Notes on Flow Measurement Experiment

The experiment aims to:

- Familiarize students with some common devices and methods used in measuring flow rate
- Present some practical aspects of Fluid Mechanics

Three devices will be used in this experiment, which is to measure water flow rate in a circular pipe. In addition, the simple method of using a bucket and a stop-watch (which has its constraints like, for example, it cannot be used with air, or when there is no opening in the pipe) is also used for comparison. The devices are the Venturi Meter, Flow Nozzle, and Plate Orifice. Description of these devices can be seen in pages 654 - 665 of Street et al.’s Elementary Fluid Mechanics (1996). Essentially, in each of these devices, flow rate is related to the pressure drop across it. Note that correction factors ($C_v$, $C$) are needed in the relevant formulas. Also, these factors vary with flow rate (or velocity) in the pipe in the form of the Reynolds number. The pressure differences are measured with electronic equipment, so pay particular attention to the calibration of the pressure sensors (i.e. the correspondence between electronic signals and pressure in kPa, say). Also, take careful notes of the devices dimensions.

A range of flow rate will be measured. Points of discussion would include:

- Accuracy of each device (compared with the bucket-and-stop-watch values)
- Consistency of values obtained by each device and method (i.e. do they vary in some irregular way?)
- Relative energy cost (in term of pressure drop across each device)
- Relative advantages and disadvantages of each device and method
- Further discussion on flow measurement: other methods, other fluids, etc.
- Suggestions on how to extend or improve upon the experiment
- Etc.

Figure 1 shows the experimental setup, and the arrangement for measuring the pressure difference in a flow measuring device; the Differential Pressure Transmitter (DP Cell) and Multimeter (Ammeter) assembly receives pressure difference from a measuring device as input, and displays electric current in mA as output. Calibrations of the DP Cells (from the Kent Taylor company) are shown in Figure 2. Figure 3 shows constructions of the three measuring devices and Figure 4 curves for the correction factors $C_v$ and $C$. Sample calculations are also included below.
Details of devices (see also Street et al. (1996), pp. 654 - 665 & AS 2360):

Venturi: $D = 52.60 \text{ mm}$, $d = 20.35 \text{ mm}$
Orifice Plate: $D = 52.60 \text{ mm}$, $d = 25.60 \text{ mm}$, Type: Square-edged, Tappings: $D$ & $D/2$
Nozzle: $D = 52.60 \text{ mm}$, $d = 20.00 \text{ mm}$

Fig. 1: Experimental Setup and Arrangement for measuring pressure difference
Date 27/4/2000

Kent Taylor DP cell calibration unit 1

unit 1 nozzle

<table>
<thead>
<tr>
<th>kPa</th>
<th>mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.01</td>
</tr>
<tr>
<td>10</td>
<td>8.15</td>
</tr>
<tr>
<td>20</td>
<td>12.38</td>
</tr>
<tr>
<td>30</td>
<td>16.66</td>
</tr>
<tr>
<td>38</td>
<td>19.99</td>
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</tbody>
</table>

Kent Taylor DP cell calibration unit 2

unit 2 orifice

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<th>kPa</th>
<th>mA</th>
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<td>4</td>
</tr>
<tr>
<td>10</td>
<td>8.19</td>
</tr>
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<td>20</td>
<td>12.4</td>
</tr>
<tr>
<td>30</td>
<td>16.61</td>
</tr>
<tr>
<td>38</td>
<td>20</td>
</tr>
</tbody>
</table>

Kent Taylor DP cell calibration unit 3

unit 3 venturi

<table>
<thead>
<tr>
<th>kPa</th>
<th>mA</th>
</tr>
</thead>
<tbody>
<tr>
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<td>4</td>
</tr>
<tr>
<td>10</td>
<td>8.18</td>
</tr>
<tr>
<td>20</td>
<td>12.4</td>
</tr>
<tr>
<td>30</td>
<td>16.61</td>
</tr>
<tr>
<td>38</td>
<td>20</td>
</tr>
</tbody>
</table>

**Fig. 2:** Calibration charts for the Differential Pressure Transmitters (DP Cells)
Fig. 3: Constructions of the three flow measuring devices.

Venturi meter coefficients (from Street et al., 1996)

Formulas for flow rate $Q$ are:

1) for venturi meters and flow nozzles:

$$Q = C_v A_2 \left[ \left( \frac{A_2}{A_1} \right)^{\frac{1}{2}} - \left( \frac{P}{\rho} + g z_1 \right) - \left( \frac{P}{\rho} + g z_2 \right) \right]^{\frac{1}{2}}$$

where $A_{1,2}$ is area at sections 1, 2 respectively (see Fig. 3).

2) for orifice:

$$Q = C A \left[ \left( \frac{P}{\rho} + g z_1 \right) - \left( \frac{P}{\rho} + g z_2 \right) \right]^{\frac{1}{2}}$$

where

$$A = \frac{\pi D^2}{4}$$

being orifice's area.

Note that often $z_1 = z_2$, and the $g z$ terms cancel out.

Fig. 4: (Correction) Coefficients for the 3 flow measuring devices.
# Data Sheet

## Flow Measuring Devices

<table>
<thead>
<tr>
<th>Dimensions in mm</th>
<th>Flow Measuring Devices</th>
<th>Date</th>
<th>Volume</th>
<th>Time</th>
<th>Q Flowrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nozzle: d = 2.0·0</td>
<td></td>
<td>litres</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orifice: d = 2.5·0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Venturi: d = 2.6·35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D = 5.2·6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D = 2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>D = 2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 1 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 2 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 3 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 4 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 5 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 6 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 7 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 8 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| 9 mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| # mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| # mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| # mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
| # mA             |                        |      |        |      |           |
| kPa              |                        |      |        |      |           |
Sample Calculations

1. Tank & stop watch measurements:
   220 kg in 2 min 22 sec (142 s)

   Multimeter (Ammeter) readings:
   - for nozzle, 9.5 mA
   - for orifice plate, 9.2 mA
   - for venturi meter, 9.29 mA.

   we do calculations for orifice plate.

   From calibration chart for orifice,
   
   \[ 9.2 \text{ mA} \Rightarrow \Delta P = 12.5 \text{ kPa} \]

   From Street et al. (1996), p.660:

   Flow rate \( Q = C A \sqrt{\frac{2 \Delta P}{ho}} \)

   Plate dimensions \( d = 25 \text{ mm}; D = 52.6 \text{ mm} \)

   \[ \frac{d}{D} = \frac{25}{52.6} = 0.48 \] ;
   \[ A = \frac{\pi d^2}{4} = \frac{\pi \times 0.025^2}{4} = 4.91 \times 10^{-4} \text{ m}^2 \]
   
   Assume a large \( Re \), say \( Re = 10^5 \); this gives
   \[ C \approx 0.63 \] for \( d/D = 0.48 \) (Street et al., p.661)

   \[ \therefore Q = 0.63 \times 4.91 \times 10^{-4} \sqrt{\frac{2 \times 12500}{100}} = 0.00155 \text{ m}^3/\text{s} \]

   This gives \( Re = \frac{4Q}{\pi d \rho} \)

   \[ = \frac{4 \times 0.00155}{4 \times 0.025 \times 1 \times 10^{-6}} = 7.9 \times 10^4 \]

   \[ C \approx 0.63 \Rightarrow Q = 0.00155 \text{ m}^3/\text{s} \]

   \[ \Rightarrow Q = 0.00155 \text{ m}^3/\text{s} \]

   \[ M = 1.55 \text{ Kg/s} \] (mass flow rate)

   \[ M \text{ measured (tank & stop watch)} = \frac{220 \text{ Kg}}{142} = 1.55 \text{ Kg/s} \]

   Excellent Agreement!
Tank & Stop Watch measurements:

220 Kg in 1 min 24 sec (84 s)

Multimeter (Ammeter) readings:

Nozzle: 19.3 mA; Orifice: 18.6 mA; Venturi: 18.75 mA

We now do calculations for nozzle.

From calibration graph for nozzle: 19.3 mA → \( \Delta P = 36.7 \) kPa

Nozzle dimensions: \( d = 20 \) mm

\( D = 52.6 \) mm (pipe diameter)

![Fig.4 or](image)

\( \text{(Referring to p.658 of Street et al.) } \)

\[
\frac{d_2}{d_1} = \frac{d}{D} = \frac{20}{52.6} = 0.38
\]

\[
A_2 = \frac{\pi d_2^2}{4} = \frac{\pi d^2}{4} = \frac{\pi \times 0.020^2}{4} = 3.14 \times 10^{-4} \text{ m}^2
\]

Assume an initial large Reynolds number, \( Re = 2 \times 10^5 \)

Coefficient \( C_v \) (see Street et al., p.658) = 0.985

For \( d_2/d_1 = 0.38 \) and \( Re = 2 \times 10^5 \)

Flow rate (see Street et al., pp. 656-659):

\[
Q = \frac{C_v A_2}{\sqrt{1 - \left( \frac{A_2}{A_1} \right)^2}} \sqrt{\frac{2 \Delta P}{\rho}}
\]

\[
Q = \frac{C_v A_2}{\sqrt{1 - \left( \frac{A_2}{A_1} \right)^2}} \sqrt{\frac{2 \times 36700}{1000}} = 0.80268 \text{ m}^3 / s
\]

\[
Re = \frac{\rho V_2 d_2}{M} = \frac{4Q}{\pi d_2 v} = \frac{4 \times 0.00268}{\pi \times 0.020 \times 1 \times 10^{-6}} = 1.71 \times 10^5
\]
This gives new \( C_v = 0.983 \)

\[
Q = 0.00267 \text{ m}^3/\text{s}
\]

\[
\Rightarrow \quad Re = 1.70 \times 10^5 = Re \text{ of previous iteration } (1.71 \times 10^5)
\]

\[
\therefore \quad \text{Accept } Q = 0.00267 \text{ m}^3/\text{s} \text{ as answer.}
\]

\[
\therefore \quad \text{Mass flow rate } M = \rho Q = 1000 \times 0.00267 = 2.67 \frac{\text{Kg}}{\text{s}} \text{ (calculated)}
\]

From tank & stopwatch measurements

\[
M_{measured} = \frac{220}{84} = 2.62 \frac{\text{Kg}}{\text{s}}
\]

Again, excellent agreement!