Komar University of Science and Technology

PTE 3315C
Reservoir Fluid Properties

LABORATORY MANUAL

December 2015

CONTENTS 1

1 LABORATORY SAFETY

1.1. THE PRINCIPLES OF SAFETY

The main principles of safety in the lab to be considered are:

1. Safety Program
2. Be concerned about the safety of others
3. Understand the hazards associated with your particular experiment
4. Know what to do in an emergency
5. Report hazards or hazardous conditions

1.1.1. Lab Practice

- Wear appropriate eye protection whenever working with any potential eye hazards.
- Use a hood for hazardous, volatile, and noxious chemicals.
- Label an experiment to show its in progress
- You are further expected to secure all gas cylinders, to label all containers, to observe posted signs, such as no smoking, and so on.

- GLASSWARE
  1. Use only Pyrex or shutter proof glassware.
  2. Never use cracked or chipped glassware.

Your concern for safety must include the people around you. Your experiment must be safely maintained so that everyone in the area is amply protected and warned of inherent dangers.

1.1.2. Understand the Hazards Associated with Your Particular Experiment

Prevention is the key to safety. Before designing any experiment, it is wise to consider the potential hazards and safety precautions involved in the work. Safety precautions should include correct materials storage, proper ventilation, proper grounding of equipment and training sessions when necessary. Material Safety Data Sheets (MSDS) and equipment manuals are important sources of information.

1.1.3. Know what to do in case of an Emergency

Student must be prepared to respond quickly and precisely to an emergency. You must familiarize yourself with the laboratory you are working in, its exits, and its associated safety equipment: eyewash stations, showers, sinks, fire blankets, fire extinguishers, and spill kits.

If there was an emergency such as a fire, gas leak, release of toxic fumes, or radiation leak, the following procedures should be followed:

1. Alert personnel in the immediate vicinity
2. Confine the fire or emergency, if possible
3. Evacuate the building to Mustered Point
4. Report to Safety Officer or Lab Manager.

1.2. FIRST AID

There are certain serious injuries in which time is so important that treatment must be started immediately.

1.2.1. DIFFICULTIES OF BREATHING

In case of difficulty of breathing (e.g. from electrical shock or asphyxiation), the mouth-to-mouth method of resuscitation is far superior to any other known. If victim is found unconscious on the floor and not breathing, rescue breathing must be started at once, seconds count.

1.2.2. SEVERE BLEEDING

Severe bleeding can almost always be controlled by firm and direct pressure on the wound with a pad or cloth. The cleaner the cloth, the more desirable it is.

1.2.3. BURNS

If the burn is minor, apply ice or cold water.
In case of deep burns:

- Distinguish the fire by a fire blanket
- Put the injured person under a safety shower, removing any clothing contaminated with chemicals.
- Keep the water running on the burn for several minutes to remove heat and wash area.
- Place clean, soaking wet, ice-packed cloth on burned areas.
- Never use a fire extinguisher on a person with burning clothing.

1.3. LABORATORY PRACTICE

- HAZARDOUS CHEMICALS

1. All containers must be labeled and do not use chemicals from unlabeled containers.
2. Never taste or smell any chemical.
3. Clean spills immediately.
4. **MERCURY SPILLS**

For small spills or well contained spills, gather mercury and put it in a closed container (wear gloves). Use special filtered mercury vacuum for picking up larger spills. Never use a regular vacuum, the mercury will contaminate the vacuum.

- GAS CYLINDERS
  - Secure gas cylinders with a strap or chain to a stable object.
  - Transport gas cylinders, with the cap security in place, and always use the proper cart.
  - Before using gas in an experiment, be sure there are no leaks in the system.
  - Never use grease or other lubricants on gauges or connections.
  - Only use regulators, pipes and fitting specified for the type of gas you will be using.
  - Do not locate gas cylinders near heat sources, like furnaces.
  - Store oxygen cylinders and combustible gases separately

2 LIQUID DENSITY

2.1 Definitions

Density (ρ) is defined as the mass of the fluid per unit volume. In general, it varies with pressure and temperature. The dimension of density is kg/m^3 in *SI* or lb/ft^3 in the English system.

Specific gravity (γ) is defined as the ratio of the weight of a volume of liquid to the weight of an equal volume of water at the same temperature. The specific gravity of liquid in the oil industry is often measured by some form of hydrometer that has its special scale. The American Petroleum Institute (API) has adopted a hydrometer for oil lighter than water for which the scale, referred to as the API scale, is

$$^{0}API = \frac{141.5}{\square} - 131.5 \qquad (2.1)$$

Note: When reporting the density the units of mass and volume used at the measured temperature must be explicitly stated, e.g. grams per milliliter (cm^3) at T(^{0}C). The standard reference temperature for international trade in petroleum and its products is 15^{0}C (60^{0}F), but other reference temperatures may be used for other special purposes.

2.2 Measurement of Density

The most commonly used methods for determining density or specific gravity of a liquid are:

1. Westphal balance
2. Specific gravity balance (chain-o-matic)
3. API hydrometer
4. Pycnometer
5. Bicapillary pycnometer.

The first two methods are based on the principle of Archimedes: A body immersed in a liquid is buoyed up by a force equal to the weight of the liquid it displaces. A known volume of the liquid to be tested is weighted by these methods. The balances are so constructed that they should exactly balance in air.

The API hydrometer is usually used for determining oil gravity in the oil field. When a hydrometer is placed in oil, it will float with its axis vertical after it has displaced a mass of oil equal to the mass of hydrometer (Fig. 2.1a). The hydrometer can be used at atmospheric pressure or at any other pressure in a pressure cylinder.

The pycnometer (Fig. 2.1b) is an accurately made flask, which can be filled with a known volume of liquid. The specific gravity of liquid is defined as the ratio of the weight of a volume of the liquid to the weight of an equal volume of water at the same temperature.

Both weights should be corrected for buoyancy (due to air) if a high degree of accuracy is required. The ratio of the differences between the weights of the flask filled with liquid and empty weight, to the weight of the flask filled with distilled water and empty weight, is the specific gravity of the unknown fluid. The water and the liquid must both be at the same temperature.

The bicapillary pycnometer (Fig. 2.1c) is another tool for accurate determination of density. The density of the liquid sample drawn into the pycnometer is determined from its volume and weight.

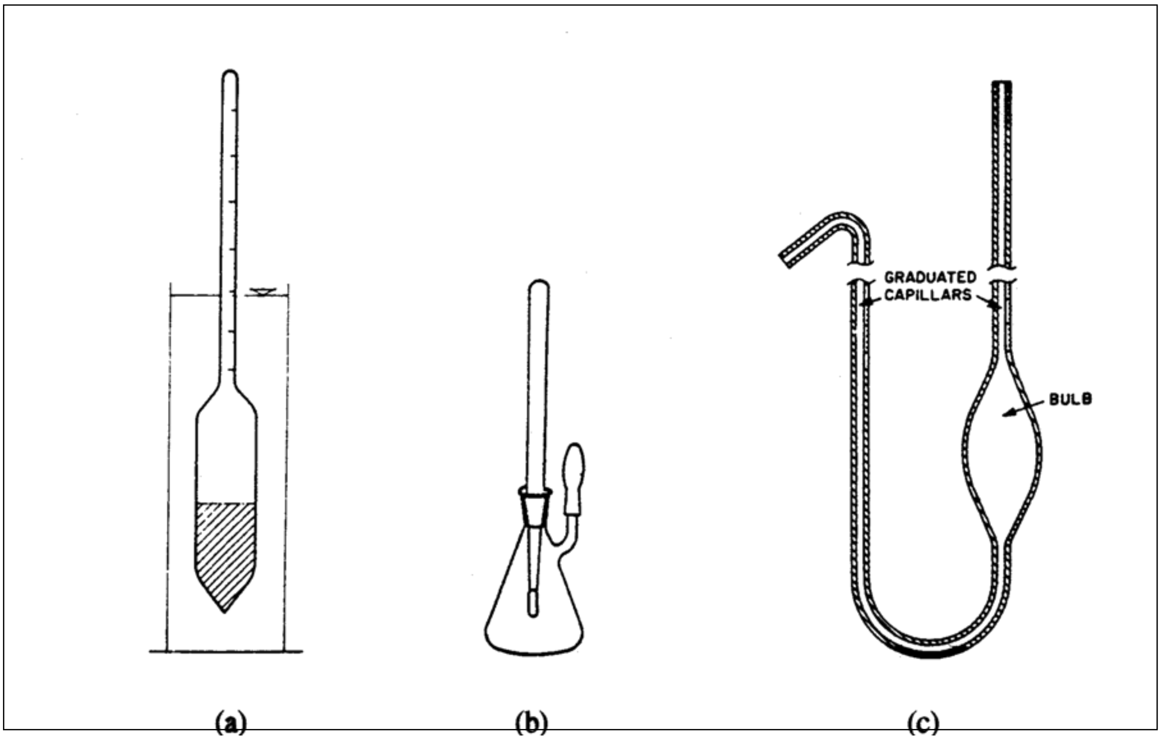


Fig. 2.1: Schematic diagram of hydrometer (a), pycnometer (b), and bicapillary pycnometer (c)

2.3 Experiments

2.3.1 Fluid density using the Pycnometer method (Experiment 1)

Description:

This method covers the determination of the density or relative density (specific gravity) of crude petroleum and of petroleum products handled as liquids with vapor pressure 1.8 bar or less, e.g. stabilized crude oil, stabilized gasoline, naphthane, kerosines, gas oils, lubricating oils, and non-waxy fuel oils.

Procedure:

1. Thoroughly clean the pycnometer and stopper with a surfactant cleaning fluid, rinse well with distilled water. Finally rinse with acetone and dry.

2. Weigh the clean, dry pycnometer with stopper and thermometer at room temperature.

3. Fill the pycnometer with the liquid (oil, brine) at the same room temperature.

4. Put on the stopper and thermometer and be sure there is no gas bubble inside, and then dry the exterior surface of the pycnometer by wiping with a lint-free cloth or paper.

5. Weigh the filled pycnometer.

Calculation and report:

1. Calculate the liquid density and the average density based on your data.
2. Calculate the *absolute* error for each measurement.
3. Calculate the specific gravity.
4. Error source analysis of the pycnometer method.

Table: Density of water, kg/m^3 at different temperatures

18.0^0C----998.5934 18.5^0C----998.4995 19.0^0C----998.4030
19.5^0C----998.3070 20.0^0C----998.2019 20.5^0C -- 998.0973
21.0^0C----997.9902 21.5^0C----997.8805 22.0^0C----997.7683
22.5^0C----997.6536 23.0^0C----997.5363 24.0^0C----997.2944

Temperature: ^{0}C

Fluid	Pycnometer mass (g)	Pycnometer + liquid (g)	Pycnometer volume (cm^3)	Density, ρ(g/cm^3)	Specific gravity, ©	Absolute error, *Ea* (g/cm^3)
ρ_{avr} =						

Equations: Average Density (ρ_{avr}) $=\frac{1}{n}\sum_{i}^{n}\rho_i$

Ea = | (*Average Density*) – (*Measured Density*) |

3 VISCOSITY

3.1 Definitions

Viscosity is defined as the internal resistance of fluid to flow. The basic equation of deformation is given by

$$\tau = \mu\gamma \tag{3.1}$$

where τ is shear stress, γ is the shear rate defined as $\partial v_x/\partial_y$ and μ is the viscosity. The term τ can be defined as *F/A* where *F* is force required to keep the upper plate moving at constant velocity v in the x-direction and *A* is area of the plate in contact with the fluid (Fig. 3.1). By fluid viscosity, the force is transmitted through the fluid to the lower plate in such a way that the x-component of the fluid velocity linearly depends on the distance from the lower plate.

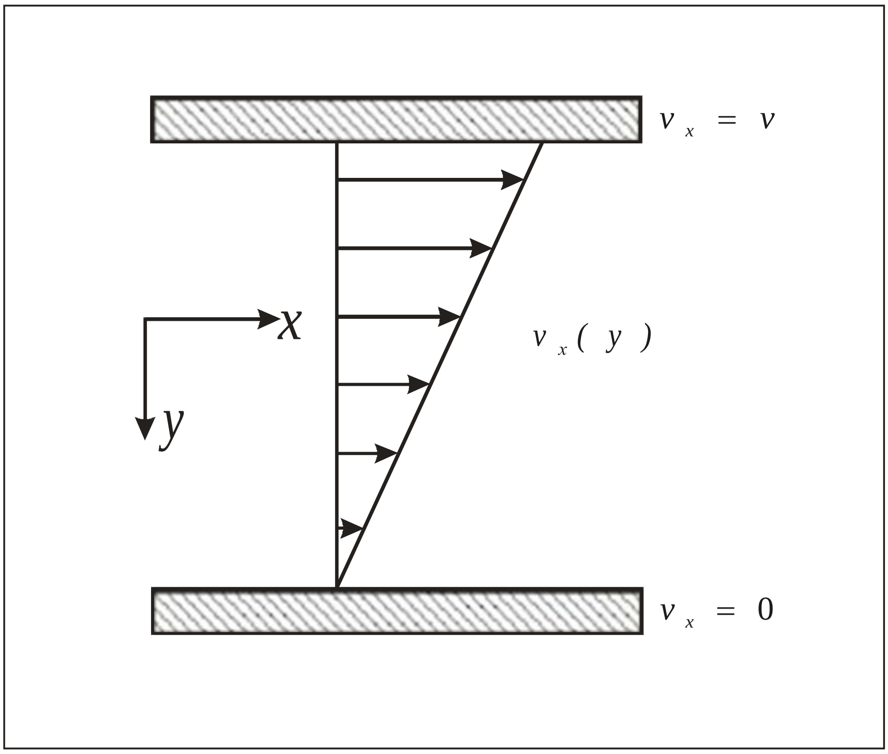


Fig. 3.1: Steady-state velocity profile of a fluid entrained between two flat surfaces.

It is assumed that the fluid does not slip at the plate surface. Newtonian fluids, such as water and gases, have shear-independent viscosity and the shear stress is proportional to the shear rate (Fig. 3.2).

In the oil industry viscosity generally is expressed in centipoise, cp (1 cp =10^{-3} Pa.s).

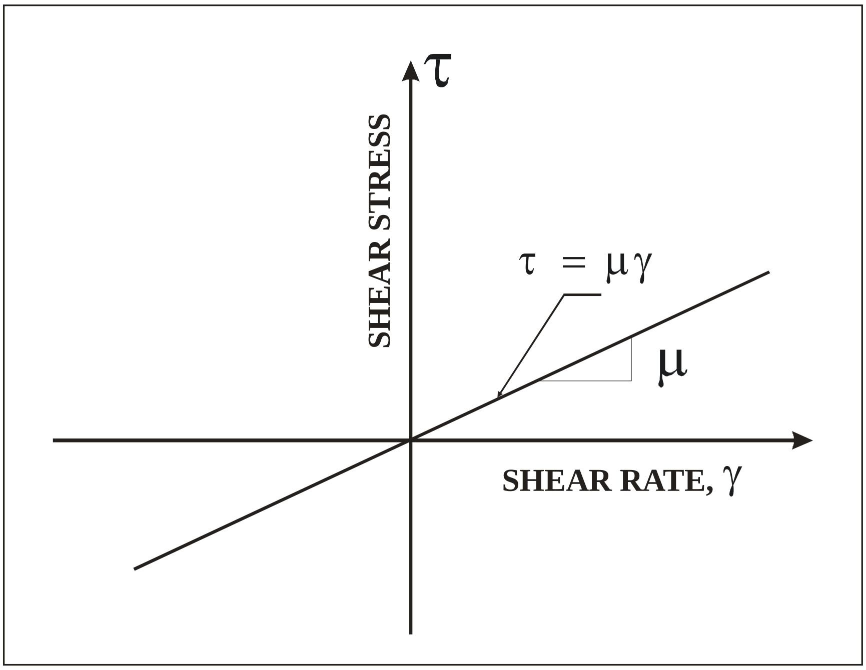


Fig. 3.2: Shear stress vs. shear rate for a Newtonian fluid.

3.2 Effect of Pressure and Temperature on Viscosity

Viscosity of fluids varies with pressure and temperature. For most fluids the viscosity is rather sensitive to changes in temperature, but relatively insensitive to pressure until rather high pressures have been attained. The viscosity of liquids usually rises with pressure at constant temperature. Water is an exception to this rule; its viscosity decreases with increasing pressure at constant temperature. For most cases of practical interest, however, the effect of pressure on the viscosity of liquids can be ignored.

Temperature has different effects on viscosity of liquids and gases. A decrease in temperature causes the viscosity of a liquid to rise. Effect of molecular weight on the viscosity of liquids is as follows; the liquid viscosity increases with increasing molecular weight.

3.3 Methods for Measuring Viscosity

3.3.1 **Capillary Type Viscometer**

Viscosity of liquids is determined by instruments called viscosimeter or viscometer. One type of viscometer for liquids is the *Ostwald viscometer* (Fig. 3.3). In this viscometer, the viscosity is deduced from the comparison of the times required for a given volume of the tested liquids and of a reference liquid to flow through a given capillary tube under specified initial head conditions. During the measurement the temperature of the liquid should be kept constant by immersing the instrument in a temperature-controlled water bath.

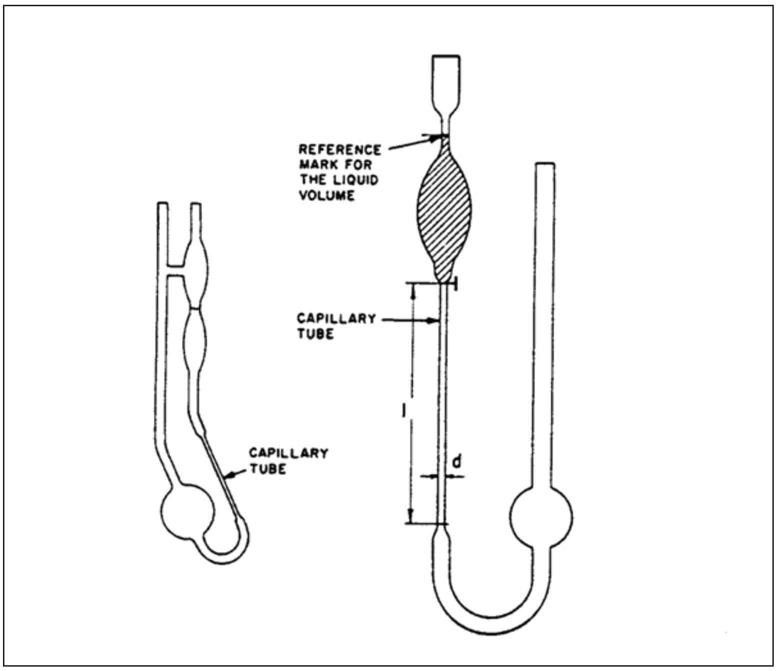


Fig. 3.3: Two types of Ostwald viscometers.

In this method the Poiseuille's law for a capillary tube with a laminar flow regime is used

$$Q = \frac{V}{t} = \frac{\Delta P \pi r^4}{8 \mu l} \tag{3.2}$$

where t is time required for a given volume of liquid V with density of ρ and viscosity of μ to flow through the capillary tube of length l and radius r by means of pressure gradient ΔP. The driving force ΔP at this instrument is $\rho g l$. Then

$$\frac{V}{t} = \frac{\pi r^4 \rho g l}{8 \mu l} \tag{3.3}$$

or

$$\mu = \frac{\pi r^4 \rho g t}{8V} = \mathrm{Const.}\rho t \tag{3.4}$$

The capillary constant is determined from a liquid with known viscosity.

3.3.2 Falling Ball Viscometer

Another instrument commonly used for determining viscosity of a liquid is the *falling (or rolling) ball viscometer* (Fig. 3.4), which is based on Stoke's law for a sphere falling in a fluid under effect of gravity. A polished steel ball is dropped into a glass tube of a somewhat larger diameter containing the liquid, and the time required for the ball to fall at constant velocity through a specified distance between reference marks is recorded. The following equation is used

$$\mu = t(\rho_b - \rho_f)K \tag{3.5}$$

where μ = absolute viscosity, *cp*
t = falling time, *s*
ρ_b = density of the ball, g/cm^3
ρ_f = density of fluid at measuring temperature, g/cm^3
K = ball constant.

The ball constant K is not dimensionless, but involves the mechanical equivalent of heat.

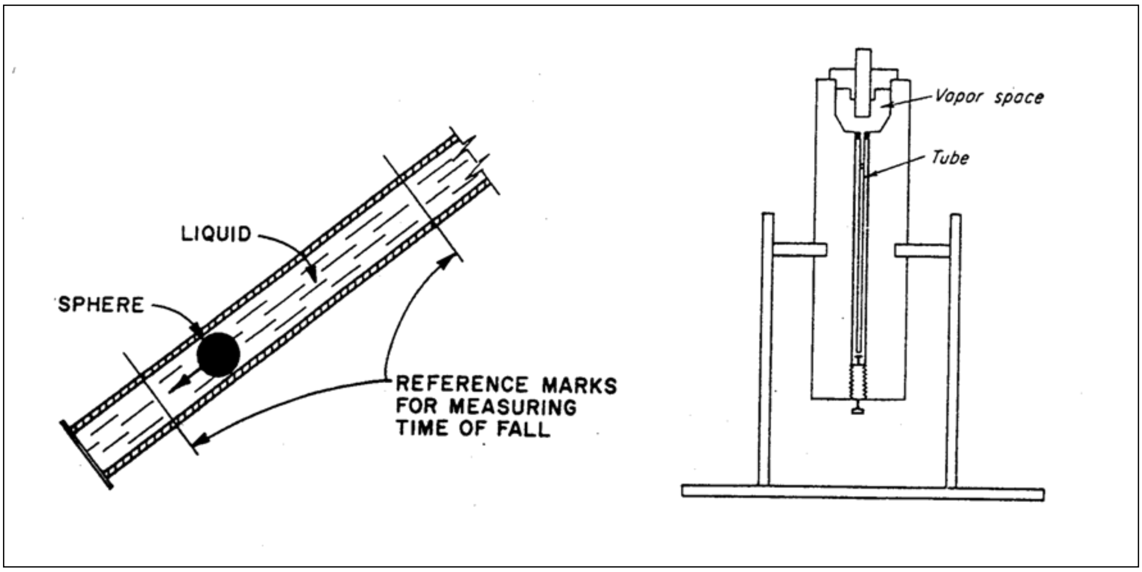


Fig. 3.4: Schematic diagram of the falling ball viscometer.

The rolling ball viscometer will give good results as long as the fluid flow in the tube remains in the laminar range. In some instruments of this type both pressure and temperature may be controlled.

3.3.3 Rotational Viscometer

Other often used viscometers especially for non-Newtonian fluids are the rotational type consisting of two concentric cylinders, with the annulus containing the liquid whose viscosity is to be measured (Figure 3.5). Either the outer cylinder or the inner one is rotated at a constant speed, and the rotational deflection of the cylinder becomes a measure of the liquid’s viscosity.

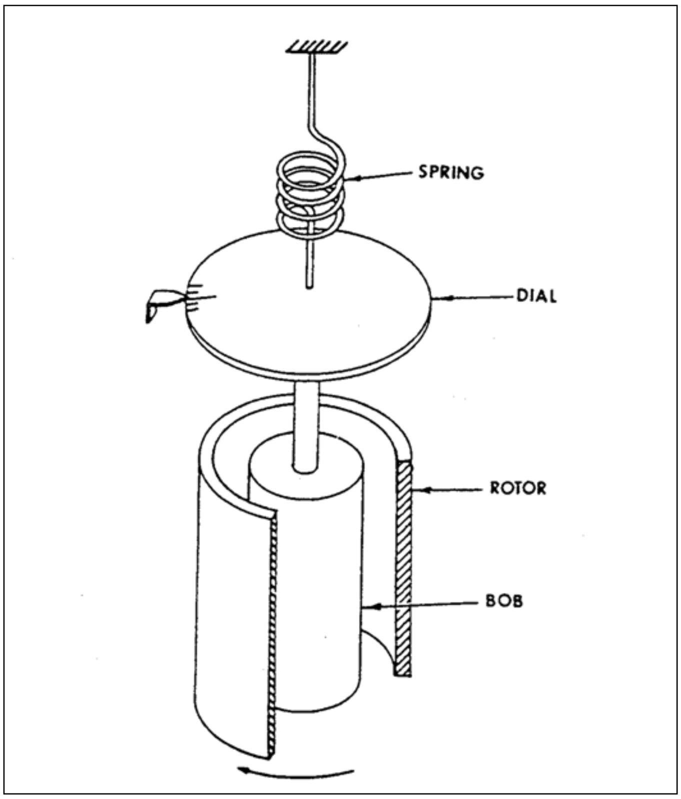


Fig. 3.5: Schematic diagram of the rotational viscometer.

When the distance between the cylinders *d*, is small, we can define the viscosity gradient for laminar flow regime as

$$\frac{dv}{dr} = \frac{\omega R}{d} \tag{3.6}$$

where *R* is radius of the inner cylinder (*bob*) and ω is angular velocity of the outer cylinder (rotor) defined by ω = *2πn*. When the rotor is rotating at a constant angular velocity ω and the *bob* is held motionless, the torque from the torsion spring on the *bob* must be equal but opposite in direction to the torque on the rotor from the motor. The effective area of the applied torque is *2π.R.h* where *h* is length of the cylinder. The viscous drag on the *bob* is *k.*θ*.R*, where *k* is the torsion constant of the spring and θ is angular displacement of the instrument in degrees. Then

$$\frac{F}{A} = \frac{k\theta R}{2\pi Rh} = \mu\frac{dv}{dr} = \mu\frac{\omega R}{d} \tag{3.7}$$

which gives

$$\mu = \frac{k\theta d}{2\pi h\omega R} = \frac{K\theta}{\omega h} \tag{3.8}$$

where *K* is the instrument’s constant which is determined by calibration.

3.4 Experiments

3.4.1 Liquid Viscosity Measurement using Capillary Type Viscometer (Experiment 2)

Description:

The main objective of the measurement is to determine the kinematic viscosity of Newtonian liquid petroleum products.

For capillary viscometers the time is measured in seconds for a fixed volume of liquid to flow under gravity through the capillary at a closely controlled temperature. The kinematic viscosity is the product of the measured flow time and the calibration constant of the viscometer. The dynamic viscosity can be obtained by multiplying the measured kinematic viscosity by the density of the liquid.

Definitions

Dynamic viscosity (μ) is the ratio between the applied shear stress and the rate of shear and is called coefficient of dynamic viscosity μ. This coefficient is thus a measure of the resistance to flow of the liquid; it is commonly called the viscosity of the liquid.

Kinematic viscosity (υ) is the ratio μ/ρ where ρ is fluid density.

Unit and dimensions:

	Symbol	cgs unit	SI unit	Dimension
Kinematic viscosity,	1 mm^2/s = 1 cSt 1 $m^2/s = 10^6$ cSt	cm^2/s	m^2/s	L^2/T
Dynamic viscosity, $\propto$	1 Dyn.s/cm^2 = 100 cp 1 Newton.s/$m^2 = 10^3$ cp	Dyn.s/cm^2	Newton.s/m^2 (= Pa.s)	M/LT (FT/L^2)

Where cSt = centistokes, cp = centipoise
1cp = 10^{-3} Pa.s, 1cSt = 10^{-6} [m^2/s]

Procedure:

1. Select a clean, dry calibrated viscometer (Fig. 3.6) having a range covering the estimated viscosity (i.e. a wide capillary for a very viscous liquid and a narrower capillary for a less viscous liquid). The flow time should not be less than 200 seconds.

2. Charge the viscometer: To fill, turn viscometer upside down. Dip tube (2) into the liquid to be measured while applying suction to tube (1) until liquid reaches mark (8). After inverting to normal measuring position, close tube (1) before liquid reach mark (3).

3. Allow the charged viscometer to remain long enough to reach the room temperature. Read the calibration constants-directly from the viscometer.

4. Measuring operation: Open tube (1) and measure the time it takes the liquid to rise from mark (3) to mark (5). Measuring the time for rising from mark (5) to mark (7) allows viscosity measurement to be repeated to check the first measurement.

5. If two measurements agree within required error (generally 0.2-0.35%), use the average for calculating the reported kinematic viscosity.

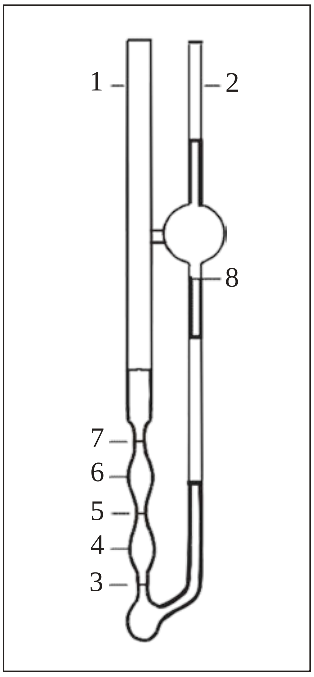


Fig. 3.6: **Viscometer apparatus.**

Calculation and report:

1. Calculate the kinematic viscosity υ from the measured flow time t and the instrument constant by means of the following equation:

$$\upsilon = C(t - \vartheta)$$

where:

υ = kinematic viscosity, *cSt*
C = calibration constant, *cSt/s*
t = flow time, *s*
ϑ = Hagenbach correction factor, when $t < 400$ seconds, it should be corrected according to the manual. When $t > 400$ seconds, $\vartheta = 0$.

2. Calculate the viscosity μ from the calculated kinematic viscosity υ and the density ρ by means of the following equation:

$$\mu = \rho_{avr}\upsilon$$

   where:

   μ = dynamic viscosity, *cp*

   ρ_{avr} = average density in g/cm^3 at the same temperature used for measuring the flow time t.

   υ = kinematic, *cSt*.

3. Report test results for both the kinematic and dynamic viscosity. Calculate the average dynamic viscosity.

Temperature: ^{0}C

Sample	Constant C, (cSt/s)	Time (s)	Hagenbach factor, ∇	Kinematic viscosity, ʆ (cSt)	Density, $\rangle_{avr}$ (g/cm^3)	dynamic viscosity, $\propto$ (cp)
$\propto_{avr}$ =						

4 SURFACE AND INTERFACIAL TENSION

4.1 Definitions

Surface and interfacial tension of fluids result from molecular properties occurring at the surface or interface. Surface tension is the tendency of a liquid to expose a minimum free surface. Surface tension may be defined as the contractile tendency of a liquid surface exposed to gases. The interfacial tension is a similar tendency which exists when two immiscible liquids are in contact. In the following, interfacial tension will be denoted for both surface and interfacial tension.

Fig. 4.1 shows a spherical cap which is subjected to interfacial tension σ around the base of the cap and two normal pressures p_1 and p_2 at each point on the surface. The effect of the interfacial tension σ is to reduce the size of the sphere unless it is opposed by a sufficiently great difference between pressures p_1 and p_2.

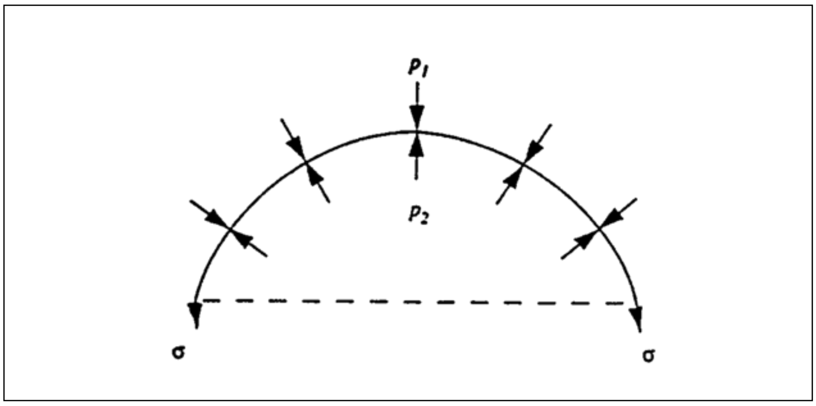


Fig. 4.1: Capillary equilibrium of a spherical cap.

The Young-Laplace equation for the mechanical equilibrium of an arbitrary surface is

$$p_2 - p_1 = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \tag{4.1}$$

where r_1 and r_2 are the principal radii of curvature. Introducing the mean radius of curvature r_m defined by

$$\frac{1}{r_m} = \frac{1}{2} \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \tag{4.2}$$

The Young-Laplace equation becomes

$$p_1 - p_2 = \frac{2\sigma}{r_m} \tag{4.3}$$

Note that the phase on the concave side of the surface must have pressure p_2 which is greater than the pressure p_1, on the convex side.

The surface tension of a liquid surface in contact with its own vapour or with air is found to depend only on the nature of the liquid, and on the temperature. Usually, surface tensions decrease as temperature increases.

4.2 Methods of Interfacial Tension Measurements

4.2.1 Capillary Rise Method

This method is based on rising of a liquid in a capillary tube and the fact that the height of the liquid, depends on interfacial tension. Let us consider a circular tube of radius r, wetted by the liquid to be tested. The liquid with density ρ immediately rises to a height h above the free liquid level in the vessel (Fig. 4.2). The column of liquid in the capillary must be held up against the gravity pull by a force, the so-called capillary suction. We may write

$$2\pi r\sigma\ \cos\theta\left(capillary\ suction\right) = g\rho h\pi r^2\left(gravity\ pull\right)$$

where θ is contact angle between liquid and glass tube and g is acceleration of gravity.

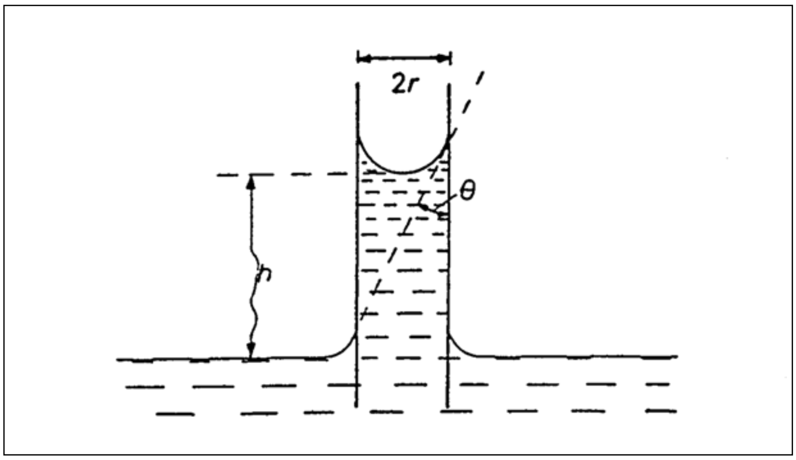


Fig. 4.2: Capillary-rise method.

Hence the value of σ is calculated by

$$\sigma = \frac{g\rho hr}{2\cos\theta} = \frac{r\Delta p}{2\cos\theta} \qquad (4.4)$$

where Δp is the hydrostatic pressure of the column of liquid in the capillary.

4.2.2 Wilhelmy Plate Method

A thin plate of glass or platinum will "carry" or hold up part of liquid which is in contact with the plate. The dynamic measurement of interfacial tension is shown in Fig. 4.3a. In this method, the necessary force to break the liquid film at this position will be determined

$$F = W_p + 2(x + y)\sigma \tag{4.5}$$

where $2(x + y)$ is the contact area between the liquid and the plate, and W_p is the weight of the plate.

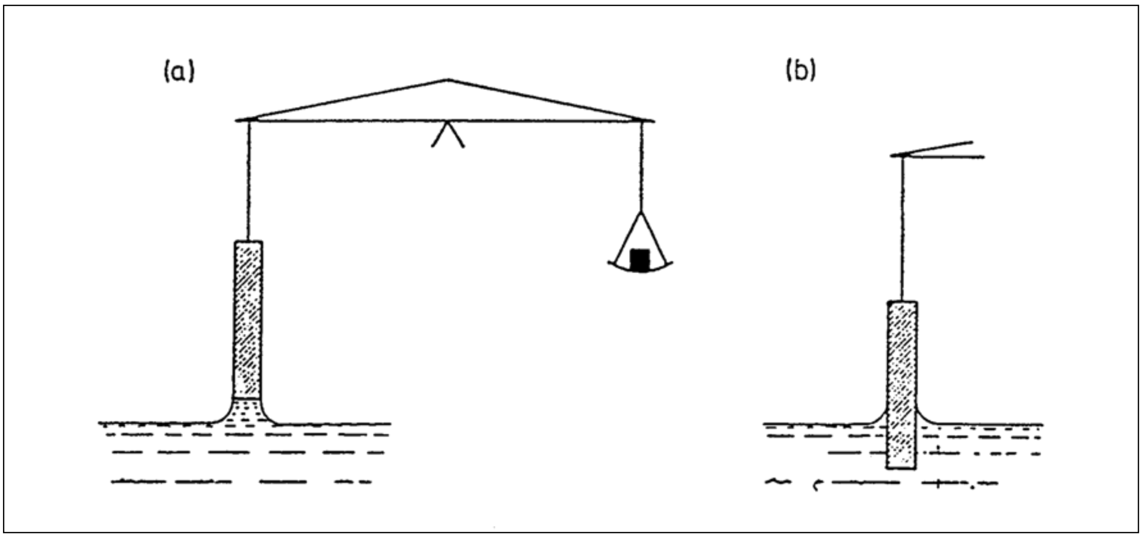


Fig. 4.3: Wilhelmy plate methods; Dynamic (a), and static method (b)

In the static method the plate is held at the position show in Fig. 4.3b, and the equation will be

$$F = W_p - b + 2(x + y)\sigma \cos\theta \tag{4.6}$$

where b is buoyancy force of immersed part of the plate in the liquid and θ is contact angle.

This instrument can be calibrated such that the interfacial tension reads directly.

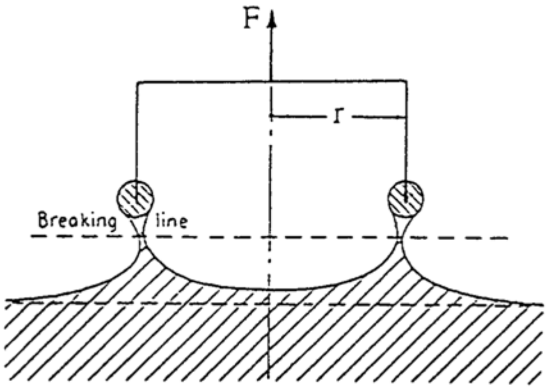
4.2.3 Ring Method

The ring or du Noüy method of measuring surface and interfacial tension is commonly used and the apparatus is called a ring tensiometer.

To measure interfacial tension, a platinum ring is placed in the test liquid. The force necessary to withdraw it from the liquid is determined (Fig. 4.4). When the ring is completely wetted by the liquid ($\theta = 0$), this equation is obtained

$$F = W_r - b + 2(2\pi r\sigma) \qquad (4.7)$$

where F is measured force, r is radius of the ring at centre (the radius of the platinum thread is negligible compared to r), W_r is weight of the ring in air and b is buoyancy force of the ring immersed in the liquid. For interfacial measurements, the ring is placed in the interface and the force necessary to break the interfacial film with the ring is determined.



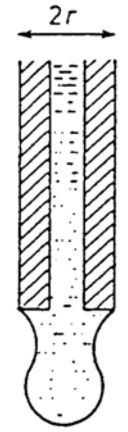


Fig. 4.4: Ring method. **Fig. 4.5:** Hanging drop from a capillary tube.

The instrument can be regulated in such a way that the ring weight and buoyancy effect are taken care of with a correction factor C:

$$\sigma = C \frac{F}{2(2\pi r)} \qquad (4.8)$$

4.2.4 Drop Weight Method

The drop weight method of measuring the interfacial tension of liquid with respect to air consists in determining the number of drops falling from a capillary. The drops are allowed to fall into a container until enough have been collected so that the weight per drop can be determined accurately. The principle of the method is that the size of the drop falling from a capillary tube depends on the surface tension of the liquid (Fig. 4.5).

The maximum amount of liquid W, which can hang from a capillary tube with radius r without falling depends on the surface tension as

$$W = mg = 2\pi r\sigma \qquad (4.9)$$

where m is the mass per drop. Observations of falling drops show that a considerable portion of the drop (up to 40%) may remain attached to the capillary end. This effect will be compensated with a correction factor f

$$\sigma = f \frac{mg}{2\pi r} \tag{4.10}$$

The correction factor *f* varies in the region of 0.5 to 1.0. The drop method can be used for the determination of both gas-liquid and liquid-liquid interfacial tensions.

4.2.5 Pendant Drop Method

Small drops will tend to be spherical because surface forces depend on area. In principle, one can determine the interface tension from measurements of the shape of the drop. In the case of the pendant drop, the most convenient and measurable shape dependent quantity is $S = d_s/d_e$. As indicated in Fig. 4.6, d_e is the equatorial diameter and d_s is the diameter measured distance d_e from the bottom of the drop. The interfacial tension can be calculated by the following equation

$$\sigma = \frac{\Delta\rho g d_e^2}{H} \tag{4.11}$$

where *H* is a shape determining variable. The relationship between the shape dependent quantity *H* and the experimentally measured shape dependent quantity *S* is determined empirically. A set of *1/H* versus *S* values is obtained in form of tables (Tab. 4.1). The quantity of *S* is calculated after measuring d_e and d_s from shape of the pendant drop, and then *1/H* can be determined from Tab. 4.1.

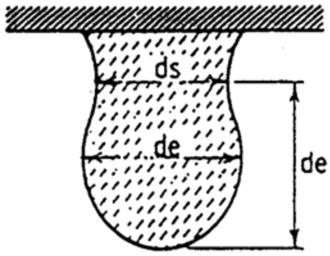


Fig. 4.6: Relationship between dimensions of a pendant drop.

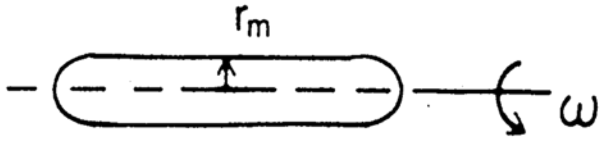


Fig. 4.7: Schematic diagram of spinning drop.

The pendant drop method is widely used and has good accuracy.

Table 4.1: Values of 1/H versus S for pendant drop method.

s	0	1	2	3	4	5	6	7	8	9
0.30	7.09837	7.03966	6.98161	6.92421	6.86746	6.81135	6.75586	6.70099	6.64672	6.59306
0.31	6.53998	6.48748	6.43556	6.38421	6.33341	6.28317	6.23347	6.18431	6.13567	6.08756
0.32	6.03997	5.99288	5.94629	5.90019	5.85459	5.80946	5.76481	5.72063	5.67690	5.63364
0.33	5.59082	5.54845	5.50651	5.46501	5.42393	5.38327	5.34303	5.30320	5.26377	5.22474
0.34	5.18611	5.14786	5.11000	5.07252	5.03542	4.99868	4.96231	4.92629	4.89061	4.85527
0.35	4.82029	4.78564	4.75134	4.71737	4.68374	4.65043	4.61745	4.58479	4.55245	4.52042
0.36	4.48870	4.45729	4.42617	4.39536	4.36484	4.33461	4.30467	4.27501	4.24564	4.21654
0.37	4.18771	4.15916	4.13087	4.10285	4.07509	4.04759	4.02034	3.99334	3.96660	3.94010
0.38	3.91384	3.88786	3.86212	3.83661	3.81133	3.78627	3.76143	3.73682	3.71242	3.68824
0.39	3.66427	3.64051	3.61696	3.59362	3.57047	3.54752	3.52478	3.50223	3.47987	3.45770
0.40	3.43572	3.41393	3.39232	3.37089	3.34965	3.32858	3.30769	3.28698	3.26643	3.24606
0.41	3.22582	3.20576	3.18587	3.16614	3.14657	3.12717	3.10794	3.08886	3.06994	3.05118
0.42	3.03258	3.01413	2.99583	2.97769	2.95969	2.94184	2.92415	2.90659	2.88918	2.87192
0.43	2.85479	2.83781	2.82097	2.80426	2.78769	2.77125	2.75496	2.73880	2.72277	2.70687
0.44	2.69110	2.67545	2.65992	2.64452	2.62924	2.61408	2.59904	2.58412	2.56932	2.55463
0.45	2.54005	2.52559	2.51124	2.49700	2.48287	2.46885	2.45494	2.44114	2.42743	2.41384
0.46	2.40034	2.38695	2.37366	2.36047	2.34738	2.33439	2.32150	2.30870	2.29600	2.28339
0.47	2.27088	2.25846	2.24613	2.23390	2.22176	2.20970	2.19773	2.18586	2.17407	2.16236
0.48	2.15074	2.13921	2.12776	2.11640	2.10511	2.09391	2.08279	2.07175	2.06079	2.04991
0.49	2.03910	2.02838	2.01773	2.00715	1.99666	1.98623	1.97588	1.96561	1.95540	1.94527
0.50	1.93521	1.92522	1.91530	1.90545	1.89567	1.88596	1.87632	1.86674	1.85723	1.84778
0.51	1.83840	1.82909	1.81984	1.81065	1.80153	1.79247	1.78347	1.77453	1.76565	1.75683
0.52	1.74808	1.73938	1.73074	1.72216	1.71364	1.70517	1.69676	1.68841	1.68012	1.67188
0.53	1.66369	1.65556	1.64748	1.63946	1.63149	1.62357	1.61571	1.60790	1.60014	1.59242
0.54	1.58477	1.57716	1.56960	1.56209	1.55462	1.54721	1.53985	1.53253	1.52526	1.51804
0.55	1.51086	1.50373	1.49665	1.48961	1.48262	1.47567	1.46876	1.46190	1.45509	1.44831
0.56	1.44158	1.43489	1.42825	1.42164	1.41508	1.40856	1.40208	1.39564	1.38924	1.38288
0.57	1.37656	1.37028	1.36404	1.35784	1.35168	1.34555	1.33946	1.33341	1.32740	1.32142
0.58	1.31549	1.30958	1.30372	1.29788	1.29209	1.28633	1.28060	1.27491	1.26926	1.26364
0.59	1.25805	1.25250	1.24698	1.24149	1.23603	1.23061	1.22522	1.21987	1.21454	1.20925
0.60	1.20399	1.19875	1.19356	1.18839	1.18325	1.17814	1.17306	1.16801	1.16300	1.15801
0.61	1.15305	1.14812	1.14322	1.13834	1.13350	1.12868	1.13389	1.11913	1.11440	1.10969
0.62	1.10501	1.10036	1.09574	1.09114	1.08656	1.08202	1.07750	1.07300	1.06853	1.06409
0.63	1.05967	1.05528	1.05091	1.04657	1.04225	1.03796	1.03368	1.02944	1.20522	1.02102
0.64	1.01684	1.01269	1.00856	1.00446	1.00037	0.99631	0.99227	0.98826	0.98427	0.98029
0.65	0.97635	0.97242	0.96851	0.96463	0.96077	0.95692	0.95310	0.94930	0.94552	0.94176
0.66	0.93803	0.93431	0.93061	0.92693	0.92327	0.91964	0.91602	0.91242	0.90884	0.90528
0.67	0.90174	89822	89471	89122	88775	88430	88087	87746	87407	87069
0.68	86733	86399	86067	85736	85407	85080	84755	84431	84110	83790
0.69	83471	83154	82839	82525	82213	81903	81594	81287	80981	80677
0.70	80375	80074	79774	79477	79180	78886	78593	78301	78011	77722
0.71	77434	77148	76864	76581	76299	76019	75740	75463	75187	74912
0.72	74639	74367	74097	73828	73560	73293	73028	72764	72502	72241
0.73	71981	71722	71465	71208	70954	70700	70448	70196	69946	69698
0.74	69450	69204	68959	68715	68472	68230	67990	67751	67513	67276
0.75	67040	66805	66571	66338	66107	65876	65647	65419	65192	64966
0.76	64741	64518	64295	64073	63852	63632	63414	63196	62980	62764
0.77	62550	62336	62123	61912	61701	61491	61282	61075	60868	60662
0.78	60458	60254	60051	59849	59648	59447	59248	59050	58852	58656
0.79	58460	58265	58071	57878	57686	57494	57304	57114	56926	56738
0.80	56551	56364	56179	55994	55811	55628	55446	55264	55084	54904
0.81	54725	54547	54370	54193	54017	53842	53668	53494	53322	53150
0.82	52978	52800	52638	52469	52300	52133	51966	51800	51634	51470
0.83	51306	51142	50980	50818	50656	50496	50336	50176	50018	49860
0.84	49702	49546	49390	49234	49080	48926	48772	48620	48468	48316
0.85	48165	48015	47865	47716	45760	47420	47272	47126	46984	46834
0.86	46690	46545	46401	46258	46116	45974	45832	45691	45551	45411
0.87	45272	45134	44996	44858	44721	44585	44449	44313	44178	44044
0.88	43910	43777	43644	43512	43380	43249	43118	42988	42858	42729
0.89	42600	42472	42344	42216	42089	41963	41837	41711	41586	41462
0.90	41338	41214	41091	40968	40846	40724	40602	40481	40361	40241
0.91	40121	40001	39882	39764	39646	39528	39411	39294	39178	39062
0.92	38946	38831	38716	38602	38488	38374	38260	38147	38035	37922
0.93	37810	37699	37588	37477	37367	37256	37147	37037	36928	36819
0.94	36711	36603	36495	36387	36280	36173	36067	35960	35854	35749
0.95	35643	35538	35433	35328	35224	35120	35016	34913	34809	34706
0.96	34604	34501	34398	34296	34195	34093	33991	33890	33789	33688
0.97	33587	33487	33386	33286	33186	33086	32986	32887	32787	32688
0.98	32588	32489	32390	32290	32191	32092	31992	31893	31793	31694
0.99	31594	31494	31394	31294	31194	31093	30992	30891	30790	30688
1.00	30586	30483	30379							

4.2.6 Spinning Drop

In this method, a drop of a less dense fluid is injected into a container of the denser fluid, and the whole system is rotated as shown in Fig. 4.7. In the resulting centrifugal field, the drop elongates along the axis of rotation. The interfacial tension opposes the elongation because of the increase in area and a configuration which minimises system free energy is reached. The method is similar to that for the pendant drop with the gravitational acceleration g replaced by the appropriate acceleration term for a centrifugal field.

If the fluid densities are ρ_A and ρ_B, and the angular velocity ω of rotation are known, then interfacial tension can be calculated from the measured drop profile. When drop length is much greater than the radius r_m, the following approximate expression holds

$$\sigma = \frac{(\rho_A - \rho_B)\omega^2 r_m^3}{4} \qquad (4.12)$$

The spinning drop device has been widely used in recent years to measure very low interfacial tensions. Unlike the other methods, no contact between the fluid interface and a solid surface is required.

4.3 Experiments

4.3.1 Interfacial Tension (IFT) Measurement, Pendant Drop Method (Experiment 3)

Pendant drop method is applied to determine the interfacial tension between two liquids. The method is intended for application to liquid pairs with normal interfacial tensions (not too low and too high).

Procedure:

The pendant drop IFT measurements will be performed together with contact angle measurements and the contact angle apparatus is used (Experiment 9), so refer to this experiment for apparatus description.

1. Fill the cell with oil.
2. Form a pendant drop of water with a syringe (diameter 1.1 mm).
3. Focus the drop and take imaging picture by photo.
4. Measure d_e and d_s, and then calculate S.
5. Determine $1/H$ from Tab. 4.1.

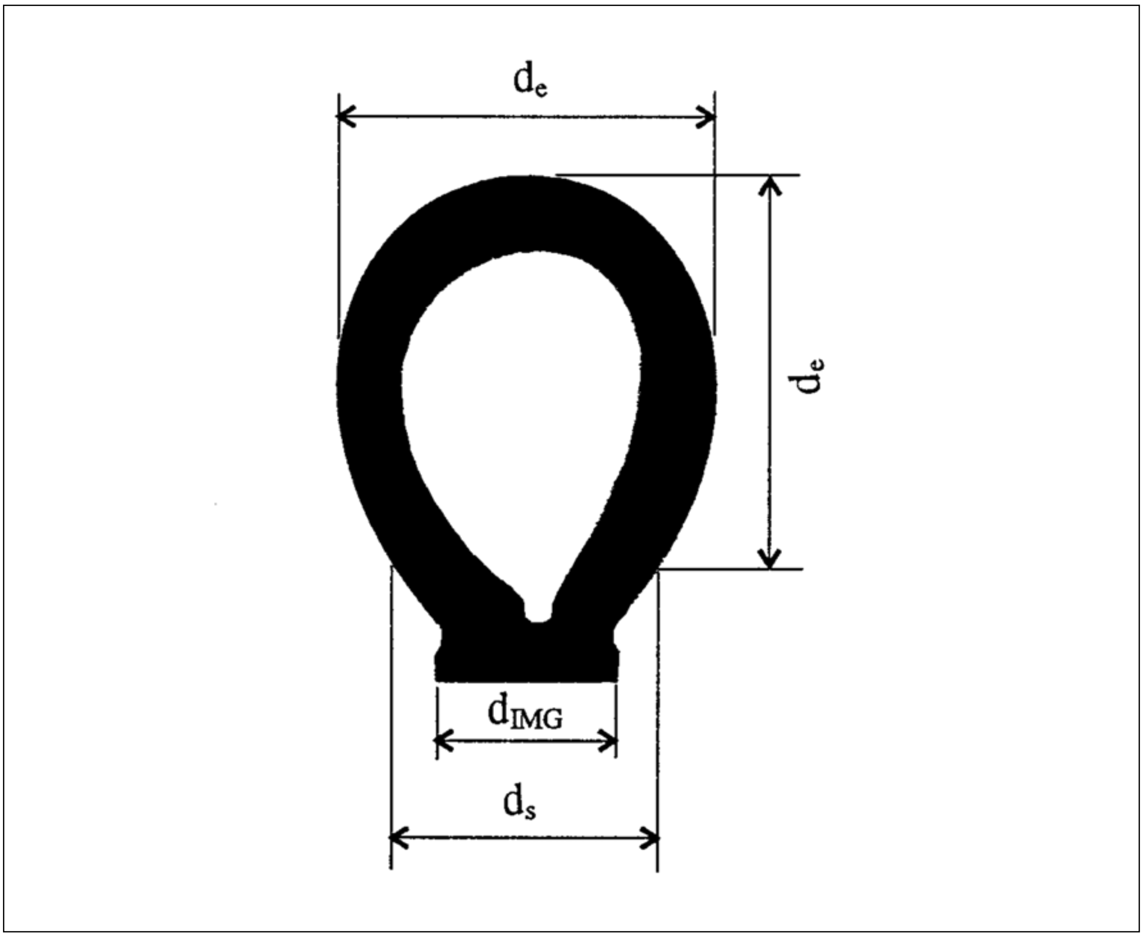


Fig. 4.8: Pendant drop imaging picture.

Calculations and report

Temperature: ^{0}C

Sys-tem	ρ_w (g/cm^3)	ρ_o (g/cm^3)	$\Delta\rho$ (g/cm^3)	Image picture sizes			S (d_s/d_e)	1/H	σ (dyne/cm)
				d_e (mm)	d_s (mm)	d_{IMG} (mm)			

Equation:

$$\sigma = \frac{\Delta\rho g D_e^2}{H}$$

where g = 981 cm/s2
D_e (real size of d_e) = $d_e(1.1/d_{IMG})$, mm.

4.3.2 Measurement of IFT with the Ring Tensiometer (Experiment 4)

Description:

This hanging ring method is also called Du Nouy method. The method can determine the interfacial tension of reservoir fluids or petroleum products at typical ambient laboratory temperature and atmospheric pressure.

Definition:

The surface or interfacial tension in the liquid film is the ratio of the surface force to the length (perpendicular to the force) along which the force acts.

$$\sigma = \frac{\text{surface force, F}}{\text{length along which force acts}}$$

Procedure:

1. Calibration of tensiometer.
2. Brine and oil interfacial tension measurements. Two or three readings should be taken, so an average value may be used for calculating apparent interfacial tension.

Calculation and report:

To obtain the true interfacial tension σ, the following relationship will be used:

$$\sigma = \sigma_a . C \tag{4.13}$$

where

σ = the true interfacial tension, dynes/cm
σ_a = the measured apparent value, dynes/cm
C = the correction factor.

The correction factor *C* is dependent on the size of ring, the diameter of the wire used in the ring, the apparent interfacial tension, and the densities of the two phases. The relationship is expressed by the following equation

$$c = 0.725 + \sqrt{\frac{0.0145\sigma_a}{l^2(\rho_l - \rho_u)} + 0.04534 - \frac{1.67r}{R}} \tag{4.14}$$

where

C = correction factor
R = radius of the ring, cm
r = radius of the wire of the ring, cm
σ_a = apparent surface or interfacial tension, dynes/cm

ρ_l = density of the lower phase, g/cm^3
ρ_u = density of the upper phase, g/cm^3
l = circumference of the ring, cm

If surface tension was measured in the container which has been open to the air during measuring, air density may be approximated by the equation:

$$\rho_{air} = 4.324\times10^{-2}\left(P/T\right) \tag{4.15}$$

where

ρ_{air} = air density at p and T, g/cm^3
p = pressure, psia (= 14.7 psia)
T = temperature, ^{0}R (= 1.8 (T^{0}C + 273.15))

Temperature: ^{0}C

Measurement	Correction factor, C	Apparent value, σ_a (dynes/cm)	True value, σ (dynes/cm)
σ_{avr} (air/water) = σ_{avr} (oil/water) =			