CHAPTER

THREE

FLUID MECHANICS

3.1. Measurement of Pressure Drop for Flow through Different Geometries

3.2. Determination of Operating Characteristics of a Centrifugal Pump

3.4. Viscosity Determination of non-Newtonian Fluids

3.1. MEASUREMENT OF PRESSURE DROP FOR FLOW THROUGH DIFFERENT GEOMETRIES

Keywords: *Pressure loss, straight pipe, pipe bend, orifice meter, venturi meter.*

Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

3.1.1. Aim

To investigate the variations in fluid pressure for flow through straight pipes, pipe bends, orifice and venturi meters.

3.1.2. Theory

In chemical engineering operations, fluids are conveyed through pipelines in which viscous actions lead to friction between the fluid and the pipe wall. When a fluid flows along a pipe, friction between the fluid and the pipe wall causes a loss of energy. This energy loss shows itself as a progressive fall in pressure along the pipe and varies with the rate of the flow. [1]

When a fluid is moving in a closed channel such as a pipe two types of flow can be occurred such as laminar and turbulent flow. At low velocities, fluid is moving without lateral mixing and there is no sign of mixing such as eddies or swirl. This type of flow regime is called laminar flow. On the other hand, at higher velocities lateral mixing occurs with eddies and swirls. This type of flow regime is called turbulent flow. [2]

The regime of the flow can be predicted using the Reynolds number [3]. The equation that is used to calculate Reynolds number is shown below:

$$Re = \frac{Du\rho}{\mu} \tag{3.1.1}$$

where,

Re: Reynolds number

D: inside diameter, m

u: mean velocity, m/s

ρ: density of fluid, kg/m^3

μ: viscosity of the fluid, kg/m s

Bernoulli equation can be applied to find the relation between the velocity difference and the pressure loss for pipes and fittings, [4]

$$\frac{\Delta P}{\rho} + g\Delta z + \frac{\Delta u^2}{2} + W + F = 0 \qquad (3.1.2)$$

where,

ΔP: pressure drop,	Pa
g: gravitational acceleration,	m/s^2
W: work done or to the system,	J
F: frictional dissipation,	J
z: elevation,	m

3.1.2.1. Pressure Drop in Straight Pipes

The head loss due to friction in straight pipe can be calculated by the expression [5]:

$$\Delta P_{st} = 2f\,\frac{Lu^2\rho}{D} \qquad (3.1.3)$$

where

ΔP_{st} : pressure drop for straight pipe, Pa

D: diameter of pipe, m

f: friction factor

L: length of pipe, m

3.1.2.2. Pressure Drop in Smooth and Sharp Bends

The change of direction forced on a fluid when it negotiates a bend produces turbulence in the fluid and a consequent loss of energy. The net loss in pressure is greater than that for the same length of straight pipes. Abrupt changes of direction produce greater turbulence and larger energy losses than do smoothly contoured changes. The relationship between pressure drop and the velocity can be derived by using the energy balance and the following equation shows the relation in smooth bend and sharp bends with a constant, K_L: [5]

$$\Delta P_{bend} = \frac{K_L\rho u^2}{2} \qquad (3.1.4)$$

where,

ΔP_{bend} : pressure drop for sharp and smooth bends, Pa

K_L: dimensionless factor for sharp and smooth bends

3.1.2.3. Pressure Drop through a Venturi Meter

Venturi meter consists of a throttling section which leads to pressure drop due to the turbulence created at this section. Fluid velocity can be measured by using Bernoulli equation and equation of continuity in order to calculate the pressure loss through the pipe. A straight line relation exists between the flow rate and the square root of the pressure drop value, and this principle is utilized in the design of venturi meter [6]. Discharge coefficient of venturi meter (C_v) is inserted into the Bernoulli equation for u_2 term, and turned into mean velocity to obtain the following relationship [5],

$$\Delta P_{venturi} = \frac{\rho {u_m}^2(1-\beta^4)}{2C_v^2} \tag{3.1.5}$$

where

$\Delta P_{venturi}$: pressure drop for venturi meter, Pa

β: dimensionless number relating the diameter of the throttling section of venturi and inside diameter of the pipe

3.1.2.4. Pressure Drop through an Orifice Meter

An orifice meter consists of a circular disk with a central hole which is bolted between the flanges on two sections of pipe. Bernoulli's equation is applied to the fluid as it flows through the orifice of a reduced area because it is found experimentally that a contracting stream is relatively stable, so that frictional dissipation can be ignored, especially over a short distances. As a result, as the velocity of the fluid increases, the pressure will decrease. Applying the mass balance and Bernoulli equation (energy balance), one can get a relation giving the pressure drop through the orifice meter as; [4]

$$\Delta P_{orifice} = \frac{\rho {u_m}^2(1-\beta^4)}{2C_o^2} \tag{3.1.6}$$

where

$\Delta P_{orifice}$: pressure drop for orifice meter, Pa

β: dimensionless number relating the diameter of the throttling section of orifice and inside diameter of the pipe.

C_o: discharge coefficient of orifice meter (which can be obtained from discharge coefficient for orifice plates [4])

Various pipe fittings can be implemented on straight pipes; such as venture meter, orifice meter as well as smooth and sharp bends. Fluid flow through pipes and fittings can be investigated with respect to changing liquid flow rate and the effect can be observed via pressure drop.

3.1.3. Experimental Setup

The apparatus used in this experiment is shown in Figure 3.1.1. It consists of 14 main parts.

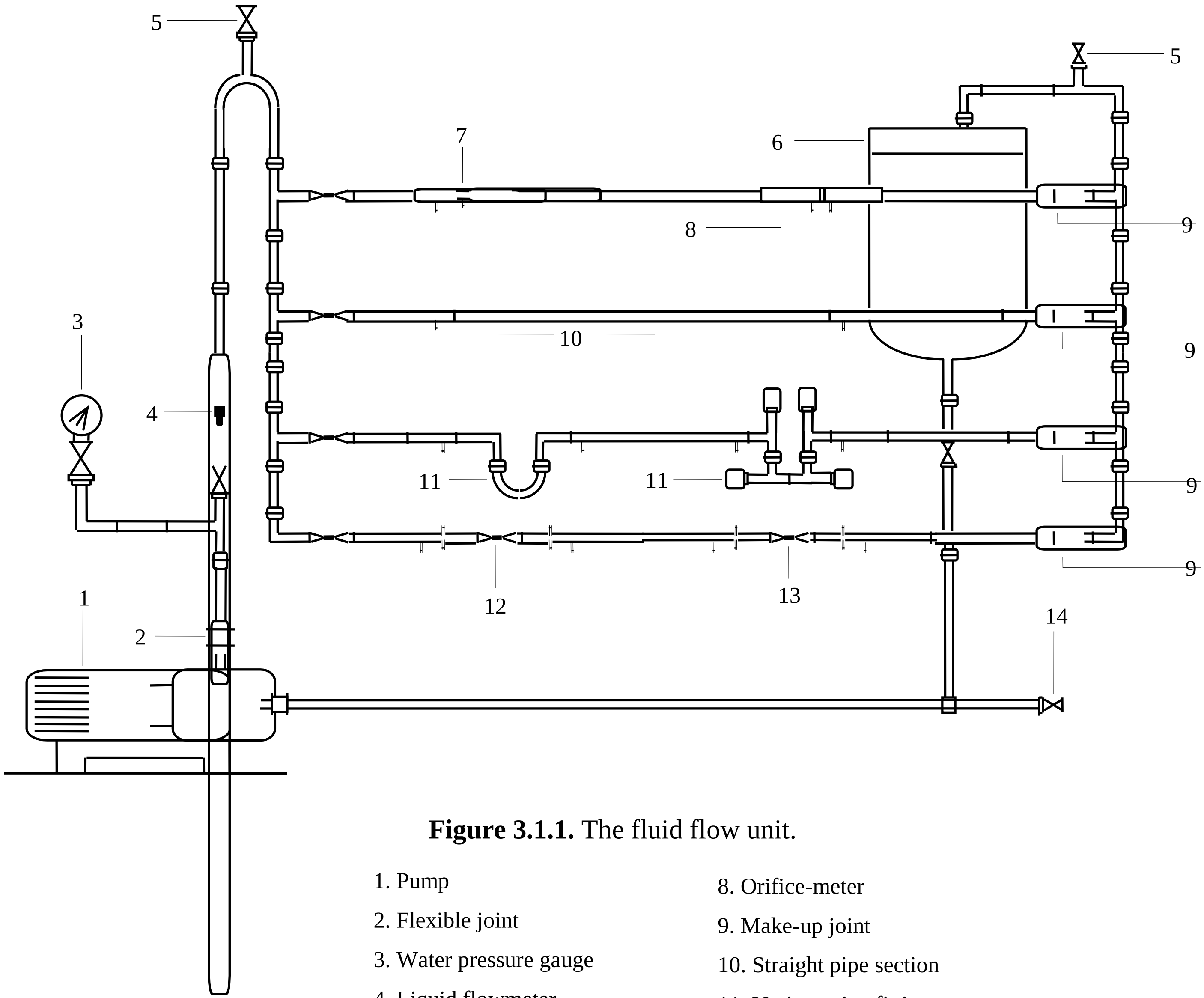

Figure 3.1.1. The fluid flow unit.

1. Pump
2. Flexible joint
3. Water pressure gauge
4. Liquid flowmeter
5. Vent valve
6. Cylindrical vessel (50 L)
7. Venturi-meter
8. Orifice-meter
9. Make-up joint
10. Straight pipe section
11. Various pipe fittings
12. Gate valve
13. Globe valve
14. Drain valve

3.1.4. Procedure

1. Be sure that all isolation valves are open.
2. Set the control valve to 440 gal/h.
3. Report the readings on all water manometers connected to the pressure tappings.
4. Select the pipe line on which the experiment will be performed by turning off the isolation valves for all other horizontal pipe runs.
5. Check that isolating valve on the selected pipe run is fully open.
6. Report the reading on the selected pipe line from the water manometer.
7. Open all isolation valves. Repeat Steps 4-6 for the remaining pipe lines.
8. Operate the control valve from 440-520 gal/h and note manometer readings for each case.
9. With the same flow rates, repeat the experiment once more to avoid vague data.
10. Turn off the flow control valve.

3.1.5. Report Objectives

1. Show the variation of friction loss with respect to flow rate. Calculate theoretical and experimental losses.
2. For the smooth and sharp bends, update K_L values depending on your experimental data.
3. Draw graphs for experimental and theoretical pressure drop values with respect to volumetric flow rate to show the effect of flow rate
4. Explain your conclusions.
5. Derive all equations in Appendix.

Safety Issues: Before starting the experiment, be sure to open all the water valves. Wear goggles in order to prevent water splash from discharge at point 5 in the apparatus. Prevent closing all the valves at the same time during the experiment.

References

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Appendix

Table A.1. List of Parameters

Diameter of straight pipe (10^{-4} m)	254
Length of pipe (10^{-2} m)	180
Diameter of venturi meter throat (10^{-2} m)	1.430
Diameter of orifice meter throat (10^{-2} m)	253
Diameter of pipe with orifice and venturi meter (10^{-2} m)	381
Area (straight pipe) (10^{-6} m^2)	510
Area (venturi) (10^{-6} m^2)	160
Area (orifice) (10^{-6} m^2)	500
Density (kg/m^3)	998.2
C_v	1.37
β (venturi) (10^{-3})	380
β (orifice) (10^{-3})	664
K_L (smooth bend) (10^{-3})	800
K_L (sharp bend) (10^{-2})	260
Area (smooth bend) (10^{-6} m^2)	248
Area (sharp bend) (10^{-6} m^2)	248

3.2. DETERMINATION OF OPERATING CHARACTERISTICS OF A CENTRIFUGAL PUMP

Keywords: *Pump, NPSH, cavitation*.

Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

3.2.1. Aim

To determine the Net Positive Suction Head (NPSH) of a centrifugal pump theoretically and experimentally, and also to investigate the operating curve of the pump.

3.2.2. Theory

The operating characteristics of a particular centrifugal pump are most conveniently given in the form of curves of discharge head developed against delivery for various running speeds and throughputs. The actual head developed is always less than the theoretical one for a number of reasons. The total discharge head of a pump, h_d, is defined as the pressure at the outlet of the pump plus the velocity head at point of attachment of the gauge, and is given by [1]:

$$h_d = h_{dg} + atm + \frac{u^2}{2g} \tag{3.2.1}$$

where h_d : total discharge head, m of liquid

h_{dg} : gauge reading at discharge outlet of pump, m of liquid

atm : barometric pressure, m of liquid

u : velocity at outlet of pump, m/sec

g : gravitational constant, m/sec^2

h_{dg} is measured from the pressure gauge on the outlet side of the pump. A height correction is necessary due to the position of the gauge above or below the impeller level.

Net Positive Suction Head is defined as the amount by which the absolute pressure of the suction point of the pump exceeds the vapor pressure of the liquid being pumped, at the operating temperature. For all pumps, there is a minimum value for the NPSH. Below this value, the vapor pressure of the liquid begins to exceed the suction pressure causing bubbles of vapor to form in the body of the pump. This phenomenon is known as cavitation and is usually accompanied by a loss of efficiency and an increase in noise. For this reason minimum values of NPSH are important and are usually specified by pump manufacturers. NPSH can be calculated using [2]:

$$NPSH = P_{in} - P_{vap} \tag{3.2.2}$$

where P_{in} : Pressure at the pump inlet, N/m3

P_{vap} : Vapor pressure of the liquid, N/m3

The pressure at the pump inlet is made up of several pressures including the static head of liquid from pump inlet to the liquid surface, external pressure above liquid, velocity head i.e. the head developed, and head due to friction losses in the suction pipework [2].

Pressure at the pump inlet can be calculated theoretically from Bernoulli's equation [1],

$$\frac{P_2}{\rho g} + z_2 + \frac{u_2^2}{2g} = \frac{P_1}{\rho g} + z_1 + \frac{u_1^2}{2g} + \frac{F}{g} \tag{3.2.3}$$

where P : pressure, N/m^2

ρ : density of the liquid, kg/m^3

u : velocity, m/sec

z : height, m

F : friction losses in pipe works

g : gravitational constant, m/sec^2

Subscripts 1 and 2 refer to pump inlet and to surface of liquid reservoir, respectively. By applying the above equation and considering the fact that the height of the liquid (z_2) in the reservoir stays constant and the velocity at the liquid surface (u_2) is zero, [1]

Then

$$\frac{P_1}{\rho g} = \frac{P_2}{\rho g} + (z_2 - z_1) - \frac{u_1^2}{2g} - \frac{F}{g} \tag{3.2.4}$$

The head due to friction losses in the inlet pipework can be calculated from [1],

$$F = 2 f_F u^2 \frac{L}{D} \tag{3.2.5}$$

where f_F : Fanning friction factor which has correlations with the Reynold's number

u : velocity at the inlet of pump, m/sec

g : gravitational constant, m/sec^2

L : Length of pipe-corrected to include the effects of bends, elbows, valves, reducers etc., m

D : diameter at the inlet and/or outlet, m

For hydraulically smooth surfaces, in which the pipe wall roughness is not important, the fanning friction factor is calculated by using the Blasius equation, which provides a correlation for the experimental observations of turbulent flows with Reynolds numbers below 100,000 [1].

$$f_F = 0.079\,\mathrm{Re}^{-1/4} \tag{3.2.6}$$

Piping installations mostly include a variety of auxiliary hardware such as valves and elbows. Additional turbulence and frictional dissipation is created by these fittings due to the course change from a straight line, which results in additional pressure drop comparable to that of the pipeline itself. The effect of the fittings is introduced in the calculation of the pressure drops simply recognizing that additional pressure drop caused by the fitting would be produced by a certain length of pipe. Therefore, the contribution of the fitting is also added into the length of pipe, based on the equivalent length (L/D_e) to the fitting [1].

The pressure at the inlet of the pump may be calculated through Bernoulli equation along with the considerations mentioned above. This allows theoretical NPSH calculation and its comparison with the experimental one. The operating curve and NPSH values enable to evaluate the working conditions for the centrifugal pump.

3.2.3. Experimental Setup

The apparatus used in this experiment is shown in Figure 3.2.1.

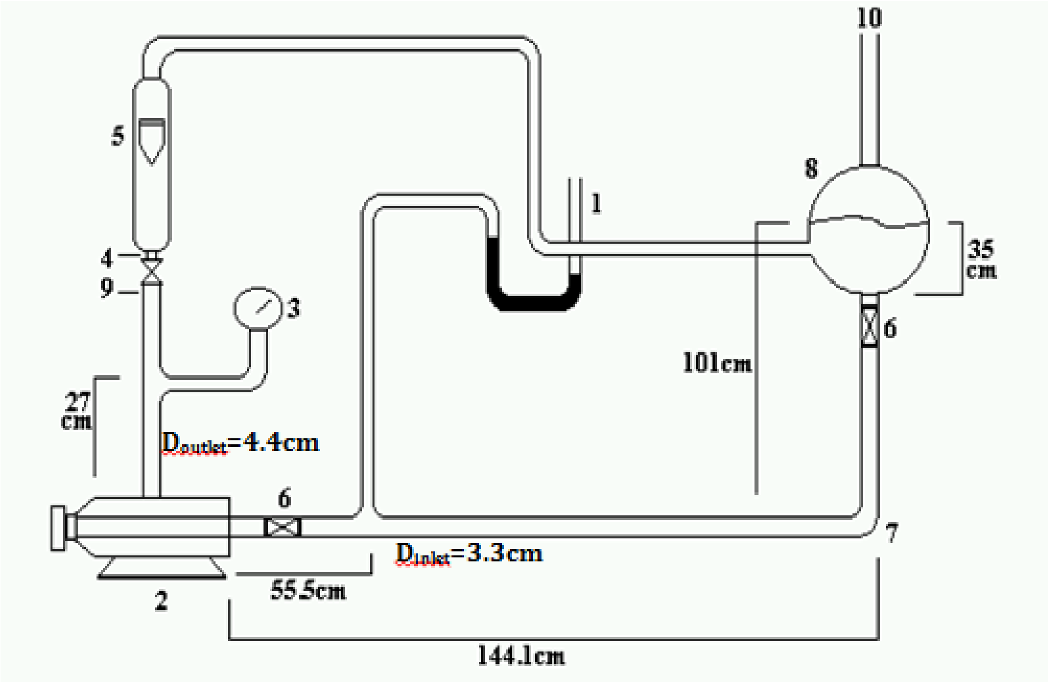

Figure 3.2.1. Pump test unit apparatus.

1. Manometer (open to atmosphere)
2. Pump
3. Barometer (water pressure gauge)
4. Bellows
5. Flowmeter
6. Valves
7. Elbow
8. Spherical buffer vessel
9. Control valve
10. Liquid feed or vacuum connection

3.2.4. Procedure

1. Get the help of the person in charge to turn on the pump.
2. Open the flow meter control valve slowly to give a scale reading of approximately 1/5th full scale value.
3. Allow the unit to settle down for a few minutes. Record flow meter reading, inlet pressure, and outlet pressure.
4. Repeat the experiment for increments of 1/5th full scale value of the flow meter from 2 to maximum throughput.

5. Measure the difference between the liquid level in spherical vessel and the center line of the pump.
6. Repeat the experiment.

Safety Issues: Do not attempt to turn on the pump on your own, get the help of the person in charge. During the experiment, do not set the flow to the zero scale reading for any reason. At the end of the experiment, be sure that the pump is turned off.

3.2.5. Report Objectives

1. Calculate total discharge head for each flow rate, and draw discharge head vs. flow rate graph. (Note that the conversion of the flow rate scale reading is done as follows: W(lt/min)=3.317R(scale reading)+8.44.)
2. Calculate NPSH experimentally.
3. Calculate NPSH theoretically. (Note that there is an open gate valve, 4:1 contraction, and a 90^o elbow between the reservoir and the pump inlet.)
4. Comment on the h_d vs flow rate graph.
5. Discuss the effects of change in flow rate on these characteristics.

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3.4. VISCOSITY DETERMINATION OF NON-NEWTONIAN FLUIDS

Keywords: *Newtonian, non-Newtonian flow, viscosity, apparent viscosity, shear rate.*

Before the experiment: *Read the booklet carefully. Be aware of the safety precautions.*

3.4.1. Aim

To determine the apparent viscosity, η_a, as a function of shear rate and to investigate the effect of diameter and the length of the glass capillaries on flow curves.

3.4.2. Theory

Fluids can be classified as Newtonian and non-Newtonian. Newtonian fluids obey the Newton's law of viscosity. According to the Newton's law of viscosity, shear stress is directly proportional to the velocity gradient defined as shear rate [1]:

$$\tau_w = \mu \dot{\gamma}_w \qquad (3.4.1)$$

where $\dot{\gamma}_w$, τ_w, and μ are shear rate, shear stress, and viscosity of the fluid, respectively.

Water, oil and air are considered as Newtonian fluids since they have constant viscosity and almost no elasticity. Fluids that do not obey Newton's law of viscosity are non-Newtonian fluids. Ketchup, custard, toothpaste, blood and paint are non-Newtonian fluids due to their viscoelastic properties, unsteady viscosity and high elasticity [2].

For incompressible Newtonian fluids the expression for the shear stress is given by Eq. 3.4.1. The generalized Newtonian fluid model is obtained by replacing the constant viscosity μ by the non-Newtonian viscosity η_a, a function of shear rate [1]:

$$\tau_w = \eta_a \dot{\gamma}_w \qquad (3.4.2)$$

with

$$\eta_a = \eta_a(\dot{\gamma}_w) \qquad (3.4.3)$$

Rabinowitsch-Mooney equation is one of the few methods to describe the shear rate of an incompressible, non-Newtonian fluid with laminar and steady flow regime, as a function of shear stress [3].

$$\dot{\gamma}_w = f(\tau_w) = \left(\frac{3Q}{\pi R^3}\right) + \tau_w \left[\frac{d(Q/(\pi R^3))}{d\tau_w}\right] \tag{3.4.4}$$

where Q and R are volumetric flow rate and radius of the capillary, respectively. This expression can be also expressed as:

$$\dot{\gamma}_w = \left[\frac{3n' + 1}{4n'}\right]\Gamma \tag{3.4.5}$$

where $\Gamma = 4Q/(\pi R^3)$ and $n' = d(\ln\tau_w)/d(\ln\Gamma)$, that is the gradient of the ln τ_w vs. ln Γ curve.

Shear stress at the wall (τ_w) is defined for all fluids as [2]:

$$\tau_w = \frac{D\,\Delta P}{4L} \tag{3.4.6}$$

where 'D' and 'L' are diameter and length of the capillary, respectively. Pressure drop (ΔP) within the capillary at any time point is given by:

$$\Delta P = \rho g h(t) \tag{3.4.7}$$

where 'ρ' is the density of the fluid, 'g' is the acceleration of the gravity, and 'h' is the height of the liquid above.

Volumetric flow rate (Q) can be evaluated from Equation 3.4.8:

$$Q = -A\frac{dh(t)}{dt} \tag{3.4.8}$$

where 'A' is the cross sectional area and 't' is the time in the latter one. Negative sign is required in the second equation to satisfy the sign convention. Volumetric flow rate can be calculated through the evaluation of time derivative at each time point in the h(t) vs. t graph.

The calculation of the gradient of the ln τ_w vs. ln Γ curve by taking the derivative of that curve at each point enables the calculation of the apparent viscosity. The change of apparent viscosity with time and shear rate can be investigated, thereby.

3.4.3. Experimental Setup

The apparatus used in this experiment is shown in Figure 3.4.1. Cross-sectional area of the burette is 1 cm^2.

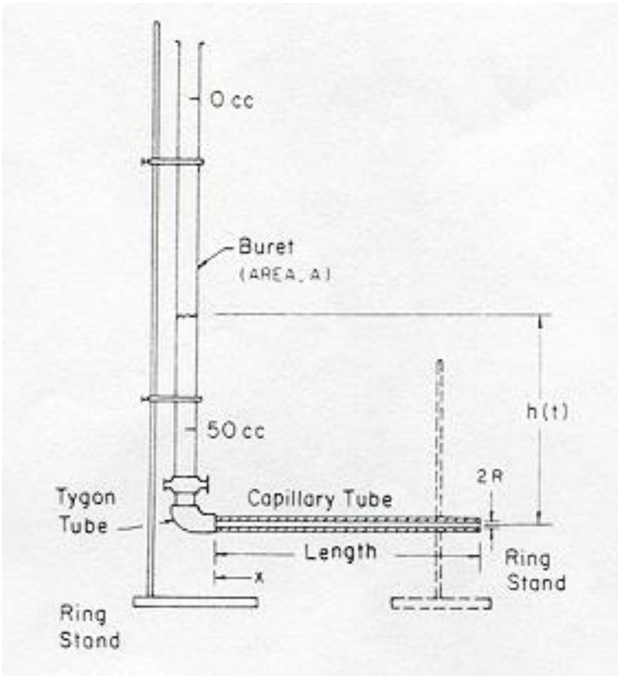

Figure 3.4.1. The experimental setup for non-Newtonian fluid flow in a capillary tube.

3.4.4. Procedure

1. Take a glass capillary 1.2 mm in diameter, 40 cm in length, and attach it to a 50 ml burette.
2. Fill the burette with 0.5% (wt.) carboxymethyl cellulose sodium (CMC) solution and note the height of the solution (h_0).
3. Open the valve of the burette and start the stopwatch at the same time.
4. Record the height for appropriate time intervals.
5. Repeat the above procedure for the capillaries 1.2 mm and 2.0 mm in diameter and 30 cm in length.
6. Determine the density of the solution using a pycnometer.
7. Repeat the measurements for each capillary.

Safety Issues: Carboxymethyl cellulose sodium (CMC) solution is used in the experiment. CMC is hazardous in case of skin contact (irritant), of eye contact (irritant), and of ingestion. Use splash goggles, lab coat, and gloves during the experiment. In case of skin contact with CMC, wash immediately with plenty of water and seek medical attention for irritation. In case of eye contact, remove any contact lenses, flush eyes with water and seek medical attention. Seek immediate medical attention in case of inhalation of CMC. In addition, please be careful while working with glass capillaries to avoid injury. In the case of glass breaking, use glass waste container and inform the person in charge.

3.4.5. Report Objectives

1. Plot h(t) vs t graph using experimental data.
2. Plot apparent viscosity vs time graphs.
3. Plot apparent viscosity vs shear rate graphs.

References

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