From: Dallin Romney
Subject: Fully Developed Pipe Flow

Attachments: 2 figures, 1 table, MATLAB code

**Summary**
The purpose of this laboratory experiment is to compare measured friction losses in fully-developed flow through a pipe to theoretical correlations. The experiment is carried out by reading pressure taps at various points along the pipe. Important results include: faster flows experience more friction loss, galvanized steel pipe has greater surface roughness than PVC, and the length of a union can be important in determining minor loss coefficients. Also, the average experimental values all fell within the range of accepted theoretical values, except for minor loss coefficients. In conclusion, empirically derived correlations and values for flow friction properties, such as surface roughness and the Colebrook equation, are useful and reasonably accurate tools for estimating friction losses.

**Results**
Figure 1 shows static pressure at each measurement point in three different flow speeds for each pipe. Some of the trials have noticeable pressure drops at the coupling, between the second and third measurement points. Figure 2 is a Moody-diagram-style log-log plot showing the friction factor as a function of Reynolds numbers at various relative roughnesses. Finally, Table 1 shows the relative roughness for each pipe, as well as the minor loss coefficient and equivalent length of each coupling/union. Values in Table 1 are the averages of the three trials for each pipe.

**Discussion**
1. State whether the flow is laminar or turbulent based on your measured Reynolds numbers. Discuss how this affects the measured pressure drop.

   The critical Reynolds number for fully developed pipe flow is $Re_c = 2300$. The measured Reynolds numbers in this experiment ranged between 7540 and 38700, so the flows are all turbulent. Turbulent flow has a steeper flow velocity profile near the pipe wall, so the shear stress is higher. As a result, the friction losses and pressure drop are greater.

2. State the percent contribution of the major and minor losses to the total pressure drop for the 9 experiments. Comment on whether there are noticeable trends. For example, does the major loss tend to contribute more to friction than the minor loss as the Reynolds number increases? What about as the pipe diameter or roughness length increases?

   Considering the minor friction losses to represent the entire length between pressure taps 2 and 3, the pressure drop due to major losses from the beginning of the pipe up to tap 5 can be calculated by $\Delta P = \frac{f\rho V^2 L}{2D}$ and the pressure drop due to minor losses can be calculated by $\Delta P = \frac{f\rho V^2}{2}\left(\frac{L_{eq}}{D}\right)$, where L is the total length excluding the union: $L = L_5 - (L_3 - L_2)$. The results are summarized in the following table:

| Pipe | Reynolds Number | Roughness Length (cm) | Major Pressure Losses (Pa) | Minor Pressure Losses (Pa) | % Major | % Minor |
|---|---|---|---|---|---|---|
| 1" PVC | 12078 | 0.0029 | 1078 | 0 | 100 | 0 |
| | 30652 | 0.00081 | 5385 | 458 | 92.2 | 7.8 |
| | 38741 | 0.0018 | 8556 | 1244 | 87.3 | 12.7 |
| ¾" PVC | 8365 | 0.0013 | 1152 | 183 | 86.3 | 13.7 |
| | 21559 | ~0.0 | 5820 | 1423 | 80.4 | 19.6 |
| | 26681 | 0.0055 | 10485 | 1930 | 84.5 | 15.5 |
| ¾" Galvanized Steel | 7540 | 0.0219 | 1206 | 80 | 93.8 | 6.2 |
| | 18863 | 0.0273 | 7397 | 517 | 93.5 | 6.5 |
| | 25028 | 0.0144 | 10725 | 995 | 91.5 | 8.5 |

As discussed below (discussion point #4), the K values are much higher than expected, because the entire length from tap 2 to 3 is considered negligible in the minor loss coefficient calculation. Thus, the calculated percent contribution of minor losses is probably much higher than reality. The correlations are very weak and inconsistent, but it appears as though minor losses are more significant at high Reynolds numbers and vice versa, and less significant with a greater roughness length and vice versa. There appears to be little correlation to diameter.

3. State the calculated roughness lengths based on your data analysis, and compare with those values listed in the textbook for similar pipe materials.

   Multiplying the average values for relative roughness in Table 1 by the pipe diameters, we obtain roughness lengths of e = 0.0018 cm for the 1" PVC, 0.0022 cm for the ¾" PVC, and 0.0212 cm for the ¾" galvanized steel. PVC is supposed to be smooth and the listed value for galvanized steel is e = 0.006-0.025 cm. The measured value for the steel falls within the listed range. The measured PVC values are clearly greater than zero, but they are about an order of magnitude less than the steel, which is much smoother.

4. State the calculated minor loss coefficients for the unions based on your data analysis, and compare to the standard values listed in the textbook.

   As shown in Table 1, the minor loss coefficient was K = 0.2332 for the 1" PVC pipe union. For the ¾" PVC, it was 0.9025, and it was 0.5011 for the ¾" galvanized steel. Using the empirical correlation $K = 0.083(\text{ID } [\text{"}])^{-0.69}$ from the textbook, the expected values were 0.0812, 0.0960, and 0.0949, respectively. These vary significantly from the measured values because we used the pressure drop across the entire union, treating it as if it was negligible length. In reality, the minor loss coefficient contributes to losses on top of length-related loses, and the length of pipe within the union was definitely not negligible: 6.25-10.75”, depending on the union.

5. State the power (in units of W) required to drive the flow through the three different pipes at the highest measured flow rate. Discuss which pipe requires the most power; explain why.

   The power can be determined by $P = Q \bullet \Delta P$, where Q is the volume flow rate and $\Delta P$ is the pressure drop across the pipe. The powers required to drive each flow at the highest flow rates are 3.05 W for the 1” PVC, 1.04 W for the ¾” PVC, and 1.05 W for the ¾” galvanized steel. The large PVC pipe requires the most power because the flow rate is so much higher – about 0.91 $m^3/s$ vs about 0.48 $m^3/s$ for the others. This is because all the trials have a similar average flow velocity (perhaps the pump is a constant-velocity pump, not power or flow rate), so the pipe with the larger diameter has a much higher flow rate and requires much more power to maintain the same flow velocity.

## Attachment: Figures and Tables

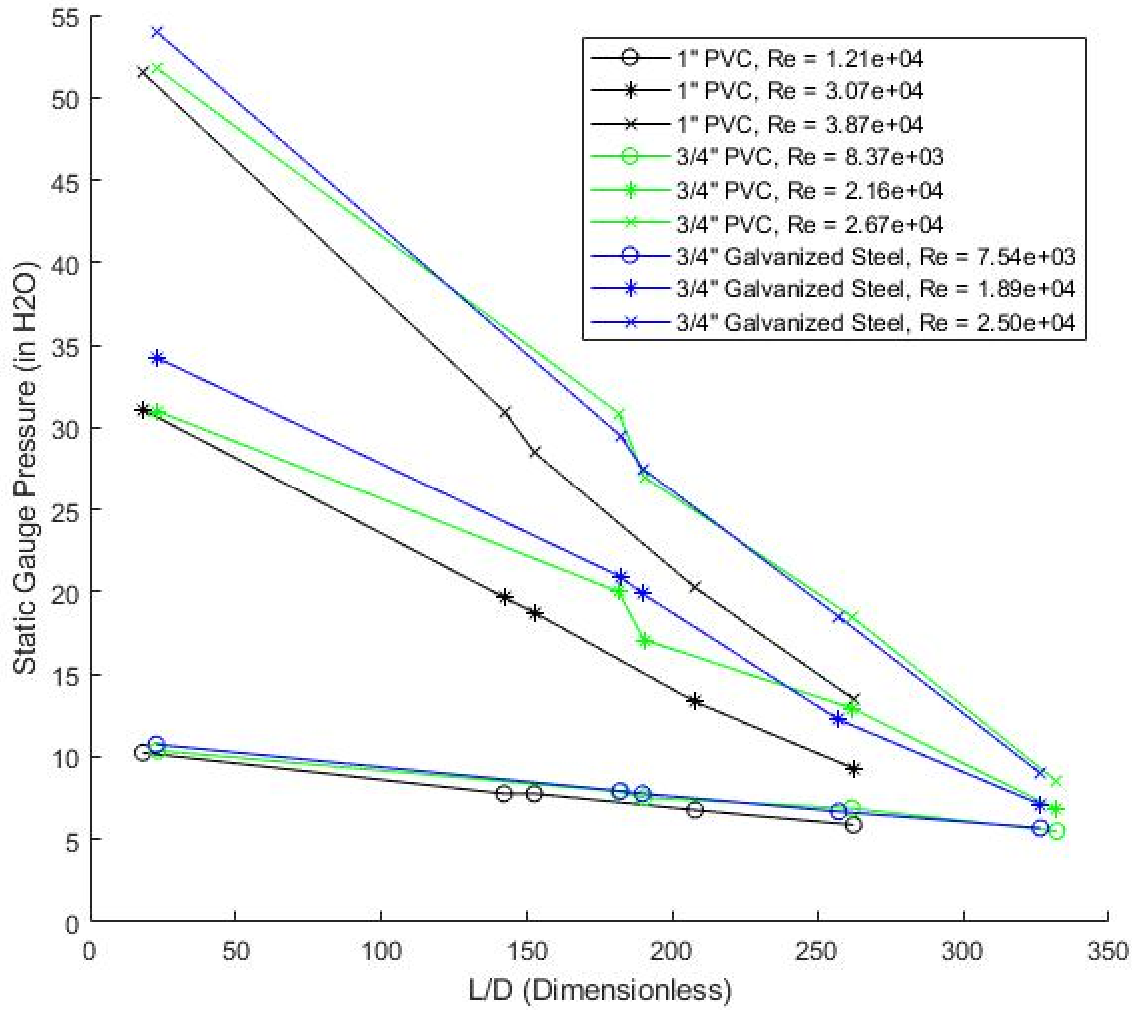


**Figure 1.** Static gauge pressure $P_s$ vs. L/D for each trial

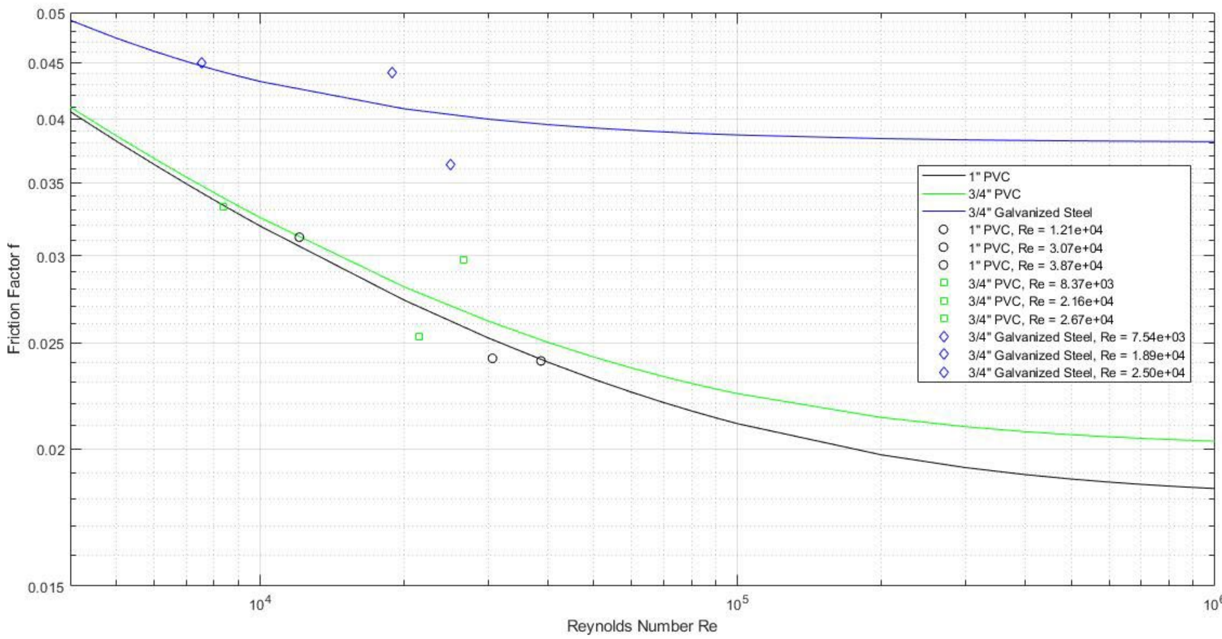


**Figure 2.** Friction factor *f* vs. Reynolds number for each trial, with Colebrook lines at averages

**Table 1.** Average relative roughness and minor loss coefficients for each pipe

| Pipe | $e/D$ | $K$ | $L_e/D$ |
|---|---|---|---|
| 1” PVC | 0.000695 | 0.2332 | 9.67 |
| ¾” PVC | 0.001088 | 0.9205 | 31.92 |
| ¾” Galvanized Steel | 0.010132 | 0.5011 | 12.16 |

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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Dallin Romney                                                            %
% TFES Lab 10 - Fully Developed Pipe Flow                                  %
% November 13, 2018                                                         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear, clc, close all

%%%%%%%%%%%%%%%%%%%%%%%%%% Experiment properties %%%%%%%%%%%%%%%%%%%%%%%%%%

    Tw = 15;       % Water temperature, degrees Celsius
    mu = 0.0011373;% Dynamic viscosity of water, Pa*s (Engineering Toolbox)
    rho = 999.06;  % Density of water, kg/m^3 (from Engineering Toolbox)
    g = 9.803;     % Acceleration due to gravity, m/s^2

    data = xlsread('PipeFlowLab_ExampleDataSet.xlsx'); % Read given data

    % Extract data. All data will be in the form of:
    %        row 1 = 1" PVC, row 2 = 3/4" PVC, row 3 = 3/4" Galvanized

    D = [1.033; 0.81; 0.824]*0.0254;                          % Pipe diam, m
    Q = [data(8,2:4); data(8,5:7); data(8,8:10)]*(0.0254^3);% Flow rate m^3

    Ldat = data(1:3, 3:7)*0.0254;                             % L1-L5, m

    % Populate a 3D array of lengths for simpler calculations later
    L = zeros(3, 3, 5);     % Initate 3D array
    for k = 1:3
        L(:, k, :) = Ldat; % Add layer to 3D array
    end

    Ps = zeros(3, 3, 5);    % Same for pressure; 3 pipes, 3 Re's, 5 taps
    for i = 1:3
        for j = 1:3
            Ps(i, j, :) = data(10:14, 3*(i-1) + j + 1);
        end
    end
    Ps  = Ps*0.0254*rho*g; % Convert Ps from in H2O to Pa

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Data Analysis %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Array of pipe areas for each flow rate
D = [D'; D'; D']';
A = pi*D.^2/4;

% Calculate average flow velocity
Vavg = Q./A;

% Reynolds number
ReExp = Vavg.*D*(rho/mu);
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% Estimate friction factor between points 3 and 5 for each flow
fExp = 2*(Ps(:,:,3) - Ps(:,:,5)).*D./(rho*Vavg.^2.*(L(:,:,5) - L(:,:,3)));

% Estimate minor loss coefficient and equivalent length of union (2 to 3)
% Assuming negligible length (non-negligible length method commented out)
P23  = Ps(:, :, 2) - Ps(:, :, 3); % Pressure drop from tap 2 to tap 3
L32  =  L(:, :, 3) -  L(:, :, 2); % Length from tap 2 to tap 3

Kt   = 2*P23./(rho*Vavg.^2); % - fExp.*L32./D; % Minor loss coeff
LeD  = 2*P23./(rho*fExp.*Vavg.^2); % - L32./D; % Equivalent Length

meanKt = mean(Kt, 2); % Average union minor loss coefficient for each pipe

% Calculate e/D for each flow for each pipe (solved from Colebrook Eq.)
eDFun = @(f, Re) 3.7*(10.^(-1./(2*sqrt(f))) - 2.51./(Re.*sqrt(f)));

eDExp = eDFun(fExp, ReExp); % e/D for every trial
meaneD = mean(eDExp, 2);    % Average per pipe

%%%%%%%%% Plot of Static Gauge Pressure vs Length/Diameter Ratio %%%%%%%%%%

LD = L./D; % Non-dimensionalized Length for every single trial

% Rotate arrays for plotting purposes - put last dimension first
LDx = permute(LD, [3,2,1]);
Psy = permute(Ps, [3,2,1])/(0.0254*rho*g);

% Array of pipe names and line styles for populating legend
pipeNames = {'1" PVC', '3/4" PVC', '3/4" Galvanized Steel'};
linestyle = {'-ko', '-k*', '-kx', '-go', '-g*', '-gx', '-bo', '-b*','-bx'};
Legend = cell(1, 9); % Initiate empty legend
figure; hold on

for pipe = 1:3 % For each pipe
  for RE = 1:3 % For each Reynolds number
    % Add the current line to the plot and an entry to the legend.
    plot(LDx(:, RE, pipe), Psy(:, RE, pipe), linestyle{3*(pipe-1) + RE});
    Legend{3*(pipe-1) + RE} = [pipeNames{pipe}, ', ', ...
            sprintf('Re = %.2s', ReExp(pipe, RE))];
  end
end

% Annotate
ylim([0, 55]);
legend(Legend);
xlabel('L/D (Dimensionless)');
ylabel('Static Gauge Pressure (in H2O)');

%%%%%%%%%%%%%% Plot of Friction Factor vs. Reynolds Number %%%%%%%%%%%%%%%%

Re = [4e3:1e3:9e3,1e4:1e4:9e4,1e5:1e5:1e6]'; % Reynolds numbers for plot
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f = zeros(length(Re), 1);                          % Empty friction factor array

% Colebrook equation, all moved to one side for fzero approximation
colebrook = @(f, Re, eD) 1/sqrt(f) + 2*log10(eD/3.7 + 2.51/(Re*sqrt(f)));

Legend = cell(1, 12);            % Initiate empty legend
pipeStyle = {'ko', 'gs', 'bd'}; % Line styles for plotting in the loop

figure;
for j = 1:length(meaneD)  % For each e/D surface roughness value
    for k = 1:length(Re)  % For each reynolds number
        % Calculate the friction factor by zeroing the above equation
        f(k,1) = fzero(@(f) colebrook(f,Re(k),meaneD(j)),0.026);
    end
    loglog(Re,f,pipeStyle{j}(1));     % Add to diagram
    hold on
    Legend{j} = pipeNames{j};         % Add entry to legend
end
grid on

meanReExp = mean(ReExp, 2)';      % Desired Reynolds number values

% Annotate and adjust y limits
xlabel('Reynolds Number Re');
ylabel('Friction Factor f');
ylim([0.015, 0.05]);

% Add data points onto plot
for pipe = 1:3 % For each pipe
  for RE = 1:3 % For each Reynolds number
    % Add the current point to the plot
    loglog(ReExp(pipe, RE), fExp(pipe, RE), pipeStyle{pipe});

    % Add a legend entry
    Legend{3*(pipe-1) + RE + 3} = [pipeNames{pipe}, ', ', ...
         sprintf('Re = %.2s', ReExp(pipe, RE))];
  end
end

% Annotate
legend(Legend);

%%%%%%%%%%%%%%%%%%%% Other calculations for discussion %%%%%%%%%%%%%%%%%%%%

% Determine theoretical union K values from empirical correlation
KCouplings = 0.083*(mean(D/0.0254, 2)).^(-0.69);

eValues    = 100*mean(eDExp, 2).*mean(D, 2); % Avg Roughness lengths, cm
eVal = 100*eDExp.*D;                          % (For every trial)

LMajor = L(:, :, 5) - L32;                     % Major L (excludes union)
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fMajor = fExp.*rho.*(Vavg.^2).*LMajor./(2*D); % Major friction losses
fMinor = fExp.*rho.*(Vavg.^2).*LeD;           % Minor friction losses

% Power required at highest flow rate
Power = Q.*Ps(:, :, end);
```