CL 232 Chemical Engineering Lab-I [2021]

Experiment Number	FM 202
Title	Nature of Flow

Sub-group Code	A2d

Date of Experiment	23rd August 2021
Date of Report Submission	25th August 2021

Roll Number	Name	**Responsibility owned** (data, analysis, plots, report, none)
190020066	Laxman Desai	Solving & plots
19D110023	Kshitij Sovanee	Report & Analysis
190020005	Akshata Jain	Observations
190020063	Kriti Chaturvedi	Hypotheses & Proofs
190020067	Mahesh Prajapati	PPT

(For use by examiners only)

Criterion	TA Grade	Faculty assigned grade
Data analysis		
Graphical plots		
Inference		
Report quality		
Bonus marks (Y/N)		
Initials with date		

R&P TA initials with date		

Objectives:

- To visually observe laminar and turbulent flow patterns.
- To determine the critical Reynolds number for transition from laminar to turbulent flow and vice versa.
- To calculate the pressure drop Δp between the two tanks and understand the relation between this and volume flow rate Q.
- To calculate the experimental and theoretical friction factor.

Set-Up Assembly:

- Overhead tank stores water
- 2 Tanks .i.e. Tank 1 and Tank 2
- Ground water reservoir
- Piping network
- Valve 1: Drain valve of Tank 1
- Valve 3: Drain valve of overhead Tank
- Valve 5: Drain valve of Tank 2
- Valve 2: Control flow from overhead Tank to Tank 1
- Tank 1 and Tank 2 connected with a glass tube (internal diameter = 25mm, length 1.65m)

Procedure:

1. Ensure valve 1,3,5 are properly closed
2. Discharge valve of tank 2 should also be in a closed position
3. Open valve 2 so that water from overhead tank flows to tank 1
4. Once the water reaches the level of the pipe it will flow from Tank 1 to Tank 2 through interconnected glass tube
5. Once the Tank 1 is filled upto a certain level excess water flows out through the funnel
6. Close valve 2 when the height in tank 1 and 2 becomes the same
7. Measure height of tank 1 and 2 using the z-traverse
8. Open valve 2 slightly such that water will start draining through the funnel
9. Open valve of tank 2 and adjust the flow to lowest possible value
10. Wait till the difference in height between the two tanks is constant and then measure the flow rate
11. Inject the ink through the flow assembly to check the flow pattern
12. Take 3 readings for the laminar region
13. Open the valve of tank 2 more to take the measurement of the transition region
14. Measure flow for 3 consecutive minutes for transition region
15. Inject the ink through the flow assembly to check the flow pattern
16. Get the critical point where flow changes from laminar to turbulent and measure the critical reynolds number
17. Increase flow rate and take 2 more readings in the transition region
18. Repeat similar steps for turbulent regime too.

Raw Data:

Diameter of pipe	25mm
Length of pipe	1.65m
Viscosity of Water	8.9×10^{-4} Pa.s
Density of Water	1000 kg/m^3
Cross Sectional Area of pipe	4.908×10^{-4} m^2

Calculations & Derived Quantities:

Reynold's Number

The Reynold's Number is given by:

$$N_{Re} = \frac{\rho V D}{\mu} = \frac{\rho Q D}{A\mu}$$

Table 1: Reynold's number calculation and Nature of Flow:

Water Level (Inlet, H1, mm)	Water Level (Outlet, H2, mm)	Volume (mm^3)	Time (s)	Velocity (m/s)	Reynold's Number (N_{Re})	Nature of observed flow
5.15	3.18	0.000353	53.73	0.01338406	375.957	Laminar
4.75	4.48	0.000767	34.25	0.04562101	1281.489	Laminar
3.32	3.44	0.00118	32.96	0.07293314	2048.684	Laminar
4.44	4.86	0.00148	35.14	0.08580055	2410.127	Transition
5.74	7.36	0.00212	34.75	0.12428284	3491.091	Turbulent
4.58	8.34	0.00248	38.26	0.13204952	3709.256	Turbulent
5.38	10.68	0.00365	32.75	0.22704485	6377.664	Turbulent
4.68	17.25	0.00528	33.45	0.32156435	9032.706	Turbulent

7.36	28.52	0.00775	36.15	0.43674054	12267.992	Turbulent

Zero Error Correction

H1= 6.38, H2=4.28 $\Longrightarrow$Hcorr = H1-H2 = 2.1 mm
Table 2: Correction for zero-error:

H1 (mm)	H2 (mm)	H2,corrected=H2+ Hcorr (mm)	$\Delta H_{\text{corrected}}$ =H2,corrected-H1 (mm)
5.15	3.18	5.28	0.13
4.75	4.48	6.58	1.83
3.32	3.44	5.54	2.22
4.44	4.86	6.96	2.52
5.74	7.36	9.46	3.72
4.58	8.34	10.44	5.86
5.38	10.68	12.78	7.4
4.68	17.25	19.35	14.67
7.36	28.52	30.62	23.26

Pressure Calculation:

The pressure is calculated from the height difference as:

$$\Delta P = \rho g \Delta H$$

Table 3: Pressure from height difference:

$\Delta H_{\text{corrected}}$ (mm)	ΔP (Pa)
0.13	1.2753
1.83	17.9523
2.22	21.7782
2.52	24.7212
3.72	36.4932
5.86	57.4866

7.4	72.594
14.67	143.9127
23.26	228.1806

Friction Factor Calculation:

The friction factor from experiment is:

$$f = \frac{\Delta P D}{2\rho L V^2}$$

While that from theoretical considerations is:

$$f = 16/\mathrm{Re}$$ (laminar flow)

$$f = 0.0014 + 0.125Re^{-0.32}$$ (3000<Re<3*10^6)

Table 4: Experimental & Theory Calculations:

ΔP (Pa)	Q(L/s)	V=Q/A(m/s)	f (expt)	f (theory)	V^2 (calc)	V (calc)	Q (calc) (L/s)
1.2753	0.006569	0.013384	0.0539	0.0425	2.27e-4	0.015067	0.007396
17.9523	0.02239	0.045621	0.0653	0.01248	1.089e-2	0.104369	0.0512
21.7782	0.0358	0.072933	0.031	0.0078	2.11e-2	0.145345	0.0713
24.7212	0.04212	0.085800	0.0254	0.0117	1.595e-2	0.126285	0.06199
36.4932	0.06108	0.124282	0.0179	0.0106	2.611e-2	0.161598	0.07932
57.4866	0.06482	0.132049	0.0249	0.0104	4.183e-2	0.204534	0.1004
72.594	0.1145	0.227044	0.0106	0.0089	6.127e-2	0.247532	0.1215
143.9127	0.1578	0.321564	0.0105	0.0082	0.133	0.365141	0.1792
228.1806	0.2144	0.436740	0.0091	0.0075	0.229	0.478664	0.2349

Error Analysis:

Least Count of Stopwatch: 0.01s
Least Count of Measuring Cylinder: 10ml (for 1000 ml) and 20ml for (2000 ml)
Error in ΔH= $0.02/\Delta H_{corrected}$
Error in V = ΔV/V
Error in T = ΔT/T
Error in ΔP= $0.02/\Delta H_{corrected}$
Error in Q = ΔV/V+ΔT/T

Error in f = Δ(ΔP)+2*ΔQ
Error in Re = Error in Q
Table 5: Error Calculations: (All reported values are in %)

Error in ΔH	Error in V	Error in T	Error in ΔP	Error in Q (Expt)	Error in f (Calc)	Error in Re
15.38	2.83	0.019	15.38	2.85	21.087	2.85
1.09	1.304	0.029	1.09	1.333	3.758	1.333
0.901	0.847	0.03	0.901	0.877	2.65	0.877
0.79	0.676	0.0284	0.79	0.704	2.202	0.704
0.54	0.472	0.0287	0.54	0.500	1.538	0.500
0.34	0.403	0.026	0.34	0.429	1.200	0.429
0.27	0.274	0.03	0.27	0.304	0.879	0.304
0.136	0.189	0.0298	0.136	0.219	0.575	0.219
0.086	0.129	0.027	0.086	0.156	0.399	0.156

Observations:

- The values of experimental and calculated flow rate do not agree exactly, however they match to a good extent. Further, the slope of the best fit line is 0.976 (which is very close to 1) implying that the line is very close to y=x.
- The relation between ΔP and Q was plotted and a linear relation was observed.
- The flow-patterns were observed visually in the video, showing that transition happened at Re=2100 and turbulence began at Re=3000.

Hypothesis & Conclusions:

The sources of error is the Qexpt vs Qcalc could be as follows:

- One intermediate in calculating Q is the friction factor. Even in the turbulent region, the friction factor equation used was the same as that for turbulent. This could lead to errors in the final result.
- The flow between the two tanks (in the tube) might not be fully developed. The entrance length for laminar flows ~0.06Re*D, while it is ~40D for turbulent flows. For values of Re which are in the 2000-3000 range, the entrance length exceeds the length of the pipe, leading to the error.
- Manual error in calculation of height of the tanks could have affected the final results.

Python Code

August 25, 2021

[1]:
```python
import math
import numpy as np
import matplotlib.pyplot as plt
from sklearn.linear_model import LinearRegression
```

[2]:
```python
D = 25e-3 # m
L = 1.65 # m
mu = 8.9e-4 # Pa*s
rho = 1000 # kg/m^3
g = 9.81 # m/s^2

H_corr = (6.38 - 4.28) * 1e-3 # m
```

1 Experimental data

[3]:
```python
H1 = np.array([5.15, 4.75, 3.32, 4.44, 5.74, 4.58, 5.38, 4.68, 7.36]) * 1e-3 # m
H2 = np.array([3.18, 4.48, 3.44, 4.86, 7.36, 8.34,10.68, 17.25, 28.52]) * 1e-3␣
↪# m

vol = np.array([0.000353, 0.000767, 0.00118, 0.00148, 0.00212, 0.00248, 0.
↪00365, 0.00528, 0.00775]) # m^3
t = np.array([53.73, 34.25, 32.96, 35.14, 34.75, 38.26, 32.75, 33.45, 36.15]) #␣
↪s
```

[4]:
```python
Q = vol / t
print(f'Volumetric flow rate: {Q} m^3/s')

area = math.pi * D**2 / 4
V = Q / area
print(f'Velocity: {V} /s')
```

```
Volumetric flow rate: [6.56988647e-06 2.23941606e-05 3.58009709e-05
4.21172453e-05
 6.10071942e-05 6.48196550e-05 1.11450382e-04 1.57847534e-04
 2.14384509e-04] m^3/s
Velocity: [0.01338406 0.04562101 0.07293314 0.08580055 0.12428284 0.13204952
 0.22704485 0.32156435 0.43674054] m/s
```

[5]:
```
N_Re = rho * V * D / mu
print(f"Reynold's number: {N_Re}")
```

```
Reynold's number: [  375.95682055  1281.48902592  2048.68367894  2410.12774099
  3491.09088654  3709.25609043  6377.66441483  9032.70660043
 12267.99256742]
```

[6]:
```
H_2_corr = H2 + H_corr
delta_H_corr = H_2_corr - H1
print(f'delta H: {delta_H_corr}')

delta_P = rho * g * delta_H_corr
print(f'delta P: {delta_P}')
```

```
delta H: [0.00013 0.00183 0.00222 0.00252 0.00372 0.00586 0.0074  0.01467
0.02326]
delta P: [  1.2753   17.9523   21.7782   24.7212   36.4932   57.4866   72.594
143.9127
 228.1806]
```

[7]:
```
f_exp = delta_P * D / (2 * rho * L * V**2)
print(f'f (Experimental): {f_exp}')
```

```
f (Experimental): [0.05393398 0.06534561 0.03101689 0.02543991 0.01789846
0.02497578
 0.0106685  0.01054361 0.0090627 ]
```

[8]:
```
f_calc = []

for Re in N_Re:
    if Re <= 2100:
        f = 16 / Re
        f_calc.append(f)
    else:
        f = 0.0014 + 0.125 * Re**(-0.32)
        f_calc.append(f)

print(f'f (Calculated): {f_calc}')
```

```
f (Calculated): [0.04255807881497671, 0.012485475627516408,
0.007809892842158002, 0.011743254083280218, 0.010586761534283576,
0.010410278837055937, 0.008975621722908453, 0.00817716850341045,
0.007544725570930351]
```

[9]:
```
V_calc_sq = delta_P * D / (2.0 * rho * L)
V_calc_sq /= f_calc
V_calc = np.sqrt(V_calc_sq)

print(f'Velocity calculated: {V_calc}')
```

```
print(f'Velocity square calculated: {V_calc**2}')

Q_calc = V_calc * area
print(f'Flow rate calculated: {Q_calc}')
```

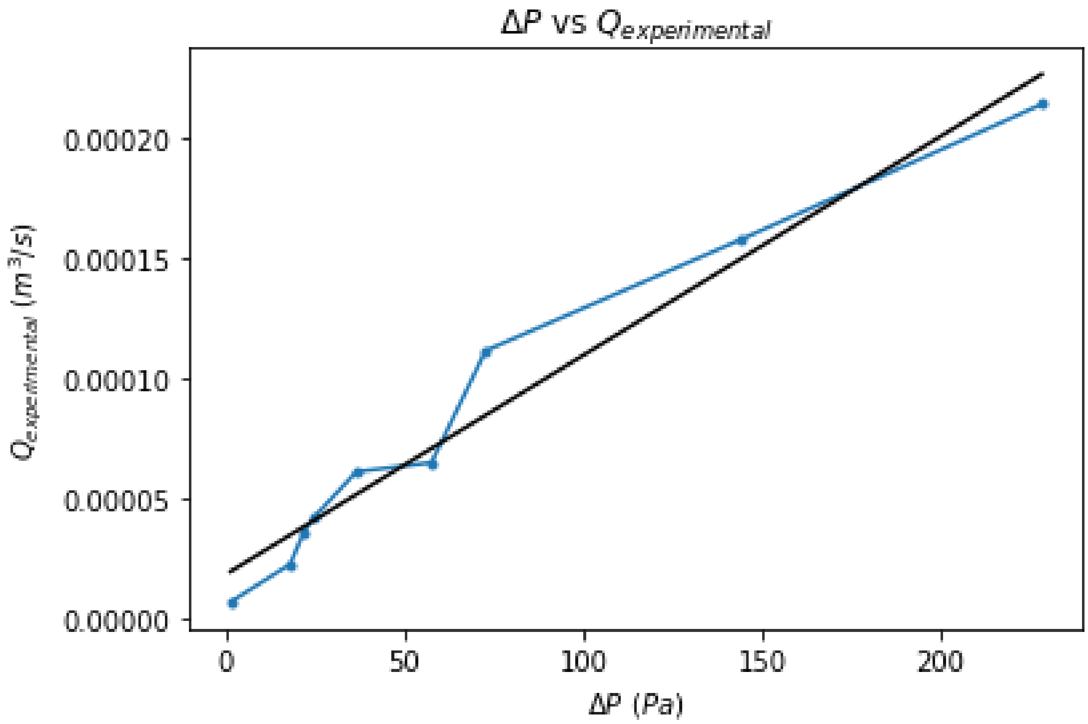
```
Velocity calculated: [0.01506705 0.10436876 0.14534547 0.12628553 0.16159854
0.20453384
 0.24753187 0.36514144 0.47866389]
Velocity square calculated: [2.27015972e-04 1.08928387e-02 2.11253044e-02
1.59480342e-02
 2.61140893e-02 4.18340904e-02 6.12720280e-02 1.33328270e-01
 2.29119123e-01]
Flow rate calculated: [7.39602049e-06 5.12318969e-05 7.13462886e-05
6.19902629e-05
 7.93244996e-05 1.00400312e-04 1.21506924e-04 1.79238384e-04
 2.34963590e-04]
```

[10]:
```
plt.title('$\Delta P$ vs $Q_{experimental}$')
plt.xlabel('$\Delta P\ (Pa)$')
plt.ylabel('$Q_{experimental}\ (m^3 / s)$')
plt.plot(delta_P, Q, '.-')

# Linear regression
reg = LinearRegression().fit(delta_P.reshape(-1, 1), Q)
Q_pred = reg.predict(delta_P.reshape(-1, 1))
plt.plot(delta_P, Q_pred, '-k')
print(f"slope of best fit line", reg.coef_)

plt.show()
```

```
slope of best fit line [9.14838243e-07]
```

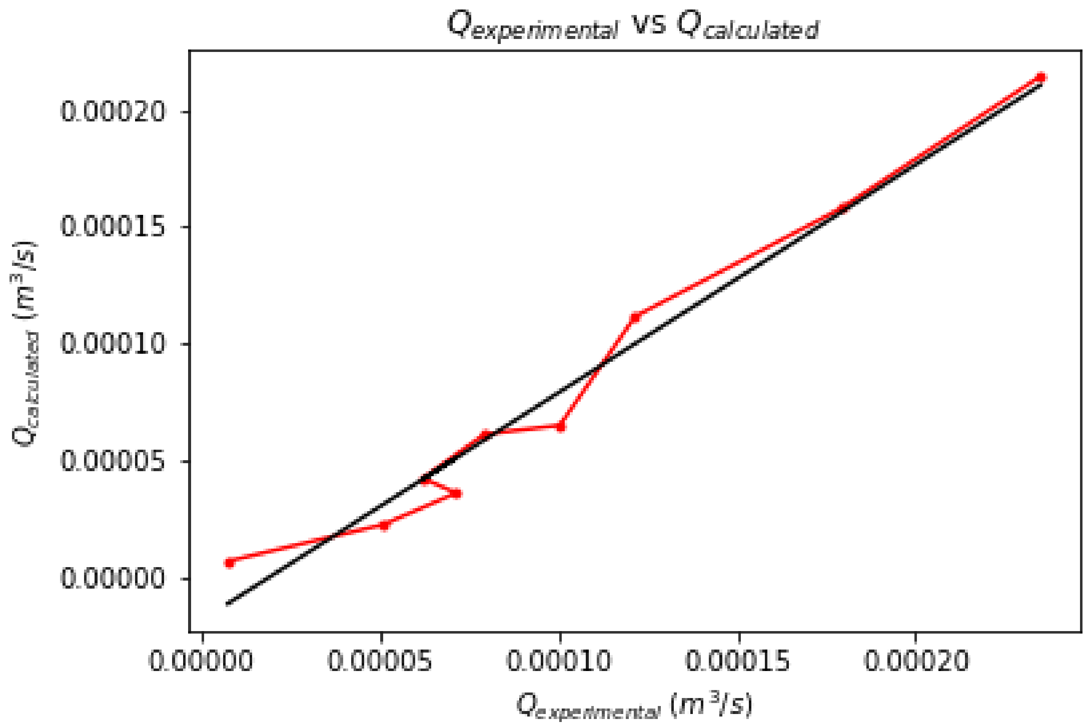


[11]:
```
plt.title('$Q_{experimental}$ vs $Q_{calculated}$')
plt.xlabel('$Q_{experimental}\ (m^3 / s)$')
plt.ylabel('$Q_{calculated}\ (m^3 / s)$')
plt.plot(Q_calc, Q, '.-r')

# Linear regression
reg = LinearRegression().fit(Q_calc.reshape(-1, 1), Q)
Q_pred = reg.predict(Q_calc.reshape(-1, 1))
plt.plot(Q_calc, Q_pred, '-k')
print(f"slope of best fit line", reg.coef_)

plt.show()
```

```
slope of best fit line [0.97641142]
```



2 Error analysis

[12]:
```
error_delta_H = (0.01 + 0.01) / (delta_H_corr * 1e3) # height (1 m -> 1e3 mm)
print('Error in delta H (%):', 100 * error_delta_H)

error_vol = 10 / (vol * 1e6) # vol (1 m^3 -> 1e6 ml)
print('Error in volume (%):', 100 * error_vol)


error_t = 0.01 / t
print('Error in time (%):', 100 * error_t)

error_delta_P = error_delta_H
print('Error in pressure difference (%):', 100 * error_delta_P)

error_Q = error_vol + error_t
print('Error in volumetric flow rate (%):', 100 * error_Q)

error_N_Re = error_Q
print('Error in Reynolds Number (%):', 100 * error_N_Re)

error_f = error_delta_P + 2 * error_Q
```

```python
print('Error in f (%):', 100 * error_f)
```

```
Error in delta H (%): [15.38461538  1.09289617  0.9009009   0.79365079
0.53763441  0.34129693
  0.27027027  0.13633265  0.08598452]
Error in volume (%): [2.83286119 1.30378096 0.84745763 0.67567568 0.47169811
0.40322581
 0.2739726  0.18939394 0.12903226]
Error in time (%): [0.01861158 0.02919708 0.03033981 0.0284576  0.02877698
0.02613696
 0.03053435 0.02989537 0.02766252]
Error in pressure difference (%): [15.38461538  1.09289617  0.9009009
0.79365079  0.53763441  0.34129693
  0.27027027  0.13633265  0.08598452]
Error in volumetric flow rate (%): [2.85147277 1.33297805 0.87779743 0.70413327
0.50047509 0.42936276
 0.30450695 0.21928931 0.15669478]
Error in Reynolds Number (%): [2.85147277 1.33297805 0.87779743 0.70413327
0.50047509 0.42936276
 0.30450695 0.21928931 0.15669478]
Error in f (%): [21.08756092  3.75885227  2.65649577  2.20191734  1.53858459
1.20002246
  0.87928418  0.57491126  0.39937407]
```