# AAE 333L

# Lab 2: Reynolds Pipe Flow

**Post-Lab Assignment**

**Name: Tomoki Koike**

**Lab Section/Team Color: GOLD**

**I. Lab Objectives (5)**

In 500 words or less, discuss the objectives of this lab and how well they were met and to what extent they were not met. If applicable, discuss reasons why particular objectives were not met during your performance of the lab and how these challenges might be addressed in the future.

The first objective of this lab was to distinguish different flows within the pipe: laminar, transitional, and turbulent flow. In order to observe different flows inside the pipes we have used dams with different heights – dams A, B, and C – to alter the pressure gradients of the inlet and outlet of the experimental set-up; and used different pipe diameters of 3/8 inch and 1/4 inch. For visual aid we have used dye which glowed in a light-green color when lightened up by LED lights in a dark/dimmed room. This dye played a pivotal role in showing the streamlines of the flow which highlighted the flow inside the pipe. Thanks to this dye, our group was able to observe the flow very clearly and were able to determine whether the flow was laminar, transitional, or turbulent and analyze how the conditions effected the resulting flow. With the low height dam A and 3/8-inch diameter pipe, the pressure gradient was low and the Reynold’s number was larger making the flow very laminar; whereas when the height of the dam increased and the diameter of the pipe decreased the flow separation became stronger making the flow inside the pipe more transitional or turbulent. Overall, we were only able to see a laminar flow for dam A of part A of the experiment.

The second objective involves calculating the pressure gradient among the surface of the water in the reservoir, the centerline of the pipe, and the outlet of the pipe. To calculate this, the Darcy friction factor was required. The Darcy friction factor is directly proportional to the pressure gradient, and therefore, is able to compute the pressure gradient from the formula. During the experiment we were required to compute the Reynold’s number and the Darcy friction factor for theoretical cases using the formula correlated from empirical data for laminar and turbulent flows. In addition, we had to calculate the experimental friction factor using the relations between the hydrostatic pressure and dynamic pressures of the pipe flow. The calculations elucidated the characteristics of the non-dimensional variable, friction factor and what the value implies about the pipe flow. Thus, we were able to thoroughly understand the relation of the pressure loss, friction factor, and the pipe flow.

For the last part of the experiment we observed the change of the flow when the pipe was bent down or up (the outlet of the pipe was bent) to change the pressure gradients of the pipe itself. This was to accomplish the third objective of this experiment, which was to explore the affect of streamwise pressure gradients on transition. When the pipe was bent down the flow in the pipe gained more velocity resulting in a more elongated transitional flow from laminar to turbulent flow, and when the pipe was bent upwards the results turned out the opposite with a lower velocity and shorter transitional flow. We were able to analyze this as being the result of the flow separation owing to a favorable pressure gradient or an adverse pressure gradient condition. The pressure gradients affect the flow to separate from laminar flow to turbulent flow. Doing this analysis, we were able to satisfy the objectives of this experiment.

**II. Data Presentation and Analysis (15 points)**

1. (10 points) Construct a Moody diagram that includes your experimental data and theory/empirical correlations for the friction factor on the same graph. Use your experimental measurements to calculate the friction factor and Reynolds number for each experiment performed during the lab. Plot these values along with the theoretical/empirical values of friction factor calculated using the expressions on page 3 of the Background document.

A picture containing text

Description automatically generated

Since in part A for dam A we examined laminar flow, the following equation was used

for the point corresponding to that specific observation, and for the rest the formula used was

which is for the turbulent flows.

As we can see, if we do this, the point for the laminar flow does not stay congruent with the other points; and therefore, we will only use the formula (2) to compute the theoretical/empirical Darcy friction factors. In addition, we will consider the condition where we assume all the flows are laminar for experimentation.

A screenshot of a cell phone

Description automatically generated

1. (5 points) In 250 words or less, discuss how well your experimental measurements compare with the theoretical/empirical friction factors and possible reasons for any disagreement.

From the plot above we can see that the experimental points lie between the friction factor for the turbulent and laminar flow cases. However, there are three outliers that do not follow the trend for the formula. The blue plot is for formula (1) and the green one is for formula (2).

Possible reasons for this discrepancy are the accumulation of human errors. There were many steps in the experiment where we could elaborate on during the experiment to obtain more accurate results. In retrospect, I believe that we have been ignoring those errors due to the time constraints. We will go over the errors we have overlooked more in detail in the next section.

For further analysis, I used the MATLAB application “curve fitting” and fitted the data points to a power equation while excluding the first three outliers.

A screenshot of a cell phone

Description automatically generated

The fitted curve has the following characteristics:

1. General model Power1:
   1. f(x) = a\*x^b
2. Coefficients (with 95% confidence bounds):
   1. a = 0.525 (-0.857, 1.907)
   2. b = -0.337 (-0.6372, -0.03672)
3. Goodness of fit:
   1. SSE: 1.954e-06
   2. R-square: 0.9188
   3. Adjusted R-square: 0.8782
   4. RMSE: 0.0009884

Thus, the fitted curve is

This fitted curve has a high correlation with the data points as you can see from the values of R-square and SSE.

Now using this fitted curve I have calculated the Discrete Frechet Distance using MATLAB, and the results retrieved are the following:

|  |  |  |
| --- | --- | --- |
|  | Fitted curve VS. Turbulent Curve | Fitted Curve VS. Laminar Curve |
| Discrete Frechet Distance | 0.6642 | 1.3661 |

When the discrete Frechet distance is 0, that indicates that the two functions are equal and as the number increases positively the dissimilarity becomes larger. From that being said, we can see that our data points have more dissimilarity with laminar flow than turbulent flow. That is, the flow we have observed were more inclined to being turbulent rather than laminar.

**III. Error and Uncertainty (10 points)**

1. (6 points) Discuss the sources of error and uncertainty in your results and how large they might be. How repeatable were your measurements?

Overall, I believe the main source of error was the velocity of flow. This is because, the Reynold’s number for part A and part B of the experiment have a large discrepancy though they have the same pipe diameter. Ideally, for lower Reynold’s number the friction factor should have been much larger, but we were not able to obtain an acceptable friction factor for a low Reynold’s number condition.

As aforementioned, the sources of error during this experiment were due to human errors. For example, the measurement of water volume to obtain the volumetric flow rate was not accurate enough in that we did not measure the meniscus horizontally and did it while the surface of the water was still sloshing in the cylinder. Another source of error was when we used the 1/4-inch diameter for part A of the experiment. The pipe was too short that we had to extend it using an extra unrigid elastic tube that was connected on to the outlet of the pipe. This tube had a larger diameter and prevented the flow from being horizontal. Therefore, the measurements for that part of the experiment has a larger magnitude of error. Even if we had repeated the experiment more than three times it is doubtful that we could have obtained better results.

1. (4 points) What would you change to get better data next time?

To retrieve more reliable results, I would have used a better cylinder to measure the volume of water and waited until the water became placid. Most importantly, it would be better to prepare a longer 1/4-inch diameter pipe, so that the water does not spill during the experiment.

**APPENDIX**

**EXCEL SHEETS**

**<data\_partA.xlsx>**

**Author: Tomoki Koike**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **PART A** |  |  |  |  |  |  |  |  |  |
|  | **Outer Diameter (m)** | **Inner Diameter (m)** | **Temperature (C)** | **Reservior Height (m)** | **Centerline Height (m)** | **Pipe Length (m)** | **Vol Flow Rates (m^3/s)** | **Average Vol Flow Rate (m^3/s)** | **Average Velocity (m/s)** |
| **DAM A** | **0.00952500** | **0.00867000** | **15.00000000** | **0.21300000** | **0.19800000** | **1.18110000** | **2.21607E-05** | **0.00002124** | **0.35976525** |
|  |  |  |  |  |  |  | **0.00002085** |  |  |
|  |  |  |  |  |  |  | **0.00002071** |  |  |
| **DAM C** | **0.00952500** | **0.00867000** | **15.00000000** | **0.41751250** | **0.19800000** | **1.18110000** | **0.00006606** | **0.00006567** | **1.11232079** |
|  |  |  |  |  |  |  | **0.00006529** |  |  |
|  |  |  |  |  |  |  | **0.00006566** |  |  |
| **DAM A** | **0.00635** | **6.38E-03** | **15.00000000** | **0.21500000** | **0.19900000** | **1.27000000** | **0.00000843** | **0.00000985** | **0.30819697** |
|  |  |  |  |  |  |  | **0.00000996** |  |  |
|  |  |  |  |  |  |  | **0.00001117** |  |  |
| **DAM C** | **0.00635** | **6.38E-03** | **15.00000000** | **0.41592500** | **0.19900000** | **1.27000000** | **0.00002523** | **0.00002649** | **0.82876241** |
|  |  |  |  |  |  |  | **0.00002709** |  |  |
|  |  |  |  |  |  |  | **2.71639E-05** |  |  |

**<data\_partB.xlsx>**

**Author: Tomoki Koike**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **PART B** |  |  |  |  |  |  |  |  |  |
|  | **Outer Diameter (m)** | **Inner Diameter (m)** | **Temperature (C)** | **Reservior Height (m)** | **Centerline Height (m)** | **Pipe Length (m)** | **Vol Flow Rates (m^3/s)** | **Average Vol Flow Rate (m^3/s)** | **Average Velocity (m/s)** |
| **DAM A** | **0.00952500** | **0.00867000** | **15.00000000** | **2.15E-01** | **0.19800000** | **1.18110000** | **1.95122E-05** | **1.94861E-05** | **0.330063575** |
|  |  |  |  |  |  |  | **1.96135E-05** |  |  |
|  |  |  |  |  |  |  | **1.93327E-05** |  |  |
| **DAM B** | **0.00952500** | **0.00867000** | **15.00000000** | **3.14E-01** | **0.19800000** | **1.18110000** | **4.67245E-05** | **4.65227E-05** | **0.788018419** |
|  |  |  |  |  |  |  | **4.42177E-05** |  |  |
|  |  |  |  |  |  |  | **4.86258E-05** |  |  |
| **DAM C** | **0.00952500** | **0.00867000** | **15.00000000** | **0.41592500** | **0.19800000** | **1.18110000** | **6.67178E-05** | **6.64524E-05** | **1.125595568** |
|  |  |  |  |  |  |  | **6.65236E-05** |  |  |
|  |  |  |  |  |  |  | **6.61157E-05** |  |  |

**MATLAB CODE**

<**data\_partA.mlx>**

### AAE333 Lab2 Matlab Code (Author: Tomoki Koike)

% Reading the excel files into matlab

file1 = readmatrix('data\_partA.xlsx');

file2 = readmatrix('data\_partB.xlsx');

% Setting variables

rho = 997; % Density of water [kg/m^3]

myu = 0.0011373; % Viscosity of water at room temperature [Pa-s]

g = 9.80665; % Gravitational acceleration [m/s^2]

% Slicing the matrix from the excel files and assigning them to specified variables

h\_diff = [(file1(:,5)-file1(:,6)); (file2(:,5)-file2(:,6))]; % Height h

h\_diff = rmmissing(h\_diff); % Removing NaN values from matrix

vel = rmmissing([file1(:,10); file2(:,10)]); % Velocity of the flow

len = rmmissing([file1(:,7); file2(:,7)]); % Length of pipe

d = rmmissing([file1(:,3); file2(:,3)]); % Diameter of the pipe

% Calculating the Reynold's number

Re = rho \* vel .\* d / myu;

% Calculating the theoretical/empirical friction factors

% Only the Dam A in part A of the experiment created a fully developed

% laminar flow. Therefore, we will use a different equation to find the

% friction factor for that flow only.

f = 0.316 ./ Re.^(0.25); % Friction factor formula for translational or turbulent flow

f(1) = 64 / Re(1); % Replace the certain one with the friction factor for laminar flow

temp = [Re f]; % Concatenate the two to sort them out correspondingly using sortrow

temp = sortrows(temp,1);

Re\_sort = temp(:,1);

f\_sort = temp(:,2);

% Plot for now

figure(1)

plot(Re\_sort, f\_sort, '.-b', 'MarkerSize', 20)

xlabel('Reynold''s Number')

ylabel('Darcy''s Friction Factor')

title({'Theoretical/Empirical Friction Factor Using Both Formulas for', ['Laminar' ...

'and Turbulent Flows - By: Tomoki Koike']})

grid on

grid minor

box on

f\_sort(3) = 0.316 / Re\_sort(3)^(0.25); % Replace with the formula for the turbulent flow

% Calculating the experimental friction factor

comp1 = rho \* g .\* h\_diff;

comp2 = rho .\* vel.^2 / 2;

comp3 = len ./ d;

f\_exp = comp1 ./ comp2 ./ comp3;

f\_lam = 64 ./ Re\_sort;

% Plot

figure(2)

plot(Re\_sort, f\_sort, '-b')

xlabel('Reynold''s Number')

ylabel('Darcy''s Friction Factor')

title({'Theoretical/Empirical and Experimental', ['Friction ' ...

'Factors - By: Tomoki Koike']})

grid on

grid minor

box on

hold on

plot(Re, f\_exp, '.r', 'MarkerSize',21)

plot(Re\_sort, f\_lam, '-g')

hold off

legend('Theoretical/Empirical','Experimental', 'Theoretical if All Laminar')

## Analysis

figure(3)

[result gof] = createFit(Re, f\_exp);

hold on

plot(Re\_sort, f\_sort, '-g')

plot(Re\_sort, f\_lam, '-m')

hold off

title('Curve Fitting for Experimental Data - By: Tomoki Koike')

legend('f\_exp vs. Re', 'Excluded f\_exp vs. Re', ['experimental' ...

' data fitting'], 'Turbulent Flow', ['Laminar ' ...

'Flow'],'Location', 'NorthEast', 'Interpreter', 'none' );

ylim([0 0.055])

% Calculating the Frechet Distance to measure dissimilarity of the

% functions

Re\_test = 1500:9000;

f\_tur = 0.316 ./ Re\_test.^(0.25);

f\_fit = 0.525 ./ Re\_test.^(0.337);

f\_lmn = 64 ./ Re\_test;

[cm1, cSq1] = DiscreteFrechetDist(f\_tur, f\_fit);

[cm2, cSq2] = DiscreteFrechetDist(f\_lmn, f\_fit);

**<createFit.mlx>**

**Author: Tomoki Koike**

function [fitresult, gof] = createFit(Re, f\_exp)

%CREATEFIT(RE,F\_EXP)

% Create a fit.

%

% Data for 'experimental data fitting' fit:

% X Input : Re

% Y Output: f\_exp

% Output:

% fitresult : a fit object representing the fit.

% gof : structure with goodness-of fit info.

%% Fit: 'experimental data fitting'.

[xData, yData] = prepareCurveData( Re, f\_exp );

% Set up fittype and options.

ft = fittype( 'power1' );

excludedPoints = excludedata( xData, yData, 'Indices', [1 3 5] );

opts = fitoptions( 'Method', 'NonlinearLeastSquares' );

opts.Algorithm = 'Levenberg-Marquardt';

opts.Display = 'Off';

opts.StartPoint = [1.12505157617623 -0.423441853468139];

opts.Exclude = excludedPoints;

% Fit model to data.

[fitresult, gof] = fit( xData, yData, ft, opts );

% Plot fit with data.

figure( 'Name', 'experimental data fitting' );

h = plot( fitresult, '-k',xData, yData, excludedPoints, 'xr');

legend( h, 'f\_exp vs. Re', 'Excluded f\_exp vs. Re', 'experimental data fitting', 'Location', 'NorthEast', 'Interpreter', 'none' );

% Label axes

xlabel( 'Re', 'Interpreter', 'none' );

ylabel( 'f\_exp', 'Interpreter', 'none' );

grid on

grid minor

box on

**<DiscreteFrechetDist.mlx>**

**MATHWORKS File Exchange (free source) - Author: Zachary Danziger**

function [cm, cSq] = DiscreteFrechetDist(P,Q,dfcn)

% Calculates the discrete Frechet distance between curves P and Q

%

% [cm, cSq] = DiscreteFrechetDist(P,Q)

% [cm, cSq] = DiscreteFrechetDist(...,dfcn)

%

% P and Q are two sets of points that define polygonal curves with rows of

% vertices (data points) and columns of dimensionality. The points along

% the curves are taken to be in the order as they appear in P and Q.

%

% Returned in cm is the discrete Frechet distance, aka the coupling

% measure, which is zero when P equals Q and grows positively as the curves

% become more dissimilar.

%

% The optional dfcn argument allows the user to specify a function with

% which to calculate distance between points in P and Q. If not provided,

% the L2 norm is used.

%

% The secondary output, cSq, is the coupling sequence, that is, the

% sequence of steps along each curve that must be followed to achieve the

% minimum coupling distance, cm. The output is returned in the form of a

% matrix with column 1 being the index of each point in P and column 2

% being the index of each point in Q. (NOTE: the coupling sequence is not

% unique in general)

%

% Explanation:

% The Frechet distance is a measure of similarity between to curves, P and

% Q. It is defined as the minimum cord-length sufficient to join a point

% traveling forward along P and one traveling forward along Q, although the

% rate of travel for either point may not necessarily be uniform.

%

% The Frechet distance, FD, is not in general computable for any given

% continuous P and Q. However, the discrete Frechet Distance, also called

% the coupling measure, cm, is a metric that acts on the endpoints of

% curves represented as polygonal chains. The magnitude of the coupling

% measure is bounded by FD plus the length of the longest segment in either

% P or Q, and approaches FD in the limit of sampling P and Q.

%

% This function implements the algorithm to calculate discrete Frechet

% distance outlined in:

% T. Eiter and H. Mannila. Computing discrete Frechet distance. Technical

% Report 94/64, Christian Doppler Laboratory, Vienna University of

% Technology, 1994.

% size of the data curves

sP = size(P);

sQ = size(Q);

% check validity of inputs

if sP(2)~=sQ(2)

error('Curves P and Q must be of the same dimension')

elseif sP(1)==0

cm = 0;

return;

end

% initialize CA to a matrix of -1s

CA = ones(sP(1),sQ(1)).\*-1;

% distance function

if nargin==2

dfcn = @(u,v) sqrt(sum( (u-v).^2 ));

end

% final coupling measure value

cm = c(sP(1),sQ(1));

% obtain coupling measure via backtracking procedure

if nargout==2

cSq = zeros(sQ(1)+sP(1)+1,2); % coupling sequence

CApad = [ones(1,sQ(1)+1)\*inf; [ones(sP(1),1)\*inf CA]]; % pad CA

Pi=sP(1)+1; Qi=sQ(1)+1; count=1; % counting variables

while Pi~=2 || Qi~=2

% step down CA gradient

[v,ix] = min([CApad(Pi-1,Qi) CApad(Pi-1,Qi-1) CApad(Pi,Qi-1)]);

if ix==1

cSq(count,:) = [Pi-1 Qi];

Pi=Pi-1;

elseif ix==2

cSq(count,:) = [Pi-1 Qi-1];

Pi=Pi-1; Qi=Qi-1;

elseif ix==3

cSq(count,:) = [Pi Qi-1];

Qi=Qi-1;

end

count=count+1;

end

% format output: remove extra zeroes, reverse order, subtract off

% padding value, and add in the last point

cSq = [flipud(cSq(1:find(cSq(:,1)==0,1,'first')-1,:))-1; sP(1) sQ(1)];

end

% debug

% assignin('base','CAw',CA)

function CAij = c(i,j)

% coupling search function

if CA(i,j)>-1

% don't update CA in this case

CAij = CA(i,j);

elseif i==1 && j==1

CA(i,j) = dfcn(P(1,:),Q(1,:)); % update the CA permanent

CAij = CA(i,j); % set the current relevant value

elseif i>1 && j==1

CA(i,j) = max( c(i-1,1), dfcn(P(i,:),Q(1,:)) );

CAij = CA(i,j);

elseif i==1 && j>1

CA(i,j) = max( c(1,j-1), dfcn(P(1,:),Q(j,:)) );

CAij = CA(i,j);

elseif i>1 && j>1

CA(i,j) = max( min([c(i-1,j), c(i-1,j-1), c(i,j-1)]),...

dfcn(P(i,:),Q(j,:)) );

CAij = CA(i,j);

else

CA(i,j) = inf;

end

end % end function, c

end % end main function