11) for each node. These equations contain one pressure unknown variable (contained in  $Q$ ) for each node. Thus, we have a system of equations and unknowns that is properly posed and solvable. Once the  $Q$ 's and pressures are determined from equation (11), we can determine the mass flow rates and velocities from the mechanical energy balances of equation (9).



**V. Node and Line numbering**

Systematic numbering of lines and nodes is essential. Here is a recommended recipe for node numbering of a system. The nodes are numbered in italicized black figures. The lines are numbered in ordinary red numbers. The variables  $m$  and  $n$  are the number of rows and columns of sprinkler heads, respectively.  $W$  and  $L$  are the width and length of the area to be sprayed by the sprinkler system.

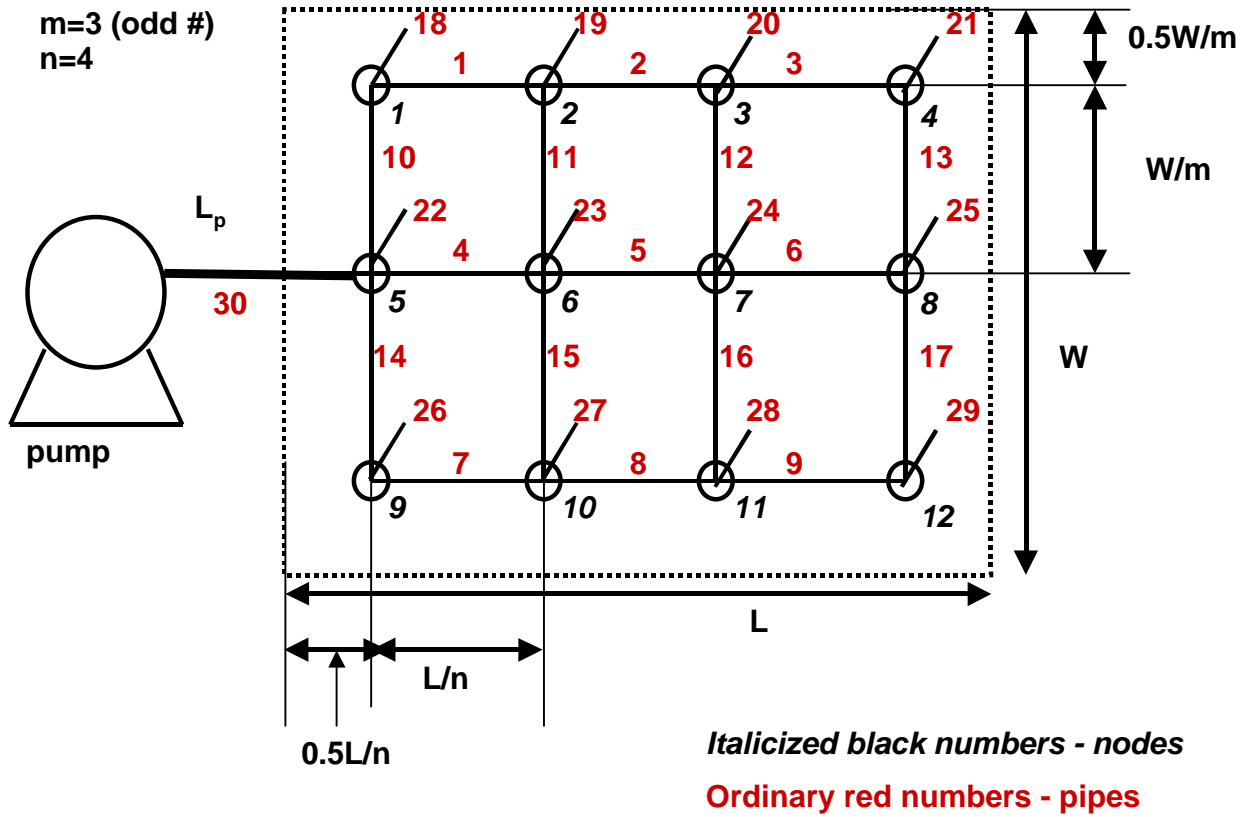


Figure Four. Node and Pipe numbering (odd number of rows case)

For the case where,  $m$  is an odd number of rows, we have

$$N_{\text{nodes}} = m \cdot n$$

$$N_{\text{pipes}} = (m - 1) \cdot (n - 1) + N_{\text{nodes}} + 1$$

$$N_{\text{pipes}} = 2m \cdot n - m - n + 2$$

The number of pipes includes the horizontal and vertical pipes connecting nodes, numbering  $(m - 1) \cdot (n - 1)$ , the sprinkler outlet pipes coming out of each node, numbering  $m \cdot n$ , and one pipe leading from the pump.

Now consider the case where  $m$  is an even number of rows, as shown in Figure Five. We have

$$N_{\text{nodes}} = m \cdot n + 1$$

$$N_{\text{pipes}} = (m - 1) \cdot (n - 1) + m \cdot n + 1 + 1$$

$$N_{\text{pipes}} = 2m \cdot n - m - n + 3$$

There is an extra node, that occurs at the T, where the pump line meets the rectangular grid. (Compare Figures 4 and 5.) There is an extra pipe where one of the pipes in the rectangular grid has been bisected by the new node. (Again, compare Figures 4 and 5.)

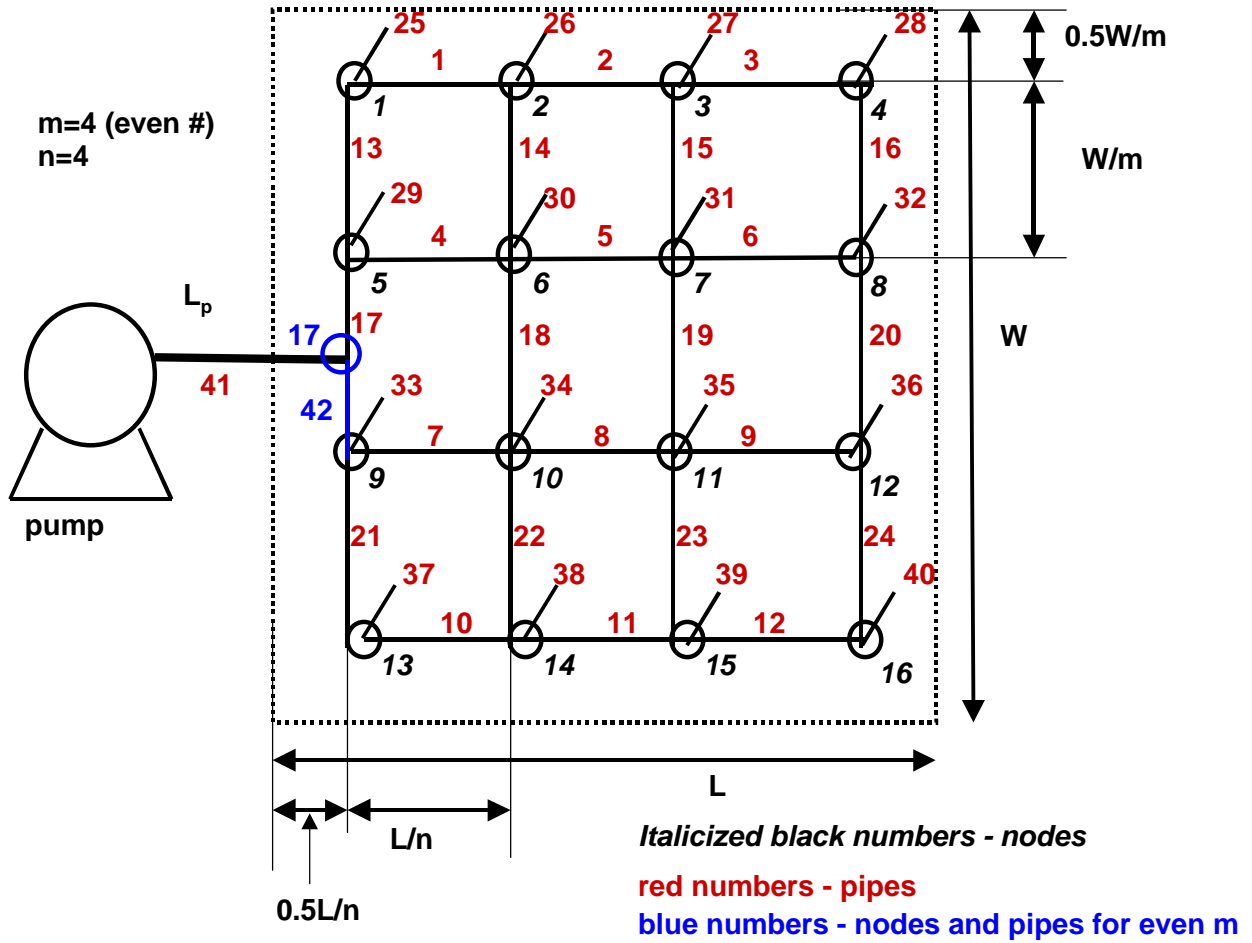


Figure Five. Node and Pipe numbering (even number of rows case)

## VI. Solution Strategy

STEP ONE. Identify number of equations and number of unknowns.

### Equations

- There are mass balances for every node. Therefore you have  $N_{\text{nodes}}$  mass balances ( $N_{\text{nodes}}$  equations)
- There are mechanical energy balances for every pipe. Therefore you have  $N_{\text{lines}}$  energy balances ( $N_{\text{lines}}$  equations)
- There are a total of  $N_{\text{nodes}} + N_{\text{lines}}$  equations.

### Unknowns

- Each node has an unknown pressure. Therefore you have  $N_{\text{nodes}}$  pressure variables,  $\{P_b\}$  for  $b = 1$  to  $N_{\text{nodes}}$ .
- Each pipe has an unknown velocity (or mass flow rate). Therefore you have  $N_{\text{lines}}$  velocity variables,  $\{V_j\}$  for  $j = 1$  to  $N_{\text{lines}}$ .
- There are a total of  $N_{\text{nodes}} + N_{\text{lines}}$  variables.

Since the number of unknowns is equal to the number of equations, you have a properly posed problem, which you can solve. The solution technique required is one which can solve a system of  $N_{\text{nodes}} + N_{\text{lines}}$  coupled, non-linear algebraic equations. MATLAB can do this. But it is still tricky.

STEP TWO. Calculate necessary parameters.

We must know each all the parameters for the problem, including:

- physical properties:  $g, \rho, \mu$
- pipe properties:  $f_j, D_j, L_j, A_j, (\sum k)_j, B_j$  for all  $j$  pipes
- node properties:  $Z_b$  for all  $b$  nodes

STEP THREE. Solve for the variables  $Q_b$ .

We can simplify the problem by first solving the  $N_{\text{nodes}}$  mass balances for the  $N_{\text{nodes}}$  pressure variables contained in the variables  $Q_b$ .

$$\sum_{a \rightarrow b} B_j \sqrt{|\Delta Q_j|} X_{ba} = 0 \quad (11)$$

This is only a system of  $N_{\text{nodes}}$  coupled, non-linear algebraic equations. MATLAB can do this with even greater ease.

STEP FOUR. Solve for pressures.

Once we have  $Q_b$ , we know the pressures via  $P_b = Q_b - \rho g Z_b$

STEP FIVE. Solve for mass flow rates.

Once we have the  $Q_b$ , we can then solve the  $N_{lines}$  mass balances for the  $N_{lines}$  velocity variables contained in the variables  $\dot{m}_j$  via

$$\dot{m}_j = B_j \sqrt{|\Delta Q_j|} X_{ba} \quad (9)$$

STEP SIX. Solve for velocities.

Once we have the  $\dot{m}_j$ , we know the velocities via  $\bar{v}_j = \frac{\dot{m}_j}{\rho A_j}$

STEP SEVEN. Solve for velocities.

At this point, the problem is solved, but if we want the Reynolds number in each pipe, to assure ourselves of either laminar or turbulent flow, we can do that now that we have the velocities,

$$N_{Re,j} = \frac{D_j \bar{v}_j \rho}{\mu} \quad (12)$$

## VII. Assumptions

Our derivation makes the following assumptions.

- (1) The system is at steady-state, so there are no accumulation terms in the mass and mechanical energy balances.
- (2) There are no chemical reactions occurring in the piping network, so there are not generation or consumption terms in the mass and mechanical energy balances.
- (3) The average velocity is calculated and used in each pipe. This amounts to neglecting the kinetic energy term in the mechanical balance equation of equation (2).
- (4) We have assumed turbulent flow in that the friction factor coefficients for contractions and tees have been chosen for turbulent flow.

**VIII. Physical Properties and Base Case Parameters**

fluid viscosity	$\mu = 0.00103$	[kg/m/s]
fluid density	$\rho = 1000$	[kg/m <sup>3</sup> ]
gravitational acceleration	$g = 9.8$	[m/sec <sup>2</sup> ]
diameter of pipes in grid system	$D_s = 1.0$	[inch]
diameter of pipes from pump	$D_p = 4.0$	[inch]
diameter of pipe in sprinkler head	$D_h = 0.5$	[inch]
length of pipes in grid system	$L_s = ?$	[m]
length of pump pipe	$L_p = 4.0$	[m]
length of sprinkler head pipe	$L_h = 0.1$	[m]
elevation of nodes in system	$Z_s = 0.0$	[m]
elevation of pump	$Z_p = 0.0$	[m]
elevation of sprinkler heads	$Z_h = -L_h$	[m]
pressure at pump	$P_p = 4.0$	[atm]
pressure at sprinkler head	$P_h = 1.0$	[atm]
contraction friction coefficients	$k_c = 0.55 \left( 1 - \frac{A_s}{A_L} \right)$	[dimensionless]
sprinkler head friction coefficients	$k_h = 1.0$	[dimensionless]
T friction coefficients	$k_T = 1.0$	[dimensionless]
friction factor of pipe j	$f_j = *$	[dimensionless]

\* obtained from Geankoplis page 88, based on Reynolds Number and a relative roughness of  $\epsilon/D = 0.005$ . (Thus it may be necessary, to iteratively run the simulation, until the Reynolds Number in the simulation and the Fanning friction factor,  $f$ , agree. For this project it is acceptable to use an average Fanning friction factor, for each of the three types of pipes, namely grid pipes, sprinkler head pipes, and the pump pipe.)

## IX. MATLAB Requirements

Students are required to use MATLAB routines to solve the system of algebraic equations arising from the piping network analysis. Students have two options. Either option is perfectly acceptable and neither option is favored by the instructor.

Option 1. Write a MATLAB code from scratch.

- Advantage: Some students feel that they want to write their codes themselves in order to cement their understanding of the project.
- Disadvantage: Major time commitment to programming and debugging a piping network code. Additional time commitment if familiarity with MATLAB is sketchy.

Option 2. Modify and use a pre-existing MATLAB code.

- Advantage: The instructor has written a code which is capable of solving the problems specified in this report. This reduces the time commitment involved in programming and debugging the code. Modifying an existing code may be more feasible for students who are not confident in their MATLAB skills.
- Disadvantage: The student exchanges the time commitment of programming the code to reading and understanding the existing code. The instructor will provide adequate documentation to use the code “as is”. Thus the instructor will not be available for extended tutorials on the use of the code. (This simulates life in research and industry, where as part of a group, you inherit someone else’s code. Frequently, the original author of the code is nowhere to be found. You must be able to decipher the code yourself, with the help of documentation, if there is any, which frequently there is not)
- Disadvantage: There is the temptation, when using a pre-existing code, to try to use the code without opening and studying the code, and thus, without understanding how the code works. Typically, this results in totally useless results from the computer. Be warned: just because the instructor makes this code available does not absolve the student of the responsibility to understand how the code functions and to modify it where necessary.

**X. Project Requirements**

- (1) Solve the case where  $m=1$  and  $n=2$  by hand. Use  $L = 10$  m and  $W = 5$  m. Use  $P_p = 2.00$  [atm].
- Draw a diagram with node numbers and line numbers.
  - Write balance equations.
  - Report pressure at each node.
  - Report velocity, mass flow, and Reynolds number in each pipe.
  - Check your solution with the MATLAB code.
- (2) Using MATLAB, solve the case where  $m=8$  and  $n=9$ . Use  $L = 45$  m and  $W = 40$  m. Use  $P_p = 4.00$  [atm]. Use  $D_h = 0.25$  [in].
- Provide a diagram with node numbers and line numbers.
  - Write equations.
  - Provide a plot of the pressure at each node.
  - Determine whether flow is laminar or turbulent in each pipe.
  - Provide a plot of the mass flow in each sprinkler pipe.
- (3) Using MATLAB, solve the following problems, where  $L = 15$  m and  $W = 30$  m. The fire codes state that a coverage of 1.9 liters of water must be dumped per square meter of the area protected by the sprinkler system per minute. Consider the case where  $m=6$  and  $n=3$ . Use  $P_p = 4.00$  [atm]. Use  $D_h = 0.25$  [in].
- What is average coverage? (Total volume of water dispensed/total area)
  - What is minimum mass flow-rate emerging from any one of the sprinklers?
  - What is the minimum coverage of that sprinkler in liters/m<sup>2</sup>.
  - What is the minimum necessary pressure in the pump line,  $P_p$ , required for the system average to meet the fire code.
  - What is the minimum necessary pressure in the pump line,  $P_p$ , required for each sprinkler to individually meet the fire code.
- (4) Using MATLAB, solve the following problems, where  $L = 12$  m and  $W = 15$  m. A yard sprinkler system can be modeled with the same system as the fire-sprinkler system. We only need to change the sprinkler heads to point up instead of point down. Change  $Z_h = L_h$  instead of  $Z_h = -L_h$ . Consider the case where  $n=4$  and  $m=5$ . (Use all other base case parameters.) However, the distribution of mass-flow rates from the sprinkler heads, vary considerably. You are to change the sprinkler head pipe diameter,  $D_h$ , to achieve no more than 5% (of the minimum flowrate) variation between the minimum and maximum mass flow rates.
- What is largest sprinkler head pipe diameter to use? Use  $P_p = 2.00$  [atm].
- (5) You must design the fire-protection sprinkler system for a room with dimensions  $L = 7.5$  m and  $W = 10.5$  m. If  $P_p = 1.50$  [atm] and  $D_h = 0.25$  [in], determine the minimum number of sprinkler heads,  $n$  and  $m$ , such that the area covered by each sprinkler head receives at least 4.8 liters of water per square meter per minute.
- (6) Using the results and parameters of question (5), simulate plugging of a sprinkler head, by setting the Fanning friction factor to a very large number for:
- one of the interior sprinkler head pipes. Comment on differences with/without plugging.
  - one of the interior sprinkler grid pipes. Comment on differences with/without plugging.

**Appendix I. Nomenclature**

$A_j$	cross-sectional area of arbitrary pipe j	[m <sup>2</sup> ]
$D_h$	diameter of sprinkler head pipes	[m]
$D_j$	diameter of arbitrary pipe j	[m]
$D_p$	diameter of pump pipe	[m]
$D_s$	diameter of sprinkler grid pipes	[m]
$f_j$	Fanning friction factor of pipe j	[dimensionless]
$g$	gravitational acceleration	[m/sec <sup>2</sup> ]
$h_j$	total frictional head loss in pipe j	[J/kg or m <sup>2</sup> /sec <sup>2</sup> ]
$k$	various friction coefficients	[dimensionless]
$K_j$	sum of all friction terms in pipe j	[dimensionless]
$L$	length of total area to be covered by system	[m]
$L_h$	length of sprinkler head pipes	[m]
$L_j$	length of arbitrary pipe j	[m]
$L_p$	length of pump pipe	[m]
$L_s$	length of sprinkler grid pipes	[m]
$m$	number of rows of nodes	[dimensionless]
$\dot{m}_j$	mass flow rate in arbitrary pipe j	[kg/sec]
$n$	number of columns of nodes	[dimensionless]
$N_{lines}$	number of pipes in system	[dimensionless]
$N_{nodes}$	number of nodes in system	[dimensionless]
$N_{Re,j}$	Reynolds number of arbitrary pipe j	[dimensionless]
$P_b$	pressure at arbitrary node b	[Pa]
$P_{out}$	pressure leaving sprinkler head outlet	[Pa]
$P_p$	pressure at pump outlet	[Pa]
$Q_b$	$P_b + \rho g Z_b$ at node b	[Nt/m <sup>2</sup> ]
$\bar{v}_j$	average velocity in arbitrary pipe j	[m/sec]
$W$	width of total area to be covered by system	[m]
$X_{ba}$	$\frac{Q_a - Q_b}{ Q_a - Q_b }$ or 0 if $Q_a = Q_b$	[dimensionless]
$Z_b$	elevation at arbitrary node b	[m]
$\mu$	fluid viscosity	[kg/m/s]
$\rho$	fluid density	[kg/m <sup>3</sup> ]



**Appendix II. Documentation for MATLAB code, “piping\_network.m”**

The code “piping\_network.m” will solve the mechanical energy and mass balances describing a rectangular grid of pipes as developed in the Problem Formulation.

The code is available on the course website. You must download it and unzip it using WinZip. Then you must move to whichever directory you have unzipped the files into. The zipped file contains two MATLAB files, “piping\_network.m” and “pnw.m”. Both are required to run the code. The code is executed by typing at the MATLAB command line interface, for example.

```
» piping_network(2.00*101325,5,10,1,2,0,1)
```

There are seven input arguments. To determine the physical meaning of each argument, you can type from the MATLAB command line interface

```
» help piping_network
```

which displays:

```
piping_network(Pp,W,L,m,n,iprint,iplot)
```

This MATLAB code describes the flow system of a network of sprinklers.

This program requires seven inputs

Pp = pump pressure (Pa)

W = width of area to be covered (m)

L = Length of area to be covered (m)

m = number of sprinklers rows (along width W)

n = number of sprinklers columns (along length L)

iprint = 1 if you want to print out information (0 otherwise)

iplot = 1 if you want to plot results (0 otherwise)

example: piping\_network(2.00\*101325.0,5,10,1,2,0,1)

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Date: January 12, 1999

The code is divided into several sections. Each section is outlined below. Some of the sections MUST be altered to solve the problems assigned. Some of the sections will never be altered.

pipingnetwork.m

Section One. Checks to make sure the correct number of input arguments were given. (No modification by user necessary.)

Section Two. State Problem Specifications. Parameters such as the diameters, elevations, and length of pipe, the density and viscosity of the fluid, and friction coefficients for tees, contractions, and sprinkler heads are defined here. (Modification by the user necessary to fit problem specifications.)

Section Three. Define positions of nodes, based on L, W, m, and n input parameters. (No modification by user necessary.)

Section Four. Define connectivity of nodes. (No modification by user necessary.)

Section Five. Define connectivity of pipes. (No modification by user necessary.)

Section Six. Make initial guesses for node pressures. (No modification by user necessary.)

Section Seven. Calculate  $K_j$  as defined in equation (4). (No modification by user necessary, unless changing friction terms, as will be required in Part (6) of the project, where plugging is simulated.)

Section Eight. Calculate  $B_j$  as defined in equation (7). (No modification by user necessary.)

Section Nine. Calculate potential energy component of  $Q_b$  as defined in equation (8). (No modification by user necessary.)

Section Ten. Solve for  $P_b$  using MATLAB intrinsic routine “fsolve.m” and the file “pnw.m”. (No modification by user necessary.)

Section Eleven. Calculate real  $Q_b$  as defined in equation (8). (No modification by user necessary.)

Section Twelve. Calculate mass flow rates, velocities, and Reynolds numbers. (No modification by user necessary.)

Section Thirteen. Verify conservation of mass. (No modification by user necessary.)

Section Fourteen. Create plots. (No modification by user necessary.)

The code “pnw.m” does not need to be modified.

So, this code can simulate an infinite variety of problems by modifying only the input parameters and Sections Two and Seven from “piping\_network.m”

**All the data generated by “piping\_network.m” is written to the file “piping.dat” The data can be viewed here. However, this file is over-written each time the code is run.**

Notes on error messages. The MATLAB fsolve routine can generate errors. It is no trivial task to solve a system of non-linear algebraic equations. The problem is compounded when we have the intrinsic symmetry of this grid, which causes the convergence path to the set of pressures to have plateaus, where convergence becomes very slow if not impossible. The end result is that MATLAB may generate errors messages when m, the number of rows, is even. These error messages can be ignored if and only if, the verification of the conversation of mass yields acceptably small errors.

## References

1. Westermann-Clark, Gerald B., "Piping Network Calculations", Version 3.2, Department of Chemical Engineering, University of Florida, 32-page document distributed in class for ECH 3203, Chemical Engineering Operations I, Fall Term, 1990, unpublished.
2. Geankoplis, Christie J., "Transport Processes and Unit Operations", Third Edition, Prentice Hall, Englewood Cliffs, New Jersey, 1993, pg. 86-100.