***Research Assistants***

Elvan Konuk Tokak
Neslişah Ulus

# BASIC MEASUREMENTS OF PRESSURE, TEMPERATURE, DENSITY AND VISCOSITY

## 1. INTRODUCTION

A quantitative property is one that exists in a range of magnitudes, and can therefore be measured[1]. Measurements of any particular quantitative property are expressed as a specific quantity, referred to as a unit. Pressure, temperature, density and viscosity can be given as examples of physical quantities[2].

**Pressure (P)** is the force per unit area applied in a direction perpendicular to the surface of an object. Pressure is a scalar quantity, has no direction[3]. Pressure is usually expressed in terms of familiar units of weight force and area or the height of a column of liquid which produces alike pressure at its base. The more common units are $N/m^2$, Pa (Pascal), millimeter of mercury, and inches or feet of water. Process pressure-measuring devices are based on measurement of the height of a liquid column, measurement of distortion of elastic pressure chamber and electrical sensing devices[2].

To most people, **temperature (T)** is an intuitive concept which tells whether a body is “hot” or “cold”. In the exposition of the second principle of thermodynamics, temperature is related to heat, as it is known that heat flows only from a high temperature to a low temperature, in the absence of other effects. In the kinetic theory of gases and statistical thermodynamics it is shown that temperature is related to average kinetic energy of the molecules of an ideal gas. Further extensions of statistical thermodynamics show the relationship between temperature and energy levels in liquids and solids. The two temperature scale in use are Centigrade ($^oC$) and Fahrenheit ($^oF$) scales. These scales are based on a specification of the number of increaments between the freezing point and boiling point of water at standard atmospheric pressure. Since pressure, volume, electrical resistance, expansion coefficients, etc., are all related to temperature through the fundamental molecular structure, they change with temperature and these changes can be used to measure temperature[2].

The **density (ρ)** of a material is defined as its mass per unit volume, for example kg/m$^3$ or lb/ft$^3$. Density is an intensive property that does not depend on the system size or the amount of material in the system. To determine the density of a substance, its volume and its mass must be determined. If the substance is a solid, a common method to determine its volume is to displace a measured quantity of inert liquid of known weight and volume, and the final weight and volume of the combination measured. The density of a liquid is commonly measured with a hydrometer (a known weight and volume is dropped into the liquid and the depth to which it penetrates into the liquid is noted). Gas densities are quite difficult to measure. Direct methods (e.g. Edward's balance) include measuring the mass of a closed vessel:

1. when evacuated,
2. after filling with the unknown gas, and
3. after filling with a known gas or liquid, respectively[3].

Key control parameters are the pressure and temperature, and the method is prone to significant errors resulting from parasitic effects, such as the small mass of the gas compared with that of the container. Devices are now available commercially for accurate measurement of the densities of gases over a wide temperature range, including the critical region[3].

**Viscosity (μ)** is a measure of the resistance of a fluid to deformation under shear stress. It is commonly perceived as "thickness", or resistance to pouring. Viscosity describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. Thus, methanol is "thin", having a low viscosity, while vegetable oil is "thick" having a high viscosity[6]. The more common units of viscosity are kg/s.m, lb.s/ft$^2$ and N/m$^2$.s. Various methods are employed for the measurement of viscosity. The two most common methods are the rotating concentric cylinder and the capillary flow method. Perhaps the most common method of viscosity measurement consists of a measurement of the pressure drop in laminar flow through a capillary tube[1].

## 2. THEORY

### 2.1 Pressure measurement

Absolute pressure refers to the absolute value of the force per unit area exerted on the containing wall by a fluid. Pressure is sometimes measured not as an absolute pressure, but relative to atmospheric pressure; such measurements are called gauge pressure (also sometimes spelled *gage pressure*)[4]. Gauge pressure represents the difference between the absolute pressure and the local atmosphere pressure[1]. An example of this is the air pressure in an automobile tire, which might be said to be "220 kPa/32psi", but is actually 220 kPa/32 psi above atmospheric pressure. Since atmospheric pressure at sea level is about 100 kPa/14.7 psi, the absolute pressure in the tire is therefore about 320 kPa/46.7 psi[4]. Vacuum represents the amount by which the atmospheric pressure exceeds the absolute pressure. From these definitions we see that absolute pressure may not be negative and the vacuum may not be greater than the local atmosphere pressure. The three terms are illustrated in Figure 2.1. It is worthwhile to mention that local fluid pressure may be dependent upon many variables, elevation, flow velocity, fluid density and temperature are parameters that are of frequent importance[1]. The SI unit for pressure is the pascal (Pa), equal to one newton per square meter ($N/m^2$ or $kg/m.s^2$). The cgs and british unit system of pressure is barye (ba), equal to 1 $dyn \cdot cm^{-2}$ pounds per square inch ($Ib_f/in^2$) respectively[4].

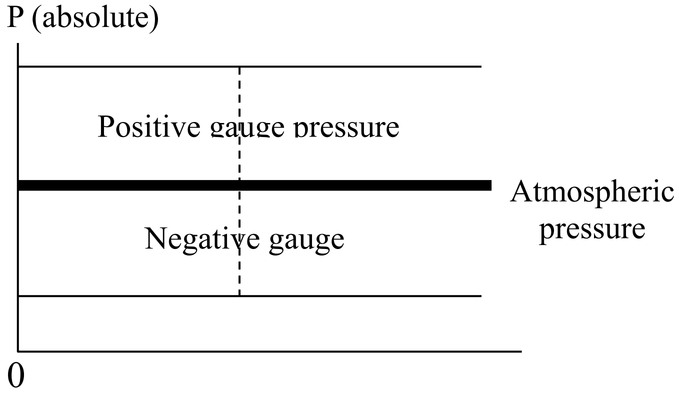


Figure 2.1. Relationship between pressure terms

Many techniques have been developed for the measurement of pressure to obtain dynamic and mechanic responses. Instruments used to measure pressure are called pressure gauges or vacuum gauges[5].

### *Dynamic response on the pressure measurement*

The transient response of pressure-measuring instruments is dependent on two factors: (1) the response of the transducer element that senses the pressure and (2) the response of the pressure transmitting fluid and the connecting tubes etc. This latter factor is frequently the one which determines the overall frequency response of a pressure of a measurement system and, eventually, direct calibration must be relied upon for determining this response [1].

### *Mechanical pressure measurement devices*

The fluid manometer is a widely used device for measurement of fluid pressures under steady-state conditions. Consider first the U-tube manometer shown in Figure 2.2(a). The difference in pressure between the unknown pressure P and the atmosphere is determined as a function of differential height h (m). The density of the fluid transmitting the pressure P is $\rho_f$ (kg/m$^3$) and the density of the manometer fluid is designated as $\rho_m$ (kg/m$^3$). Let $A_1$ and $A_2$ are the cross sectional area of the the tubes for Figure 2.2. A pressure balance of the two columns dictates that,

$$P_a + gh\,\rho_m = P + gh\rho_f \quad \text{(SI)} \qquad (1)$$

$$P_a + \frac{g}{g_c} h\,\rho_m = P + gh\rho_f \quad \text{(BUS)}$$

or

$$P - P_a - gh\,(\rho_m - \rho_f) \quad \text{(SI)} \qquad (2)$$

$$P - P_a = \frac{g}{g_c} h\,(\rho_m - \rho_f) \quad \text{(BUS)}$$

Eq.(2) gives the basic principle of the U-tube manometer. A well type manometer operates in the same manner as the U-tube manometer except that the construction is shown in Figure 2.2(b). In this case the pressure balance of Eq.(2) still yields,

$$P - P_0 = \frac{g}{g_c} h\,(\rho_m - \rho_f) \qquad (3)$$

This equation is seldom used, however, because the height h is not the fluid displacement which is normally measured. Typically, the well-type manometer is filled to a certain level at zero-pressure differential conditions.

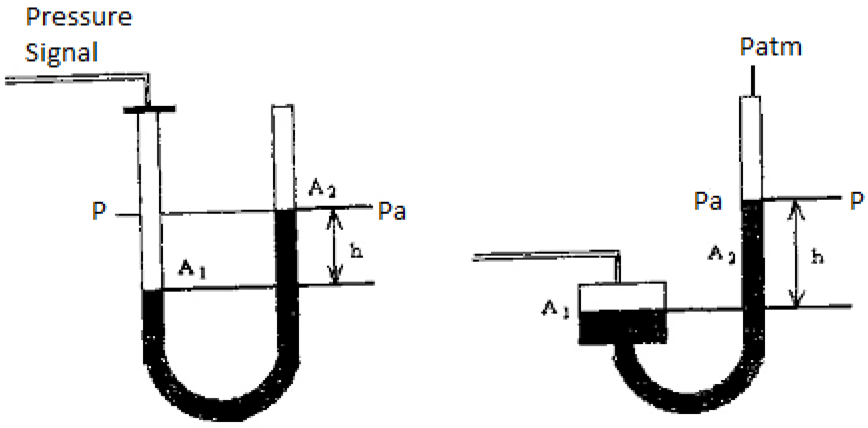


Figure 2.2 (a) U-tube manometer[1] (b) Well-type manometer[1]

A measurement is then made of the displacement of the small column from this zero level. Designating displacement by h', we have

$$h'A_2 = (h - h')A_1 \tag{4}$$

since the volume displacements are the same on both sides of the manometer. Inserting Eq.(4) in Eq.(2) gives,

$$P - P_a = \frac{g}{g_c} h'\left(\frac{A_1}{A_2} + 1\right)(\rho_m - \rho_f) \tag{5}$$

***Bourdon-tube pressure gauges***

The Bourdon pressure gauge uses the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy[8].

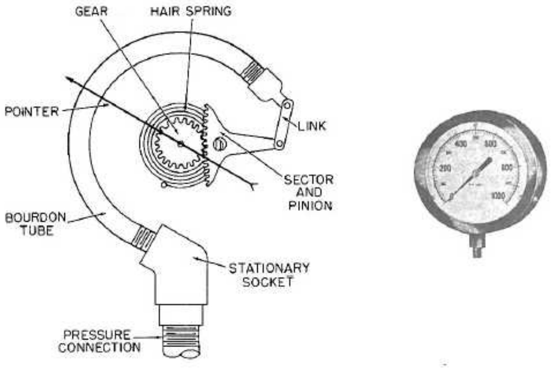


Figure 2.3. Bourdon tube pressure gauges[10]

### *Diaphragm gauges and bellow gauges*

The diaphragm gauge gives sensitive and reliable indications of small pressure differences. We use the diaphragm gauge to measure the air pressure in the space between inner and outer boiler casings. In this type of gauge, a diaphragm connects to a pointer through a metal spring and a simple linkage system (Fig. 2.4). One side of the diaphragm is exposed to the pressure being measured, while the other side is exposed to the pressure of the atmosphere. Any increase in the pressure line moves the diaphragm upward against the spring, moving the pointer to a higher reading. When the pressure decreases, the spring moves the diaphragm downward, rotating the pointer to a lower reading[10].

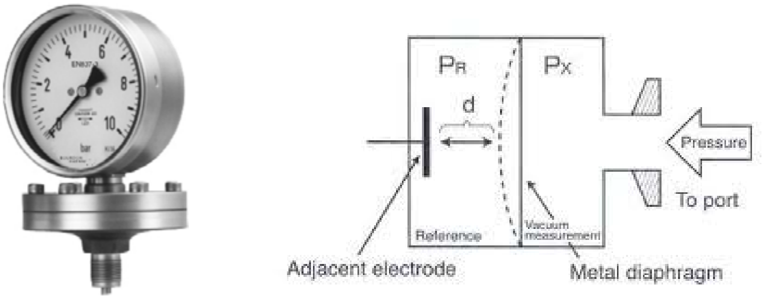


Figure 2.4 (a) Schematic of a diaphragm gauge[10] (b) Diaphragm gauge principle[10]

Thus, the position of the pointer is balanced between the pressure pushing the diaphragm upward and the spring action pushing down. When the gauge reads 0, the pressure in the line is equal to the outside air pressure.

### *Low Pressure Measurement*

The science of low-pressure measurement is a rather specialized field which requires considerable care on the part of the experimentalist. The purpose of our discussion is to call attention to more prominent types of vacuum instruments and describe the physical principles upon which they operate. For moderate vacuum measurements the bourdon gauge, manometers and various diaphragm gauges may be employed[1].

Low pressure measurement devices are:

- McLeod gauge
- Pirani Thermal-Conductivity gauge
- The Knudsen gauge
- The Ionization gauge
-

## 2.2 Temperature Measurement

The Centigrade scale has 100 units between the top and bottom points of thermometer, while Fahrenheit scale has 180 units. The absolute Centigrade scale is called the Kelvin scale, while the absolute Fahrenheit scale is named the Rankine scale. It is evident that the following relations apply[11]:

$$°F = 32{,}0 + 9/5°C \tag{6}$$

$$°R = 9/5°K \tag{7}$$

There are several ways to measure temperature in different manners (electrically, mechanically etc.)

### *The ideal-gas thermometer*

The behaviour of an ideal gas at low pressures furnishes the basis for a temperature measurement device that may serve as a secondary experimental standard. For the gas thermometer a fixed volume is filled with gas and exposed to the temperature to be measured, as shown in Figure 2.5. At the temperature T the gas system pressure is measured. Next, the volume is exposed to a standard reference temperature, and the pressure is measured under the conditions[11].

The ideal gas equation of state is,

$$PV = \frac{m}{M_w}RT \tag{8}$$

where; V ($m^3$) is the volume occupied by the gas,

M (kg mol/kg) is the molecular weight,

T (K) is the temperature,

m (kg) is the mass and

R ($m^3$.Pa/K.kg mol) is the gas constant.

According to Eq. (8). at constant volume

$$T = T_{ref}\left(\frac{P}{P_{ref}}\right) \qquad (9)$$

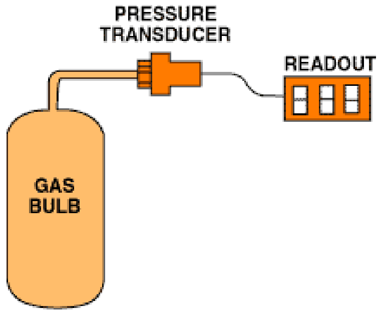


Figure 2.5. Schematic of ideal gas thermometer[12]

***Temperature measurement by mechanical effect***

Several temperature-measurement devices may be classified as mechanically operative. In this sense we shall be concerned with those devices operating on the basis of a change in temperature[11].

The liquid-in-glass thermometer is one of the most commen types of temperature measurement devices. The construction details of such an instrument are shown in Figure 2.6. A relatively large bulb at the lower portion of the thermometer holds the major portion of the liquid, which expands when heated and rises in the capillary tube upon which are etched appropriate scale markings. At the top of the capillary tube another bulb is placed to provide a safety feature in case the temperature range of the thermometer is inadvertently exceeded. Alcohol and mercury are the most commonly used liquids. Alcohol has the advantage that it has a higher coefficient of expansion than mercury, but it is limited to low-temperature measurements because it tends to boil away at high temperatures. Mercury can not be used below its freezing point of -39.32 ºC. The size of the capillary depends on the size of the sensing bulb, the liquid, and the desired temperature range for the thermometer[11].

Mercury-in-glass thermometers are generally applicable up to about 315.56 ºC, but their range may be extended to 537.78 ºC by filling the space above the mercury with a gas like nitrogen. This increases the pressure on the mercury, raises its boiling point, and thereby permits the use of the thermometer at higher temperatures.

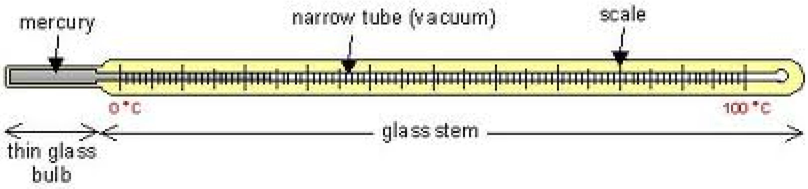


Figure 2.6. Schematic of mercury in glass thermometer[13]

Fluid-expansion thermometers represent one of the most economical, versatile, and widely used devices for industrial temperature-measurement applications. A bulb containing liquid, gas, or vapor is immersed in the environment. The bulb is connected by means of a capillary tube to some type of pressure-measuring device such as the Bourdon gauge shown. An increase in temperature causes the liquid or gas to expand, thereby increasing the pressure on the gauge; the pressure is thus taken as an indication of the temperature. The entire system consisting of the bulb capillary, and gauge may be calibrated directly. It is clear that the temperature of the capillary tube may influence the reading of the device because some of the volume of fluid is contained therein. If an equilibrium mixture of liquid and vapor is used in the bulb, however, this problem may be alleviated, provided that the bulb temperature is always higher than the capillary-tube temperature. In this circumstance the fluid in the capillary will always be in a sub cooled liquid state, while the pressure will be uniquely specified for each temperature in the equilibrium mixture contained in the bulb[1].

### *Temperature measurement by electrical effects*

Electrical methods of temperature measurement are very convenient because they furnish a signal that is easily detected, amplified, or used for control purposes. In addition, thay are usually quite accurate when properly calibrated and compensated[1].

### *Surface thermometers*

The surface thermometer is designed to measure the surface temperature of curing concrete, fresh laid asphalt and other materials. The thermometer is placed on the material surface. It reaches sensing equilibrium within three minutes with an accuracy of ±2% of full scale range. The surface thermometer has a 5.1 cm (2 in) diameter dial and a depth of 1.3 cm (½-in) (Figure 2.7).

Figure 2.7. Surface thermometer[14]

### Electrical-resistance thermometer

One quite accurate method of temperature measurement is the electrical-resistance thermometer. It consists of some type of resistive element, which is exposed to the temperature to be measured. The temperature is indicated through a measurement of the change in resistance of the element. Several types of materials may be used as resistive elements, and their characteristics are given in Table 2.1.[1].

Table 2.1. Resistance-Temperature Coefficients (α), at room temperature[15]

| **Material** | **α ($^oC^{-1}$)** |
|---|---|
| Nickel | 0,0067 |
| Iron (Alloy) | 0,002 to 0,006 |
| Tungsten | 0,0048 |
| Aluminum | 0,0045 |
| Copper | 0,0043 |
| Lead | 0,0041 |
| Gold | 0,004 |
| Platinum | 0,000392 |
| Mercury | 0,00099 |
| Manganin | ±0,00002 |
| Carbon | -0,0007 |
| Electrolytes | -0,02 to -0,09 |
| Semiconductors (thermistors) | -0,068 to 0,14 |

The linear temperature coefficient of resistance α is defined by

$$\alpha = \frac{R_2 - R_1}{R_1 T_2 - R_2 T_1} \tag{10}$$

where $R_2$ (ohm) and $R_1$ (ohm) are the resistances of the material at temperatures $T_2$ (K) and $T_1$ (K), respecrively. The relationship in Eq. (10) is usually applied over a narrow temperature range such that the variation of resistance with temperature approximates a linear relation. For wider temperature ranges the resistance of the material is usually expressed by a quadratic relation[10].

$$R = R_0(1 + aT + bT^2) \tag{11}$$

where R is resistance at temperature T, $R_0$ is resistance at $T_0$, a and b are experimentally determined constants.

### *Thermistors*

The termistor is a semiconductor device that has a negative-temperature coefficient of resistance in contrast to the positive coefficient displayed by most metals. Furthermore, the resistance follows an exponential variation with temperature instead of a polynomial relation like Eq. (11). Thus, for a thermistor,

$$R = R_0 exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{12}$$

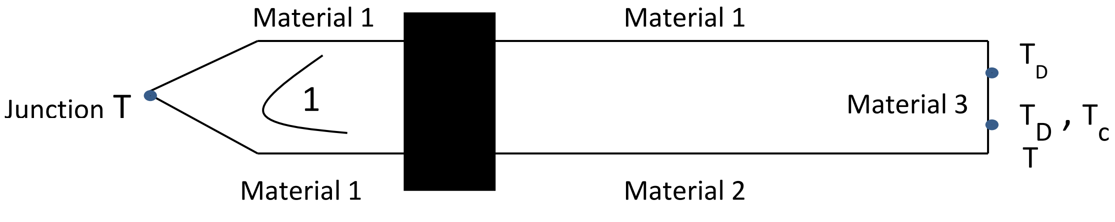
Where; $R_0$ (ohm) is the resistance at the reference temperature $T_0$ (K) and β is an experimentally determined constant. The numerical value of β varies between 3500 and 4600 K, depending on the thermistor material and temperature. The thermistor is an extremely sensitive device, and consistent performance within 0.01°C may be anticipated with with proper calibration. A rather nice feature of the thermistor is that it may be used for temperature compensation of electric circuits. This is possible because of the negative temperature characteristic that it exhibits, so that it can be used to counteract the increase in resistance of a circuit with a temperature increase[1].

### *Thermoelectric effects*

The most common electrical method of temperature measurement is the use of thermocouple. When two dissimilar metals are joined together as shown in Figure 2.8(a), a voltage will exist between the two points A and B, which is primarily a function of the junction temperature. This phenomenon is called the Seebeck effect. If the two materials are connected to an external circuit such that is drawn, the emf may be altered slightly owing to a phenomenon called the Thompson effect. There are, then, three emfs present in a thermoelectric circuit the Seebeck emf, caused by the junction of dissimilar metals; the Peltier emf, caused by a current flow in the circuit; and the Thomson emf, which results from a temperature gradient in the materials. The Seebeck emf is of prime concern since it is dependent on junction temperature. If the emf generated at the junction of two dissimilar metals is carefully measured as a function of temperature, then such a junction may be utilized for the measurement of temperature. The main problem arises when one attempts to measure the potential. When the two dissimilar materials are connected to a measuring device, there will be another thermal emf generated at the junction of the materials and the connecting wires to the voltage-measuring instrument. This emf wll be dependent on the temperature of the connection, and provision must be made to take account of this additional potential[1].

Two rules are available for analysis of thermoelectric circuits:

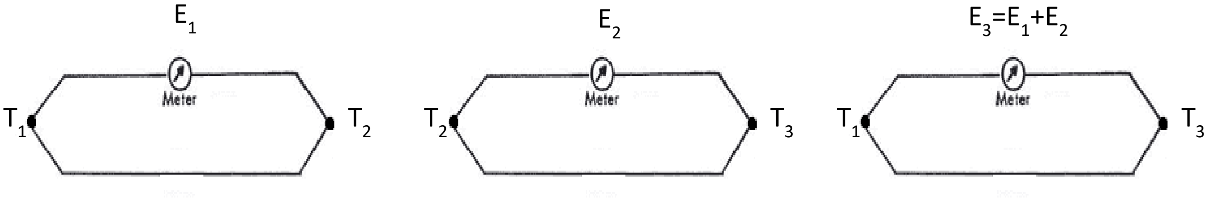
- If a third metal is connected in the circuit as shown in Figure 2.8(b) the net emf of the circuit is not affected as long as the new connections are at the same temperature. This statement may be proved with the aid of the second law of thermodynamics and is known as the law of intermediate metals.
- Consider the arrangements shown in Figure 2.9. The simple thermocouple circuits are constructed of the same materials but operate between different temperature limits. The circuit in Figure 2.9 (a) develops an emf of $E_1$ between temperatures $T_1$ and $T_2$; the circuit in Figure 2.9 (b) develops and emf of $E_2$ between temperatures $T_2$ and $T_3$. The law of intermediate temperatures states that this same circuit will develop an emf of $E_3=E_1+E_2$ when operating between temperatures $T_1$ and $T_3$, as shown in Figure 2.9(c)[1].



(a) (b)

Figure 2.8. (a) Junction of two dissimilar metals indicating thermoelectric effect

(b) Influence of a third metal in a thermoelectric circuit; law of intermediate metals



(a) (b) (c)

Figure 2.9. Circuits illustrating the law of intermediate temperatures

It may be observed that all thermocouple circuits must involve at least two junctions. If the temperature of one junction is known, then the temperature of the other junction may be easily calculated with the thermo-electric properties of the materials. The known temperature is called the reference temperature. A common arrangement for establishing the reference temperature is the ice bath shown in Figure 2.10. An equilibrium mixture of ice and air-saturated distilled water at standard atmospheric pressure procedures a known temperature of 0°C. When the mixture is contained in a Dewar flask, it may be maintained for extended periods of time. Note that the arrangement in Figure 2.9(a) maintains both thermocouple wires at a reference temperature 32°C, whereas the arrangement in Figure 2.9(b) maintains only one at the reference temperature. The systems in instrument were at different temperatures, while the connection in Figure 2.9(b) would be satisfactory if the binding posts were at the same temperature. To be effective the system in Figure 2.9(a) must have copper binding post i.e., the binding post and leads must be of the same material[1].

It is common to express the thermoelectric emf in terms of the potential generated with a reference junction at 32°C. Standard thermocouple tables have been prepared on the basis, and a summary of the output characteristics of the most common thermocouple combinations is given in Figure 2.10[1].

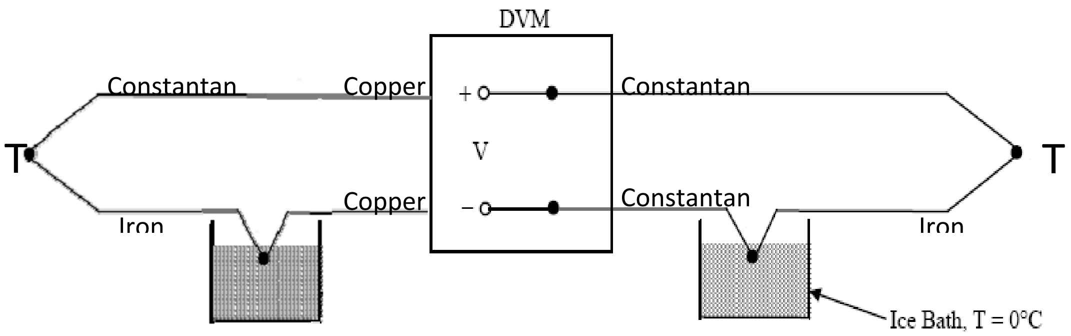


Figure 2.10. Conventional methods for establishing reference temperature in iron-constantan thermocouple circuit.

The output voltage E of a simple thermocouple circuit is usually written in the form,

$$E = AT + \left(\frac{1}{2}\right)BT^2 + \left(\frac{1}{3}\right)CT^3 \qquad (13)$$

where T is the temperature in ºC and E is based on a reference junction temperature of 0ºC. The constants A, B and C are dependent on the thermocouple material. The sensitivity, or thermoelectric power, of a thermocouple is given by

$$S = \frac{dE}{dT} = A + BT + CT^2 \qquad (14)$$

The relation between the thermocouples materials according to the emf and temperatures change can be seen in Figure 2.11[1].

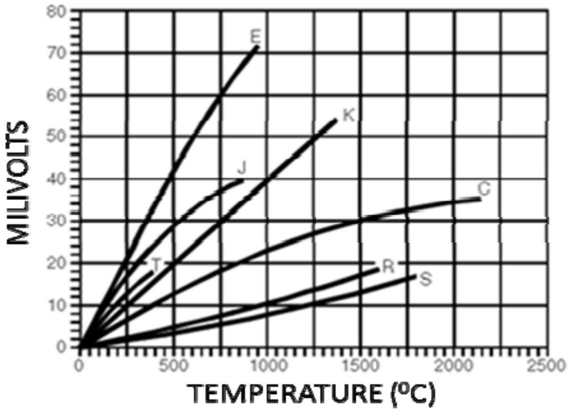


Figure 2.11. Emf temperature relations for thermocouple materials[16]

***Copper-Constantan Thermocouple (T Curve)***

The copper-constantan thermocouple, with a positive copper wire and a negative constantan wire is recommended for use in mildly oxidizing and reducing atmospheres up to 400ºC. They are suitable for applications where moisture is present. This alloy is recom-mended for low temperature work since the homogeneity of the component wires can be maintained better than other base metal wires. Therefore, errors due to the non-homogeneity of wires in zones of temperature gradients is greatly reduced[16].

***Iron-Constantan Thermocouple (J Curve)***

The iron-constantan thermocouple with a positive iron wire and a negative constantan wire is recommended for reducing atmospheres. The operating range for this alloy combination is 870ºC for the largest wire sizes. Smaller wire sizes should operate in correspondingly lower temperatures[16].

### *Chromel-Constantan Thermocouple (E Curve)*

The chromel-constantan thermocouple may be used for temperatures up to 870ºC in a vacuum or inert, mildly oxidizing or reducing atmosphere. At sub-zero temperatures, the thermocouple is not subject to corrosion. This thermocouple has the highest emf output of any standard metallic thermocouple[16].

### *Chromel-Alumel Thermocouple (K Curve)*

The chromel-alumel thermocouple, with a positive chromel wire and a negative alumel wire, is recommended for use in clean oxidizing atmospheres. The operating range for this alloy is 1260ºC for the largest wire sizes. Smaller wires should operate in correspondingly lower temperatures[16].

### *Platinum-Rhodium Thermocouple (S and R Curve)*

Three types of noble-metal thermocouples are in common use. They are:

1. The S curve shows a positive wire of 90% platinum and 10% rhodium used with a negative wire of pure platinum,
2. The R curve indicates a positive wire of 87% platinum and 13% rhodium used with a negative wire of pure platinum, and
3. (not shown) a positive wire of 70% platinum and 30% rhodium used with a negative wire of 94% platinum and 6% rhodium.

They have a high resistance to oxidation and corrosion. However, hydrogen, carbon and many metal vapors can contaminate a platinum-rhodium thermocouple. The recommended operating range for the platinum-rhodium alloys is 1540ºC although temperatures as high as 1780ºC can be measured with the Pt-30% Rh vs Pt-6% Rh alloy combination[16].

### *Tungsten-Rhenium Thermocouple (C Curve)*

Three types of tungsten-rhenium thermocouples are in common use for measuring temperatures up to 2760ºC. These alloys have inherently poor oxidation resistance and should be used in vacuum, hydrogen or inert atmospheres[16].

## 2.3. Density Measurement

Densities of liquids and solids do not change very much with pressure, but for precise measurements for common substances it should be taken into account. The change in density with temperature is illustrated in Figure 2.12 for liquid water and liquid ammonia.

Specific gravity (sp gr), is the ratio of the density (ρ) of a substance to the density of a given reference material.

$$sp\ gr = \frac{\rho substance}{\rho reference} \tag{15}$$

$\rho_{substance}$ is the density of the substance being measured, and $\rho_{reference}$ is the density of the reference meterial. For liquids and solids reference meterial is normally assumed to be water at 4 °C. The specific gravity of gases frequently is referred to air, but may be referred to other gases. Since the density of water at 4ºC is 1.0000 g/cm$^3$ in the SI system, the numerical values of the specific gravity and density in this system are essentially equal. Since densities in the American engineering system are expressed in lb/ft$^3$ and the density of water is about 62.4 lb/ft$^3$, it can be seen that the specific gravity and density values are not numerically equal in the American engineering system[17, 18].

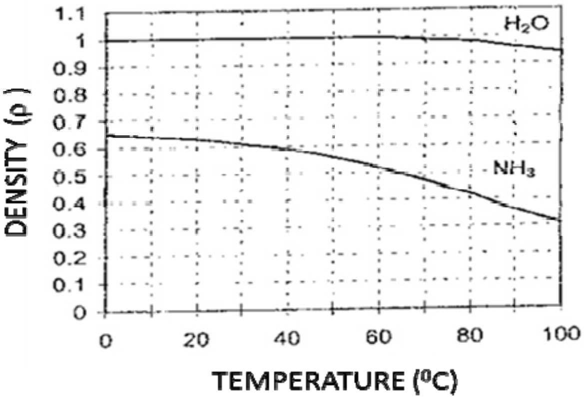


Figure 2.12. Densities of liquid $H_2O$ and $NH_3$ as a function of temperature[9]

Various methods are employed for measuring specific gravity. A **hydrometer** is an instrument used to measure the specific gravity of liquids. A hydrometer is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright. The liquid to be tested is poured into a tall container, often a graduated cylinder, and the hydrometer is gently lowered into the liquid until it floats freely. The point at which the surface of the liquid touches the stem of the hydrometer is noted[22].

In the petroleum industry the specific gravity of petroleum products is usually reported in terms of a hydrometer scale called °API. The equation of API scale is

API = 141/sp. gr. (60°C/60°C)-131.5[1] (16)

The volume and therefore the density of petroleum products vary with temperature, and the petroleum industry has established 60°C as the standard temperature for volume and API gravity.There are many other systems of measuring density and specific gravity, that are somewhat specialized; for example, the Baume (°Be) and the Twaddell (°Tw) systems. These systems are defined as;

°Be=140/sp. gr.(60°C/60°C)-130 (for lighter liquids than water) (17)

and

°Tw=200 (sp. gr.-1.0) (18)

## 2.4 Viscosity measurement

Viscosity ($\mu$), is the ratio of the shear stress ($F/A$) to the velocity gradient ($\Delta v/\Delta y$ or $dv/dy$) in a fluid[19].

$$\tau = -\mu(dv/dy) \tag{19}$$

where; $\tau$ =shear stress between fluid layers in laminar flow (N/m$^2$ or lb/ft$^2$)

$\mu$ =viscosity (kg/m.s or lb/s.ft)

$dv/dy$=normal velocity gradient (s$^{-1}$)[19]

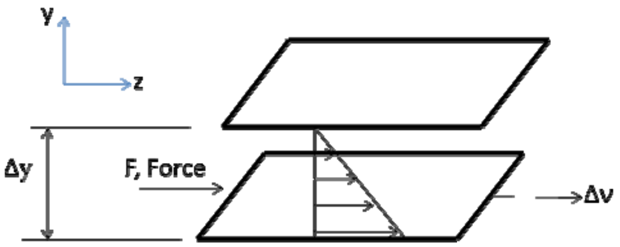


Figure 2.13 Fluid shear between two parallel plates

In Figure 2.13 a fluid is contained between two infinite (very long and very wide) parallel plates. Suppose that the bottom plate is moving parallel to the top plate at a constant velocity. $\Delta v$ m/s faster relative to the top plate because of steady force F newtons being applied. This force is called viscous drag and it arises from the viscous forces in the fluid. The plates are $\Delta y$ m apart. Each layer of liquid moves in the z direction. The layer immediately adjacent to the bottom plate is carried a long at the velocity of this plate. The layer just above is slightly slower velocity, each layer moving at a slower velocity as we go up in the y direction. This velocity profile is linear with y direction as shown in Figure 2.13. An anology to a fluid is a deck of playing cards, where if the bottom card is moved, all the other cards above will slide to some extent[20].

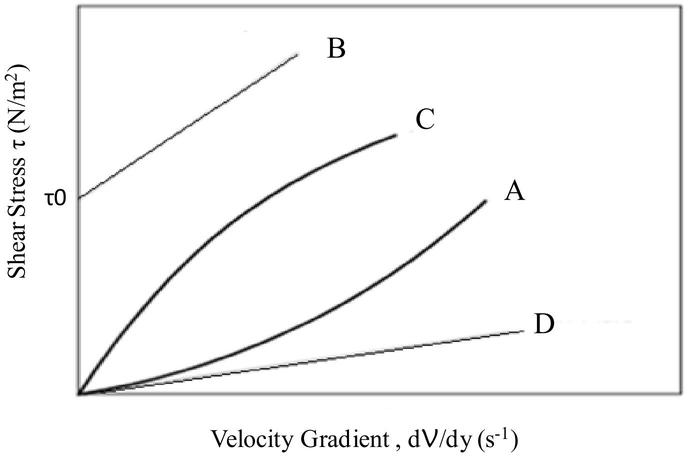


Figure 2.14 Rheological behaviors of Newtonian and non-Newtonian fluids[21]

The relationship between the shear stress and the shear rate in a real fluid are part of the science rheology. Figure 2.13 shows several examples of the rheological behavior of fluids. The curves are plots of shear stress vs. rate of shear and apply at constant temperature and pressure. The simplest behavior is that shown by curve A, which is a straight line passing through the origin. Viscosity it is a constant over a wide range of shear rates Fluids following this simple linearity are called Newtonian fluids. Gases and most liquids are Newtonian[7].

Non-Newtonian fluids exhibit a variety of different correlations between shear stress and shear rate. The other curves shown in Figure 2.13 represent the rheological behavior of liquids called non-Newtonian[1].

Some liquids, e.g., sewage, do not flow at all until a threshold shear stress, denoted by $\tau_0$, is attained and then flow linearly at shear stresses greater than $\tau_0$. Curve B is an example of this relation. Liquids acting this way are called Bingham plastics. Line C represents a pseudoplastic fluid. The curve passing through the origin, is concave downward at low shears, and becomes linear at high shears. Rubber latex is an example of such fluid. Curve D represents a dilatant fluid. The curve is concave upward at low shears and become linear at high shears. Quick sand and some sand-filled emulsions show this behavior. Pseudo-plastics are said to be shear-rate-thinning and dilatant fluids shear-rate-thickening[1].

Various methods are employed for the measurement of viscosity. The two most common methods are the rotating concentric cylinder method and the capillary flow method. Perhaps the most common method of viscosity measurement of the pressure drop in laminar flow through a capillary tube.

The Reynolds number defined by:

$$Re = \rho v D/\mu \tag{20}$$

where $\rho$=density of fluid (kg/m$^3$)

$\mu$=viscosity of fluid (kg/m.s)

$v$=linear velocity (m/s)

D=diameter of the tube (m)

If Re is less than 1000 laminar flow will exist in the tube and the familiar velocity profile will be experienced as shown in fluid mechanics. If the fluid is incompressible and the flow is steady, it can be shown by means of momentum balance over the shell in Figure 2.15 that the volumetric flow rate Q (m$^3$/s) can be written as

$$Q = \pi r^4 (P_1 - P_2)/8\mu L \tag{21}$$

where; r = radius of the tube (m)

P = pressure (N/m$^2$)

$\mu$ = viscosity of fluid (kg/m.s)

L = length of the tube (m)

Hence, Eq. (21), which is the ***Hagen-Poiseuille equation***, relates the pressure drop and average velocity for laminar flow in a horizontal pipe.

A viscosity determination may be made by measuring the volumetric flow rate and the pressure drop for flow in such a tube. To ensure that laminar flow exists, a small diameter capillary tube is used; the small diameter reduces the Reynold number as calculated from Eq. (20) the product r.$v$ may be calculated from;

$$\rho.v = \dot{m}/(\pi.r^2) \qquad (22)$$

where $\dot{m}$ is the mass flow rate. (kg/s)[1].

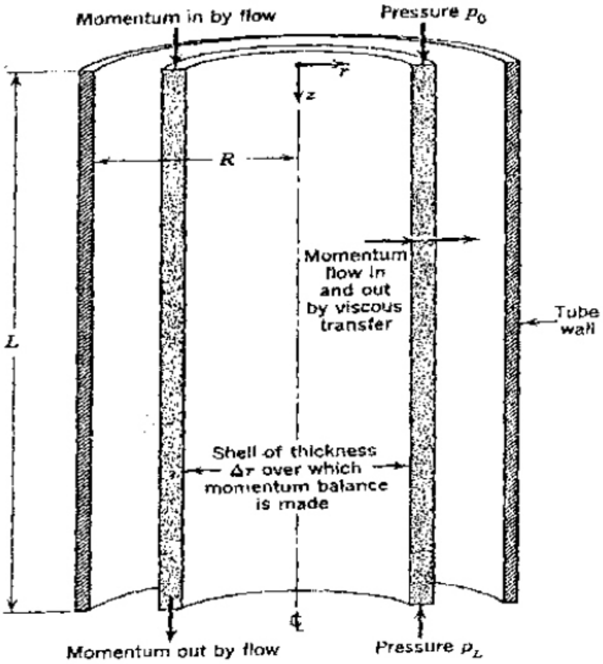


Figure 2.15 Cylindrical shell of fluid over which momentum balance is made to get the velocity profile and the Hagen-Poiseuille formula (Eq. 21) for the volumetric flow rate[1]

When a viscosity measurement is made on a gas the compressibility of the gas must be taken into account. The resulting expression for the mass flow of the gas under laminar flow conditions in the capillary is:

$$\dot{m} = (\pi.\frac{r^4}{16.\mu.R.T})(P_1^2 - P_2^2) \qquad (23)$$

where R is the gas constant for the particular gas. Care must be taken to ensure that the laminar flow in the capillary is fully developed, i.e., the parabolic velocity profile has been established. This means that the pressure measurement should be taken far enough down-stream from the entrance of the tube to ensure that developed flow conditions persist. It may be expected that the flow will be fully developed when;

$$L/D>Re/8 \qquad (24)$$

where L (m) is the distance from the entrance of the tube.

The viscosity of the liquids depends on the shape and dimensions of the molecules and the attractive forces between the molecules. The viscosity of liquids increases with the pressure. The effect of temperature on the liquid viscosity may be given by the ***Arrhenius equation***:

$$\mu = A.\exp(\frac{B}{T}) \qquad (25)$$

where; T : Absolute temperature (K)

A,B : Constants depend on the liquid

The simplest device used in the measurement of viscosity in liquids is Ostwald viscometer (Figure 2.15). For measuring the viscosity; a certain volume of liquid is put into the C bulb. The top level of the liquid is set to the top mark indicated by X, by means of vacuum. The time necessary for flowing of liquid from X to the Y level is measured by chronometer. Then viscosity can be calculated by using Eq. (21). But in common way, the viscosity of a liquid is determined against a reference liquid. More satisfactory results can be obtained, using this indirect measurement technique in which the same measurement is repeated in the same flow conditions with a reference liquid which has a known viscosity, i.e., pure water. The efflux time is measured both for reference liquid and sample. The viscosity is calculated by means of the following expression.

$$\mu_1/\mu_2 = (t_1/t_2)(\rho_1/\rho_2) \qquad (26)$$

where; $\mu_1$ and $\mu_2$ (kg/s.m) are the viscosities, $t_1$ and $t_2$ (s) are the efflux times, and $\rho_1$ and $\rho_2$ (kg/m$^3$) are the densities of reference solution and the solution whose viscosity will be determined, respectively.

Engler viscometer is used for the determination of viscosity in more viscous fluids. It contains two concentric cylinders equipped with an electrical heater. The outer one is used as oil bath. The inner one is filled with the liquid up to the marked level and the flowing hole present at the bottom of the inner one is opened. If it is necessary the inner cylinder may be heated by oil bath. The efflux time is measured with a chronometer. The same experiment is repeated with a reference liquid and the unknown viscosity is calculated by means of Eq. (26)[1].

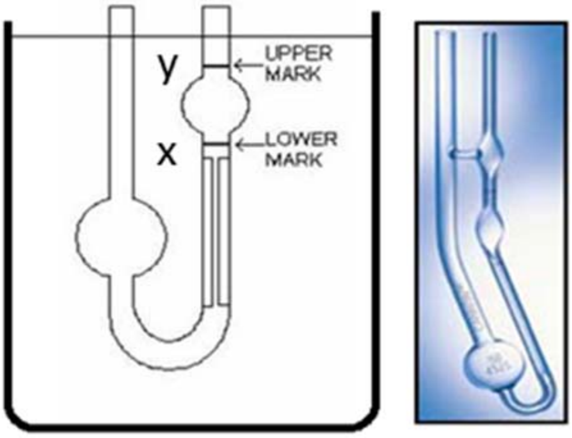


Figure 2.15. Ostwald viscometer[10]

Torsion viscometer works on the principle that when a cylinder is rotated in a sample a viscous drag is exerted on it. In this instrument the cylinder is rigidly attached to a heavy flywheel are rotated manually through one 360° turn and then released. They rotate back through the starting position and continue rotating to an angle of overswing which can be read on a graduated scale. The viscosity of the sample is a function of the angle of overswing. For greatest accuracy, a combination of torsion wire and cylinder should be selected to give an overswing of between 100° and 300°.

The “Viskotester VT 01” is sample rotational viscometer, especially suited for fast comparison tests on liquids. A rotor, driven by a speed-controlled, battery-operated motor, is immersed into the liquid to be tested. The viscosity of the liquid is measured as a resulting torque and is indicated directly on the scale[1].

## 3. EXPERIMENTAL PROCEDURE

### 3.1. Safety

There are many potential hazards in the laboratory and some of them can cause quite a serious accident. However, many accidents in the laboratory can be prevented if each person in the laboratory observes a set of common precautions and uses proper experimental techniques and procedures at all times[23].

Some of the more important specific laboratory rules and precautions while performing this experiment are summarized here:

- In the event of a mercury spill, regardless how small, first warn your instructor, and then pick up as much of the mercury as possible (use a glass or metal capillary tube connected to a trap bottle and an aspirator). If there is very small amount of mercury, sprinkle any contaminated area with sulfur, and after 48 hours sweep up as much of it as possible[24].
- Broken thermometer parts with mercury should not throw away to garbage or a sink, you should warn your instructor.
- Your hands and the buttons of the device have to be dry when you working with an electrical device.
- You have to be careful when you are working with the pump. The amount of pressure and the vacuum that you apply should not change without permission of the instructor.

### 3.2. Part I : Pressure Measurement

- Determine the differential height of the fluid for each monometer when pressure and vacuum are applied.
- Measure the pump outlet pressure by C-Bourdon tube monometer.
- Measure the vacuum by the C-Bourdon tube manometer.
- Measure the pressure difference using diaphragm gauge for different liquid heights.
- Measure the pressure difference using test manometer for different liquid heights.
- Measure the pressure difference using digital manometer for different liquid heights.
- Calculate the pressure as mm water, mmHg, Ibf/in$^2$, atm, bar and Pascal for each manometer.
- Calculate the sensitivity, i.e. the minimum pressure value that can be read, for each manometer.
- Calculate the pressure as mbar for diaphragm gauge and U-tube manometer and calculate the sensitivity of the diaphragm gauge

## 3.3. Part II : Temperature Measurement

- Put the reference point thermocouple in an ice-water mixture and the measurement thermocouple into a hot water bath. While the liquid in the tank is being heated from 25℃ to 80℃, record thermocouple output voltages and all thermometer readings for 10℃ intervals using platinum resistance thermometer as reference.
- Put mercury, alcohol and resistance thermometers in an ice bath. Then immerse thermometers immediately in water at 80℃. Record the time vs temperature with 10℃ intervals. Repeat the same procedure for 50℃.
- Measure the temperature of hot and ice bath's surface with the surface temperature, compare the values with mercury and alcohol thermometers and record the temperatures values.
- Determine the deviation from linearity and sensitivity of thermocouples. Compare thermocouples on the base of sensitivity.
- Show the pulse effect and the response on a graph for both thermometers (mercury and alcohol) by drawing the temperature vs. time. Find on this graph the time when thermometer temperature is equal to the bath temperature. This time value is the response time for the thermometer. Compare and discuss the response curves of both thermometers.

## 3.3. Part III : Density Measurement

### *Picnometric Determination of Liquid Density*

- Weight dry and clean picnometer (a small flask having an exact volume)
- Fill the liquid up to the marked level of the picnometer
- Weight the picnometer after filling with liquid
- The liquid density may be determined using the following formula:

$$\rho = m/V$$

where; ρ is the liquid density (g/cm$^3$), m is the mass of the liquid in the picnometer (g) and V is the volume of the picnometer (cm$^3$).

### *Hydrometric Determination of Liquid Density*

- Read the point on the scale corresponding to the liquid level after immersing the hydrometer (a known weight with a definite volume is dropped into the liquid and the depth penetrating into the liquid and the depth penetrating into the liquid is noted, Figure 2.16) into the liquid (50% glycerol solution at different temperatures in the range of 50-70 ºC). a right hydrometer with a suitable scale should be chosen from the set according to the density value of the liquid.

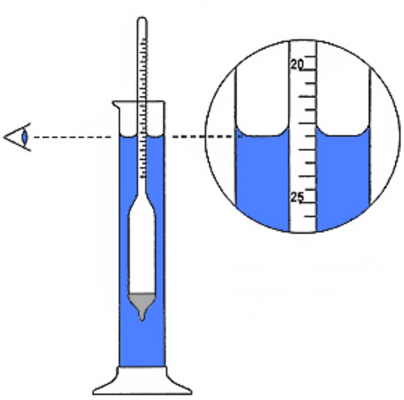


Figure 2.16. A Hydrometer[11]

***Picnometric Determinatin of Solid Density***

- Weight a dry and clean picnometer ($m_1$)
- Put about 1 gr of solid meterial with unknown density into the picnometer. ($m_2$)
- After removing the solid meterial fill the reference liquid up to the marked level of picnometer and reweigh ($m_3$)
- Then put the solid meterial into the liquid filled picnometer and reweigh ($m_4$)

$$\rho_s = \frac{(m_2 - m_1)}{[(m_1 - m_2) - (m_4 - m_3)] / \rho_{water}} \tag{27}$$

where; $\rho_s$ is the solid density (kg/m$^3$),

$\rho_{water}$ is the density of reference liquid (kg/m$^3$),

m is the mass (kg).

### 3.4. Part IV : Viscosity Measurement

- Determination the viscosity of 50% glycerol-water solution at different temperatures in the range of 50-70ºC with Ostwald Viscometer by using pure water as reference liquid.

Discuss the effect of temperature on liquid viscosity and determine A and B constants of Eq. (25).

- Determine the viscosity of 50% glycerol-water solution at different temperatures in the range of 50-70ºC with Engler Viscometer. Discuss the effect of temperature on liquid viscosity and determine A and B constants of Eq. (25).
- Determine the viscosity of 100% glycerol-water solution at different temperatures in the range of 50-70ºC with Torsion viscometer. Discuss the effect of temperature on liquid viscosity and determine A and B constants of Eq. (25).

## 3. REFERENCES

[1] Glasstone S.,Lewis D., "Elements of Physical Chemistry", 2nd Ed, Mac Millian Co., London, pp:28-29, 147-150, (1960).

[2] Michell, J., "The origins of the representational theory of measurement: Helmholtz, Hölder, and Russell" Studies in History and Philosophy of Science, Vol. 24, 185-206, (1993).

[3] http://www.evitherm.org/default.asp?ID=249

[4] Giancoli, Douglas G., "Physics: principles with applications", Upper Saddle River, N.J.:Pearson Education. ISBN 0-13-060620-0, (2004).

[5] Beckwith, Thomas G.; Roy D. Marangoni and John H. Lienhard V, "Measurement of Low Pressures". Mechanical Measurements (Fifth ed.). Reading, MA: Addison-Wesley. pp. 591–595. ISBN 0-201-56947-7, (1993).

[6] Massey, B S., Mechanics of Fluids, 5th edition, (1983).

[7] Raymond A. Serway, "Physics for Scientists & Engineers" (4th ed.). Saunders College Publishing. ISBN 0-03-005932-1, (1996).

[8] http://www3.museumofmaking.org/dbtw-wpd/indicators.htm

[9] McCabe W.L., Smith J.C., "Unit Operations of Chemical Engineering", 2nd Ed., Mc. Graw Hill Book Company, Tokyo, pp:51-52, (1967).

[10] http://www.tpub.com/content/engine/14037/css/14037_58.htm

[11] Himmelbau, D. M., "Basic Principles and Calculations in Chemical Engineering", Prentice-Hall International Inc., USA,

[12] http://www.sensorsmag.com/sensors/temperature/temperature-measurement-1030

[13] http://schoolnet.gov.mt/physics/HeatEnergy1.htm

[14] http://www.johnsherman.com/therms/Surface.html

[15] Robert C. Weast, "Handbook of Chemistry and Physics", 55th Ed., CRC Press, (1975)

[16] http://www.megatron.co.il/Thermocouple.html

[17] Dana, Edward Salisbury, A text-book of mineralogy. John Wiley and Sons. pp. 195–200, 316, (1922).

[18] Schetz, Joseph A.; Allen E. Fuhs, Fundamentals of fluid mechanics. Wiley, John & Sons, Incorporated. pp. 111,142,144,147,109,155,157,160,175, (1999).

[19] http://physics.info/viscosity

[20] Geankoplis, C. J., "Transport Processes and Unit Operations", 3rd Edition, p. 47-48

[21] http://en.wikipedia.org/wiki/Non-Newtonian_fluid

[22] "The New Student's Reference Work/Lactometer - Wikisource". en.wikisource.org. http://en.wikisource.org/wiki/The_New_Student%27s_Reference_Work/Lactometer. Retrieved 2009-10

[23] delloyd.50megs.com/hazard/labsafety.html

[24] ehs.colorado.edu/download/LabSaf.pdf

## 4. NOMENCLATURE

A : Constant in Eq. 13
$A_1$,$A_2$ : Cross sectional area of U manometer tubes
a : Experimentally determined constants in Eq. (11)
B : Constant in Eq. 13
b : Experimentally determined constants in Eq. (11)
BUS : British Unit System
C : Constant in Eq. 13
°C : Centigrade
E : Electro motor force (emf)
°F : Fahrenhait
g : Gravity (9.80665 m/s$^2$)
$g_c$ : Gravitational conversion factor (32.1740 Ibm$_f$.ft/Ib$_f$.s$^2$)
h : Displacement in the manometer (m)
°K : Kelvin
$\dot{m}$ : Mass flow rate (kg/s)
mV : Milivolt
$M_w$ : Molecular weight (kgmol/kg)
Pt : Platinium
$P_{ref}$ : Reference pressure (N/m$^2$)
P : Pressure (N/m$^2$)
$P_o$ : Athmospheric pressure (N/m$^2$)
psia : Absolute psig (N/m$^2$)
°R : Rankine
R : Gas constant (m$^3$.Pa/K.kgmol)
$R_i$ : Resistance of the material at Ti (ohm)
S : Sensitivity or electric power of a thermocouple
SI : Standard International Unit
T : Temperature (K)
$T_{ref}$ : Reference temperature
$T_o$ : Experimentally determined constant in Eq. (12) (K)
V : Volume (m$^3$)

$\beta$ : Experimentally determined constant in Eq. (12)

$\mu$ : Viscosity (kg/m.s)

$\alpha$ : Linear temperature coefficient

$\rho_f$ : Density of the fluid transmitting the pressure f (kg/m$^3$)

$\rho_m$ : Density of the manometer fluid (kg/m$^3$)

Name Surname:

Number: Date:

Group Number:

*Assistants*

A. Aslıhan Bayraktar

G. Dicle Demir

## 5. DATA SHEET

Experiment: Basic measurements of pressure, temperature, density and viscosity

### PART I. PRESSURE MEASUREMENTS

### U-Tube Manometers

| **Manometer Fluid** | **Pressure Reading**<br>**Δh (cm Fluid)** | **Pressure Reading**<br>**Δh (cm Fluid)** |
|---|---|---|
| **Glycerin** | | |
| **Water** | | |
| **Motor oil** | | |

### Bourdon-tube Pressure Gauge

| | |
|---|---|
| **Pressure (kgf/cm$^2$)** | |
| **Vacuum (mm Hg)**<br>**Vacuum (mm Hg)** | |

### Diaphragm Gauge

| **$\Delta P_D$ (torr)** | **Δh (cm water)** |
|---|---|
| | |
| | |
| | |
| | |

| | |
|---|---|
| | |

## PART II. TEMPERATURE MEASUREMENTS

### Thermometer and thermocouple settings

| Pt Resistance Thermometer (ºC) | Alcohol Thermometer (ºC) | Mercury Thermometer (ºC) | Thermal Expansion Thermometer (ºC) | Iron-Constantan Thermocouple (milivolt) | Chromel-Alumel Thermocouple (milivolt) |
|---|---|---|---|---|---|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

### Response Time of Alcohol and Mercury Thermometers

Hot water bath temperature: 80 $^0$C

| Temperature (ºC) | Time (s) | Time (s) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Hot water bath temperature: 50 $^0$C

| **Temperature ($^o$C)** | **Time (s)** | **Time (s)** |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

## PART III. DENSITY MEASUREMENTS

### 1. Determination of Liquid and Solid Density by Pycnometer

| Liquid Density | Solid Density |
|---|---|
| $m_1$= | $m_1$= |
| $m_2$= | $m_2$= |
| V= | V= |
| T= | T= |

### 2. Determination of Density by Hydrometer

| **T(°C)** | **ρ(g/ml)** |
|---|---|
| | |
| | |
| | |

## PART IV. VISCOSITY MEASUREMENTS

### 1. Determination of Viscosity by Engler Viscometer

| $T(^oC)$ | $t_1(s)$ | $t_2(s)$ |
|---|---|---|
| | | |
| | | |
| | | |

### 2. Determination of Viscosity by Ostwald Viscometer

| $T(^oC)$ | $t_1(s)$ | $t_2(s)$ |
|---|---|---|
| | | |
| | | |
| | | |